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AID TO DISABLED VEHICLES

by

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DEDICATION

I dedicate this thesis to my wife, Gail.

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Abstract

AID TO DISABLED VEHICLES

This research focuses on an analysis of various highway aid dispatching strategies using the theory of queues and a Monte Carlo computer simulation. Two important highway aid dispatching problems are solved using the theory of queues. In particular, the solutions of the first encounter, first serve and first disabled, first serve highway patrol problems are derived. In the latter problem, it is assumed that as soon as a vehicle becomes disabled, an aid vehicle is immediately dispatched. The impact on the queuing models is discussed when this assumption is relaxed.

A Monte Carlo computer simulation is conducted to evaluate and compare various dispatching strategies according to the benefits derived by the disabled motorist and the maintenance and operating costs for implementing each strategy. The main focus of the simulation is a comparison between the conventional highway patrolling system and an electronic surveillance system which employs automatic vehicle identification. There it is shown that under certain traffic conditions, the system utilizing electronic surveillance is more favorable to the conventional patrol.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Motorist Aid Systems

The primary purpose of a highway system is to provide a safe and efficient flow of goods and movement of people. Major causes of loss of efficiency and safety on the highway system are those events which are related to vehicle incidents. In this research, a vehicle incident is considered to be either a highway accident or a disabled vehicle problem. Highway accidents involve loss of life, injury and/or major damage to the vehicles, while stoppages due to mechanical and tire trouble, and out of gas, oil or water are considered to be disabled vehicle problems.

The obvious consequences of vehicle incidents include reduced traffic flow and increased congestion and delay, chain reactions and secondary incidents, and death and injury. In a two year study[1] on the effects of vehicle incidents on the level of highway service, it was discovered that vehicle incidents create a reduction of flow disproportionate to the physical reduction of roadway width. Furthermore, of all the vehicle incidents observed during this period, those which involved disabled vehicles created a delay of 1610 vehicle hours while the 1 lane and 2 lane highway accidents caused delays of 2940 and 4620 vehicle hours, respectively. In reference (2), it is reported that there are 1,460,000 secondary accidents per year due to stopped vehicles and

67 percent of all accidents may be attributed to off lane traffic.[3] Death rates, although decreased since the 1973 fuel crisis, are still very high. In 1974 there were 46,200 deaths reported, while in the month of January 1975, 3,220 persons were killed as opposed to 4,140 deaths in January 1972 prior to the fuel crisis.[4] The New York State Thruway Authority in 1970 recorded 95 fatalities and 2,674 injuries after more than 4 billion vehicles miles traveled.[5] Furthermore, motorists involved in highway incidents create hazards for themselves and fellow motorists by abandoning their vehicles, crossing operating lanes, hitchhiking and climbing fences.[6]

In independent studies,[3,7,8] it was reported that highway incident rates are proportional to the average daily traffic and average trip length and increase as highway conditions degrade. Over 126 million stops, for reasons other than accidents, occur each year.[3] In Table 1-1, a typical emergency stop distribution is illustrated.[9]

Beset with these overwhelming statistics, possible solutions to reduce the effects of vehicle incidents are reduction of traffic volumes and congestion and the improvement of fast and efficient dispensing of aid to the victims of vehicle incidents. Reducing traffic congestion requires increasing roadway capacity or reducing vehicular demand by such techniques as modal shifts to high occupancy vehicles or bus travel.[10] This research focuses on the implementation of the latter solution, that is, providing fast and efficient

Table 1-1 A Typical Emergency Stop Distribution

Cause	Percent
Mechanical	33.7
Tire	33.7
Gas/Oil/Water	22.4
Medical Aid	2.3
Fire	2.3
Accident	5.6

motorist aid.

In 1970 there existed 19 operating radio and telephone motorist aid systems in 12 states and more than a dozen in the planning stages.[6] Reference (11) reports on eleven freeway surveillance and control systems used for detecting and dispensing aid to motorists involved in highway incidents.

Motorist aid systems may be considered to be comprised of the following three essential components: detection, communication and verification, and assistance. Detection is the ability of a motorist aid system to determine the position and time of occurrence of a vehicle incident. Most research to date has focused on this aspect of six motorist aid systems. Present day methods of detection are numerous. Police and citizen patrolling systems such as REACT[6] provide rapid response in detecting vehicle incidents; however, the maintenance and operating costs of a patrolling system are prohibitively high.[6,11,12] Involved and passing motorist detection systems such as roadside telephone and radio systems,[6,13,14,15] cooperative motorist systems,[16,17] and off ramp telephones[6] have been developed within the last decade. Reportedly successful, these systems are cheaper than patrols but are not as reliable. Surveillance and control systems[11,18,19] use presence detectors imbedded in the roadway and apply various mathematical algorithms to analyze traffic flow patterns for indications of vehicle incidents.[11,20,21,22,23,24] This approach is considered to be the most effective method of incident detection and much research is presently being conducted in this direction.[11,23] Other methods of incident detection are helicopter and fixed wing aircraft surveillance, TV monitorings and permanently stationed observers.[6]

Methods of communicating and verifying vehicle incidents include roadside telephone and radio systems, TV monitoring, commercial radio,[25] and dedicated radio units which transmit information between the involved vehicle and the highway headquarters.[26,27]

This research focuses on the final and, probably, the most important component of a motorist aid system: assistance. A motorist aid system is useless unless aid is dispatched in the most effective manner possible. In this research, various dispatching strategies are evaluated and compared according to benefits derived by the disabled motorist and the maintenance and operating costs for implementing each strategy.

1.2 The Need for the Efficient Dispatching of Aid

In a 1962 report, the American Association of State Highway Officials (AASHO) stated: "The sole purpose of an emergency communication system is to save time -- that is, to reduce the time that a motorist in distress has to wait for assistance and... that other highway users, might be subjected to accident hazards and delays to traffic movement."[28] Another report[29] investigating the problems of motorist aid suggests that the benefits of any emergency aid system must be measured in terms of the reduction of the total waiting time experienced by the disabled motorist and if lower response times cannot be achieved by improving the detection time alone, efforts should be made to reduce the response time of aid vehicles. Yet, to date little research has been addressed to investigating and evaluating the response times of aid vehicles for various aid dispatching strategies. This fact is reflected in the present procedures that highway officials use to dispatch aid.[30,31,32,33] Local agencies were polled regarding this issue and the ambiguity and lack of information on efficient ways of dispatching aid may be summed up by the following response of one of the officials:[34] "Service calls are usually handled in the order they are received or the one closest to the tow truck." Most agencies which operate and maintain services on the rural and urban highways contract private tow truck operators on a 24-hour standby basis.[9,30,33] When an incident has been detected (usually via police patrol, passing motorist, telephone communications, etc.) the closest contractor is determined and an aid vehicle is dispatched. This research questions these procedures and attempts to discover how and if these practices should be changed. The aid dispatching procedures or policies evaluated in this study are analyzed according to a cost-benefit criteria.

1.3 Summary of Research

In this research, two approaches for evaluating aid dispatch policies are utilized: (1) analytic solutions of aid dispatch problems using the theory of queues and (2) experimental investigation and comparison of various dispatch policies using the technique of Monte Carlo simulation.

Analytic solutions of aid dispatch problems were obtained for the average waiting time experienced by a disabled motorist when either of the following dispatch service rules are employed: an aid vehicle services incidents in (1) the time sequence in which incidents occur and (2) the order in which incidents are encountered along the roadway.

The aid dispatch problem defined by the first rule is shown to be isomorphic to a simple temporal priority queuing problem and is solved by applying the results of the well known M/G/1 queuing theory. In terms of queuing classification, the second aid dispatch problem may be described as a dynamic priority preemptive queue where the priority structure is defined by the service time distribution.*

Much work[36,37,38,43] may be found in the queuing literature concerning dynamic priority queuing problems and queuing problems associated with priorities which are functions of the customers' service time; however, to date there is little

*The service time of an incident is considered to be the sum of the times accumulated by the aid vehicle traveling and rendering aid to the incident.

research which simultaneously considers both constraints. For example, Jackson[37] and Kleinrock[38] consider queues where a customer's service priority increases linearly with the time the customer spends in the queue. However, in both studies, only a discrete number of priority classes are admissible. Since the service time distribution of incidents is continuous, it is obvious that these works are inapplicable.

In this research the solution of this aid dispatch problem is achieved by applying the theory of queues with periodic service and constant changeover time.[39] By considering the roadway divided into M equal sections, it is shown that an approximate solution for the average wait time experienced by the disabled motorist may be obtained using this theory. Furthermore, as M becomes large, the approximate solution will approach the exact solution. The computations of the waiting time obtained using the analytic solution are compared to those obtained from a Monte Carlo simulation and the results compare favorably.

Empirical data gathering and experimental studies for evaluating transportation systems is usually very time consuming and costly and thus undesirable. However, with the advent of high speed digital computers, an alternative approach is computer simulation. An up-to-date and extensive list of the various digital computer simulation programs designed for transportation applications may be found in reference (40). In particular, much computer simulation research on evaluating various motorist aid systems has been conducted by the University of California at Berkeley.[41,42]

In this present research study, various aid dispatch systems are compared and evaluated using Monte Carlo simulation. Specifically, the conventional highway patrolling system is compared to a proposed electronic detection system and it is found that under certain conditions, the electronic detection system employing a first encounter, first service aid dispatch policy (i.e. the second service rule described above) is cost-benefit superior to the patrolling system. Preceding the discussion of the results of the simulation, the procedures and techniques for conducting a Monte Carlo simulation experiment are examined. Fundamental questions pertaining to the proper values of the initial and final conditions of the simulation run, the need for replication to determine statistical confidence, etc. are addressed. A new method for determining when a discrete stochastic sequence has reached a stationary state is also presented.

CHAPTER 2

FORMULATION OF A FIRST ENCOUNTER FIRST SERVE HIGHWAY PATROLING PROBLEM USING THE THEORY OF QUEUES

2.1 Introduction

In the following two chapters, a first encounter first serve highway patrol problem and a first disabled first serve highway aid dispatch problem are analyzed and solved using the theory of queues. Isomorphisms may be shown to exist between some aid dispatch problems and queuing systems. In this study these queuing isomorphisms are exploited in order to obtain the mean waiting time experienced by a disabled motorist. For example, the highway aid dispatch policy in which a single aid vehicle renders aid to disabled vehicles in the sequence in which they break down may be shown to be isomorphic to the well known M/G/1 queuing system. The solution and a discussion of this policy are given in Chapter 3.

In this chapter the theory of queues with periodic service and changeover time developed by Eisenberg[1] is redeveloped and expanded in order to provide the basis for solving the queuing problem associated with the continuous patrol of a highway for disabled vehicles.

In order to obtain the mean waiting time experienced by a disabled motorist in such a continuous patrol system, the following assumptions are made. A limited access rural highway environment is assumed in which one patrol vehicle continuously cruises a highway loop at constant speed, V, and renders aid to disabled vehicles in the sequence in which they are encountered. Vehicle malfunction occurs as a random process temporally Poisson distributed, with parameter λ, and spatially distributed uniformly around the loop. It is also assumed that the patrol vehicle spends an average service time T_f, from distribution $F_s(t)$, with each disabled vehicle. An approximate solution for the mean waiting time experienced by a disabled motorist is obtained by considering the highway loop, of length D divided into M equal length sections, each of length D/M and applying Eisenberg's results to the resultant periodic service queue. When M is large, the sectioned loop approaches the continuous loop. An algorithm for efficiently formulating and sequentially solving two sets of simultaneous equations required to obtain the mean waiting time is developed. The approximate mean waiting time is calculated as a function of the number of sections, M, for different values of λ. For large M the asymptotic mean waiting time is compared to a sample mean waiting time obtained independently from a Monte Carlo simulation of the continuous highway loop. The results compare favorably and are discussed in the following chapter.

2.2 The Continuous Patrol Queuing Problem Approximated As a Periodic Service Queue

In each highway section, of length D/M, vehicles become disabled at an average rate λ/M. It is assumed that all vehicles break down at the center of each section and are served first-in, first-out until that section is empty. A constant changeover time equal to D/MV, the transport delay required by a patrol vehicle (travelling at constant speed V) to traverse a single section, is required before the server may switch from one queue to an adjacent queue. Thus, we have a periodic service system of M queues attended to by a single server. It is noted that for large M the periodic service queuing system closely approximates the continuous first encounter first serve patrol vehicle system and thus, it serves as the basis for solving the continuous queuing problems.

2.3 The Application of the Periodic Service Queue Structure to the Highway Patrol Problem

For the sake of continuity and clarity, the periodic service queuing structure analyzed by Eisenberg is applied, in this section, to the highway patrol problem. Many additions and simplifications not found in Eisenberg's work on periodic service queues will be included in this presentation.

2.3.1 Notation

Imbedded Markov chains are formed at the instants of service beginning, service completion, stage beginning and stage completion; where a stage is defined as the time interval in which a patrol vehicle services a single section. The cycle time is the time interval required for the patrol vehicle to execute one revolution of the highway loop. The intervisit time is the time interval from a section i stage completion to the section i stage beginning, It is noted that the cycle time equals the intervisit time plus the time required to service section i. The state of each Markov chain at regeneration epochs is described by i, the section in which the patrol vehicle is servicing, and by $\tilde{n} = (n_1, n_2, \ldots, n_M)$, the number of disabled vehicles present in sections 1, 2, ..., M respectively. The asymptotic probabilities of the Markov chains are defined as $w^i_{\tilde{n}}, \pi^i_{\tilde{n}}, \alpha^i_{\tilde{n}}, \beta^i_{\tilde{n}}$ which are the section i state probabilities at the service beginning instants, service completion instants, stage beginning instants and stage completion instants respectively. The generating functions are defined as

$$\varpi^i(\tilde{z}) = \omega^i(z_1, z_2, \ldots, z_M) = \sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_M=0}^{\infty} \varpi^i_{\tilde{n}} z_1^{n_1} z_2^{n_2} \cdots z_M^{n_M}$$

and likewise for $\pi^i(\tilde{z})$, $\alpha^i(\tilde{z})$, and $\beta^i(\tilde{z})$. Since section i is empty at a section i stage completion, $\beta^i(\tilde{z})$ is independent of z_i.

The number of section i service beginnings, service completions, stage beginnings, and stage completions, with state $(n_1, n_2, \ldots n_M)$ that occur in the interval (0,t) are defined as $\varpi^i(t,\tilde{n})$, $\pi^i(t,\tilde{n})$, $\alpha^i(t,\tilde{n})$ and $\beta^i(t,\tilde{n})$ respectively. The total number of service beginnings and section i stage beginnings that occur (0,t) is, therefore, given by

$$\varpi(t) = \sum_{i=1}^{i=M} \sum_{n_1=0}^{\infty} \cdots \sum_{n_M=0}^{\infty} \varpi^i(t,\tilde{n}),$$

and

$$\alpha^i(t) = \sum_{n_1=0}^{\infty} \cdots \sum_{n_M=0}^{\infty} \alpha^i(t,\tilde{n})$$, respectively,

and likewise for $\pi(t)$ and $\beta^i(t)$.

2.3.2 The Steady State Equations

When $\lambda/M < 1/T_f$, i.e. the probability that the patrol will spend an infinite time in any section is zero, then $\varpi(t)$, $\alpha^i(t)$, $\pi(t)$ and $\beta^i(t)$ approach infinity as t goes to infinity. Therefore, using the strong law of large numbers,[2] it follows that

$$\lim_{t\to\infty} \frac{\varpi^i(t,\tilde{n})}{\varpi(t)} = \varpi^i_{\tilde{n}}, \qquad \lim_{t\to\infty} \frac{\pi^i(t,\tilde{n})}{\pi(t)} = \pi^i_{\tilde{n}},$$

$$\lim_{t\to\infty} \frac{\alpha^i(t,\tilde{n})}{\alpha^i(t)} = \alpha^i_{\tilde{n}}, \qquad \lim_{t\to\infty} \frac{\beta^i(t,\tilde{n})}{\beta^i(t)} = \beta^i_{\tilde{n}}, \tag{2-1}$$

with probability one.

Since for every service completion or stage beginning a service beginning or stage completion occurs, it is evident that

$$\alpha^i(t,\tilde{n}) + \pi^i(t,\tilde{n}) = \varpi^i(t,\tilde{n}) + \beta^i(t,\tilde{n}). \tag{2-2}$$

The following relation may be obtained by dividing Eq. (2-2) by $\pi(t)$, then taking the limit as t approaches infinity and using Eq. (2-1):

$$\alpha^i_{\tilde{n}} \lim_{t\to\infty}\left[\frac{\alpha^i(t)}{\pi(t)}\right] + \pi^i_{\tilde{n}} = \varpi^i_{\tilde{n}} \lim_{t\to\infty}\left[\frac{\varpi(t)}{\pi(t)}\right] + \beta^i_{\tilde{n}} \lim_{t\to\infty}\left[\frac{\beta^i(t)}{\pi(t)}\right]. \tag{2-3}$$

Since for any interval (0,t) the number of service beginnings may not differ from the number of service completions by more than unity, i.e. $|\varpi(t) - \pi(t)|$, then

$$\lim_{t\to\infty}\left[\frac{\varpi(t)}{\pi(t)}\right] = 1. \tag{2-4}$$

The long term ratio of the number of section i stage completions to the number of disabled vehicles serviced is denoted as γ^i:

$$\gamma^i = \lim_{t\to\infty}\left[\frac{\beta^i(t)}{\pi(t)}\right]. \tag{2-5}$$

Since for a given time interval, $|\alpha^i(t) - \beta^i(t)| \leq 1$, it follows that

$$\gamma^i = \lim_{t\to\infty}\left[\frac{\alpha^i(t)}{\pi(t)}\right]. \tag{2-6}$$

Since the patrol visits every section once every cycle,

$$|\beta^i(t) - \beta^j(t)| \leq 1,$$

and therefore $\gamma^i = \gamma$ is independent of i.

Using Eqs. (2-4) through (2-6), Eq. (2-3) may be written in terms of the generating functions as:

$$\gamma \alpha^i(\tilde{z}) + \pi^i(\tilde{z}) = w^i(\tilde{z}) + \gamma \beta^i(\tilde{z}). \tag{2-7}$$

The Laplace transforms of the service time, $S(s)$, and constant changeover time, $C(s)$ are given by $S(s) = \int_0^\infty e^{-st} dF_s(t)$ and $C(s) = e^{-sD/MV}$, respectively. The probability that n_1 breakdowns occur in section 1, n_2 breakdowns in section 2, etc. during the service of a vehicle in any section, because of the Poisson assumption for vehicle breakdowns, is

$$\int_0^\infty \frac{\left(\frac{\lambda t}{M}\right)^{n_1}}{n_1!} \cdots \frac{\left(\frac{\lambda t}{M}\right)^{n_M}}{n_M!} e^{-\lambda t} dF_s(t). \tag{2-8}$$

The generating function of this distribution is related to $S(s)$,

$$\begin{aligned} &\sum_{n_1=0}^{\infty} z_1^{n_1} \cdots \sum_{n_M=0}^{\infty} z_M^{n_M} \int_0^\infty \frac{\left(\frac{\lambda t}{M}\right)^{n_1}}{n_1!} \cdots \frac{\left(\frac{\lambda t}{M}\right)^{n_M}}{n_M!} e^{-\lambda t} dF_s(t) \\ &= \int_0^\infty e^{-\lambda\left(1 - \sum_{j=1}^{M} \frac{z_j}{M}\right)} dF_s(t) \\ &= S\left(\lambda\left[1 - \sum_{j=1}^{M} \frac{z_j}{M}\right]\right) \triangleq \tilde{S}(\tilde{z}). \end{aligned} \tag{2-9}$$

In a similar fashion, the generating function for the distribution that $\tilde{n} = (n_1, n_2, \ldots, n_M)$ breakdowns occur during the changeover time is related to $C(s)$ as

$$\tilde{C}(\tilde{z}) = C\left(\lambda\left[1 - \sum_{j=1}^{M} \frac{z_j}{M}\right]\right) = e^{-\left(1 - \sum_{j=1}^{M} \frac{z_j}{M}\right)\frac{\lambda D}{MV}} \tag{2-10}$$

The number of breakdowns at a section i service completion is equal to the number present at the beginning of the service plus the number which occurs during the service minus the breakdown just serviced. Since the generating functions of the probability distributions of the number of breakdowns at a section i service completion, the number of breakdowns at a section i service beginning, and the number of breakdowns which occur during a service are $\pi^i(\tilde{z}), \omega^i(\tilde{z})$, and $\tilde{S}(\tilde{z})$, respectively, the above relation may be interpreted as

$$\pi^i(\tilde{z}) = \frac{\omega^i(\tilde{z})\,\tilde{S}(\tilde{z})}{z_i}, \tag{2-11}$$

where from the definition of a probability generating function, the generating function of the distribution,

$$P_r(n_i = -1) = 1,$$
$$P_r(n_i \neq -1) = 0,$$

is $1/z_i$. Similarly, it follows that since the number of breakdowns at a section i stage beginning is equal to the number at the section i-1 stage completion plus the number that occurred during the changeover,

$$\alpha^i(\tilde{z}) = \beta^{i-1}(\tilde{z})\,\tilde{C}(\tilde{z}), \tag{2-12}$$

where i-1 is replaced by M for i=1.

Substituting Eqs. (2-11) and (2-12) into Eq. (2-7), the following important steady state equation is obtained:

$$\pi^i(\tilde{z}) = \frac{\gamma\tilde{S}(\tilde{z})\left[\beta^{i-1}(\tilde{z})\hat{C}(\tilde{z}) - \beta^i(\tilde{z})\right]}{z_i - \tilde{S}(\tilde{z})}. \tag{2-13}$$

2.3.3 The Recursive Equation for $\beta^{i}(\tilde{z})$

The denominator of Eq. (2-13) is zero when

$$z_i = \tilde{S}(\tilde{z}) = S(\lambda[1 - \sum_{j=1}^{M} z_j/M]). \tag{2-14}$$

Since $\pi^{i}(\tilde{z})$ represents a probability generating function and $|\tilde{S}(\tilde{z})| > 0$, the numerator of Eq. (2-13) must be zero when Eq. (2-14) holds for $|z_j| < 1$, j=1,2,...M. If the solution of Eq. (2-14) is given by

$$\begin{aligned} z_i' &= g^{i}(\tfrac{\lambda}{M} - \tfrac{\lambda}{M}z_1 + \cdots + \tfrac{\lambda}{M} - \tfrac{\lambda}{M}z_{i-1} + \tfrac{\lambda}{M} - \tfrac{\lambda}{M}z_{i+1} + \cdots + \tfrac{\lambda}{M} - \tfrac{\lambda}{M}z_M) \\ &= \tilde{g}^{i}(\tilde{z}), \end{aligned} \tag{2-15}$$

where from M/G/1[3] theory, $g^{i}(s)$ is the Laplace transform of the busy period distribution of section i, then,

$$\beta^{i}(\tilde{z}) = \beta^{i-1}[f^{i}(\tilde{z})]\, \tilde{C}[f^{i}(\tilde{z})], \tag{2-16}$$

where $f^{i}(\tilde{z})$ is an argument function defined as

$$f^{i}(\tilde{z}) = (z_1, z_2, \ldots, z_{i-1}, \tilde{g}^{i}(\tilde{z}), z_{i+1}, \ldots, z_M). \tag{2-17}$$

It is useful to introduce the following notation:

$$\begin{aligned} h_1^i &= \tilde{g}^{i}(z_1, \ldots, z_{i-1}, z_{i+1}, \ldots, z_M), \\ h_2^i &= \tilde{g}^{i-1}(z_1, \ldots, z_{i-2}, h_1^i, z_{i+1}, \ldots, z_M), \\ h_3^i &= \tilde{g}^{i-2}(z_1, \ldots, z_{i-3}, h_2^i, h_1^i, z_{i+1}, \ldots, z_M), \\ &\vdots \\ h_\ell^i &= \tilde{g}^{i-\ell+1}(z_1, \ldots, z_{i-\ell}, h_{\ell-1}^i, \ldots, h_1^i, z_{i+1}, \ldots, z_M), \end{aligned} \tag{2-18}$$

and specifically,

$$h_M^i = \tilde{g}^{i-M+1}(h_i^i, \ldots, h_1^i, h_{M-1}^i, \ldots, h_{i+1}^i),$$

also,

$$\begin{aligned} f_1^i(\tilde{z}) &= f^{i}(\tilde{z}) = (z_1, z_2, \ldots, z_{i-1}, h_1^i, z_{i+1}, \ldots, z_M), \\ &\vdots \\ f_\ell^i(\tilde{z}) &= (z_1, \ldots, z_{i-1}, h_\ell^i, \ldots, h_1^i, z_{i+1}, \ldots, z_M), \end{aligned} \tag{2-19}$$

and specifically,

$$f_M^i(\tilde{z}) = (h_i^i, \ldots, h_1^i, h_M^i, \ldots, h_{i+1}^i).$$

When Eq. (2-16) is iterated once, $\beta^i(\tilde{z})$ may be expressed in terms of $\beta^{i-2}(\tilde{z})$ as follows:

$$\beta^i(\tilde{z}) = \beta^{i-2}[f_2^i(\tilde{z})]\,\tilde{C}[f_2^i(\tilde{z})]\,\tilde{C}[f_1^i(\tilde{z})]. \tag{2-20}$$

Continuing this iteration M-1 times, and using the fact that $\tilde{C}(\cdot)$ is an exponential function, β^i may be related to β^i as follows:

$$\beta^i(\tilde{z}) = \beta^i[f_M^i(\tilde{z})]\,\tilde{C}\Big[\sum_{j=1}^{M} f_j^i(\tilde{z})\Big]. \tag{2-21}$$

2.3.4 Determination of the Average Cycle Time

The value of γ , defined by Eq. (2-5), may be found by imposing the condition

$$\sum_{i=1}^{M}\sum_{n_1=0}^{\infty}\cdots\sum_{n_M=0}^{\infty}\pi_{\tilde{n}}^i = \sum_{i=1}^{M}\pi^i(\tilde{z}=1) = 1, \tag{2-22}$$

or simply

$$\pi^i(\tilde{z}=1) = 1/M. \tag{2-23}$$

Eq. (2-23) is obtained because of the assumption of a uniform spatial distribution of vehicle breakdowns. From Eq. (2-13) and using L'Hospital's rule, it may be shown that

$$\pi^i(\tilde{z}=1) = \frac{\gamma\left[\left.\frac{\partial\beta^{i-1}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} + \frac{\lambda D}{M^2 V}\right]}{1-\lambda T_F/M}. \tag{2-24}$$

The quantity $\left.\frac{\partial\beta^{i-1}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1}$ is interpreted as the expected number of breakdowns in section i at the section i-1 stage completion instant and $\frac{\lambda}{M}\left(\frac{D}{MV}\right)$ expected number of breakdowns occurring in section i during the changeover from section i-1 to i. Therefore, $\left.\frac{\partial \beta^{i-1}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} + \frac{\lambda D}{M^2 V}$ is the expected number of breakdowns present in section i at the section i stage beginning instant. If ν^i is the average time between the previous section i stage completion and the current section i stage beginning, i.e. the average intervisit time, then

$$\frac{\lambda}{M}\nu^i = \left.\frac{\partial \beta^{i-1}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} + \frac{\lambda D}{M^2 V} . \tag{2-25}$$

The expected cycle time is just the sum of the expected time the patrol vehicle spends in section i, i.e. the expected busy period of section i, and ν^i. From M/G/1[4] queuing theory, the expected length of the busy period, given that there are j customers at the start of the period, is

$$\frac{1/\mu \, j}{1-\rho} ,$$

where $1/\mu$ is the expected service time, $\rho = \lambda/\mu$, and λ is the average customer arrival rate. From Eq. (2-25), the expected cycle time, C, is

$$C = \nu^i + \frac{\frac{\lambda}{M}\nu^i T_F}{1-\frac{\lambda T_F}{M}} = \frac{\nu^i}{1-\frac{\lambda T_F}{M}} . \tag{2-26}$$

From Eqs. (2-23), (2-24) and (2-26) the value of γ may be shown to be

$$\gamma = \frac{1}{\lambda C} . \tag{2-27}$$

Using Eq. (2-16) it may be shown that

$$\begin{aligned} 1/\lambda/M \left.\frac{\partial \beta^i(\tilde{z})}{\partial z_{i-1}}\right|_{\tilde{z}=1} &= \frac{\frac{\lambda T_F}{M}\nu^i}{1-\frac{\lambda T_F}{M}} + \frac{D}{MV} \\ &= \frac{\lambda T_F C}{M} + \frac{D}{MV} , \end{aligned} \tag{2-28}$$

where the quantity $1/\lambda/M \left.\frac{\partial\beta^i(\tilde{z})}{\partial z_{i-1}}\right|_{\tilde{z}=1}$ is the expected time between section i-1 and section i stage completions. Therefore, the average time the patrol vehicle spends servicing every loop, i.e. the cycle time, is just the sum of all the expected times between successive stage completions; that is,

$$C = \sum_{i=1}^{M} 1/\lambda M \left.\frac{\partial\beta^i(\tilde{z})}{\partial z_{i-1}}\right|_{\tilde{z}=1} . \tag{2-29}$$

When Eq. (2-28) is substituted into the right side of Eq. (2-29) the cycle time, C, may be obtained as

$$C = \frac{D/V}{1-\lambda T_F} . \tag{2-30}$$

2.3.5 The Stability Condition

The probability that the highway is devoid of breakdowns may be found from Eq. (2-13) as

$$\sum_{i=1}^{M} \dot{\pi}^i(\tilde{z}=0) = \gamma \sum_{i=1}^{M} \dot{\beta}^i(\tilde{z}=0)\left[1-c^{i+1}(\lambda)\right]. \tag{2-31}$$

Since for a stable queue $\dot{\pi}^i(\tilde{z}=0)$ and $\dot{\beta}^i(\tilde{z}=0)$ must be positive for all i and $1-\dot{c}^i(\lambda) = 1-e^{-\lambda D/M^2V}$ is also positive, γ must be positive for the sum on the left side of Eq. (2-31) to be positive. From Eqs. (2-27) and (2-30) this will only occur if

$$1-\lambda T_F > 0 \tag{2-32}$$

It may be noted that the stability condition is independent of the changeover time. This independence may be expected since the relative amount of time the patrol vehicle spends traveling from section to section diminishes as the conditions of instability are approached.

2.3.6 Determination of the Wait Time and Intervisit Time Distribution

The probability that n_i breakdowns occur in section i during the period that a disabled motorist waits for service and is being served is $\int_0^\infty \frac{(\lambda t/M)^{n_i}}{n_i!} e^{-\frac{\lambda t}{M}} dF_W^i(t) \circledast dF_S(t)$ where $F_W^i(t)$ is the wait time distribution with Laplace transform $W^i(s)$ and $\circledast$ is the symbol for convolution. Since in each section the patrol vehicle services breakdowns in the order of first come first serve, this probability is equal to the probability there are n_i breakdowns in section i given a section i service completion has just occurred. Using the definition of conditional probabilities, it may be seen that

$$\frac{\sum_{n_1=0}^{\infty}\cdots\sum_{n_{i-1}=0}^{\infty}\sum_{n_{i+1}=0}^{\infty}\cdots\sum_{n_N=0}^{\infty}\pi_{\tilde{n}}^{i}}{\sum_{n_1=0}^{\infty}\cdots\sum_{n_N=0}^{\infty}\pi_{\tilde{n}}^{i}} = \int_0^\infty \frac{\left(\frac{\lambda t}{M}\right)^{n_i}}{n_i!} e^{-\frac{\lambda t}{M}} dF_W^i(t) \circledast dF_S(t). \qquad (2\text{-}33)$$

taking the z-transform of Eq. (2-33) with respect to z_i yields

$$\frac{\pi^i(1,\ldots,1,z_i,1,\ldots,1)}{\pi^i(\tilde{z}=1)} = W^i[\lambda/M(1-z_i)]\, S[\lambda/M(1-z_i)],$$

or

$$W^i(s) = \frac{\pi^i(1,\ldots,1,(1-sM/\lambda),1,\ldots,1)}{\pi^i(\tilde{z}=1)\, S(s)} . \qquad (2\text{-}34)$$

To determine the distribution of the intervisit time, it may be noted that the probability that there are n_i disabled vehicles in section i at the section i-1 stage completion must be equal to the probability that n_i breakdowns occur in section i in the time between the previous section i stage completion and the current section i-1 stage completion. This may be written as

$$\sum_{n_1=0}^{\infty}\cdots\sum_{n_{i-1}=0}^{\infty}\sum_{n_{i+1}=0}^{\infty}\cdots\sum_{n_n=0}^{\infty}\beta_{\tilde{n}}^{i-1}=\int_0^{\infty}\frac{\left(\frac{\lambda t}{M}\right)^{n_i}}{n_i!}e^{-\frac{\lambda t}{M}}dF_y(t), \qquad (2\text{-}35)$$

where $F_y(t)$ is the probability distribution of the time between successive section i and section i-1 stage completions. Taking the z-transform of Eq. (2-35) with respect to z_i yields

$$\beta^{i-1}(1,\ldots,1,z_i,1,\ldots,1)=\int_0^{\infty}e^{-\lambda/M(1-z_i)t}dF_y(t)=Y[\lambda/M(1-z_i)], \qquad (2\text{-}36)$$

where $Y(s)$ is the Laplace transform of $F_y(t)$. Since the intervisit time equals the sum of the changeover time and the time between successive section i and section i-1 stage completions, it may be shown that the Laplace transform of the intervisit time, $V^i(s)$, is given by

$$V^i(s)=\beta^{i-1}(1,\ldots,1,1-sM/\lambda,1,\ldots,1)\,C(s), \qquad (2\text{-}37)$$

and from Eqs. (2-26) and (2-30)

$$\nu^i=\frac{(1-\lambda/MT_F)\,D/V}{1-\lambda T_F}. \qquad (2\text{-}38)$$

The mean intervisit time for the continuous loop, i.e.

$\nu=\lim_{M\to\infty}\nu^i$, becomes, from Eq. (2-38)

$$\nu=\lim_{M\to\infty}\nu^i=\frac{D/V}{1-\lambda T_F},\ \text{for } \lambda T_F<1. \qquad (2\text{-}39)$$

From Eqs. (2-13), (2-24) and (2-38) the Laplace transform of the wait time distribution is

$$W^i(s)=\frac{\left(1-\frac{\lambda T_F}{M}\right)\left(1-V^i(s)\right)}{\nu^i\left(s-\lambda/M+\lambda/M\,S(s)\right)}, \qquad (2\text{-}40)$$

and upon differentiating $-W^i(s)$ with respect to s and setting s equal to zero, the mean wait time becomes

$$\dot{W}^{i} = \frac{E[\nu^2]}{2\nu^i} + \frac{\lambda/M\, E[s^2]}{2(1-\lambda/M\, T_F)}, \qquad (2\text{-}41)$$

where $E[\nu^2]$ and $E[s^2]$ are the second moments of the intervisit time and service time distributions respectively.

2.3.7 Calculation of the Mean Wait Time

In order to evaluate the mean wait time, the second moment of the intervisit time must be obtained from Eq. (2-37), i.e.

$$E[\nu^2] = \left.\frac{d^2 V^i(s)}{ds^2}\right|_{s=0} = \left.\frac{\partial^2 \beta^{i-1}(\tilde{z})}{\partial z_i^2}\right|_{\tilde{z}=1} (M/\lambda)^2 + 2\left.\frac{\partial \beta^{i-1}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} \left.\frac{dC(s)}{ds}\right|_{s=0}(-M/\lambda) + \left.\frac{d^2C(s)}{ds^2}\right|_{s=0}.$$

The values of the first and second partial derivatives of $\beta^{i-1}(\tilde{z})$ with respect to z_i must be evaluated at $\tilde{z}=1$.

These partial derivatives may be obtained from Eq. (2-21) by differentiating with respect to $z_1, z_2, \ldots, z_{i-2}, z_i, \ldots, z_M$, evaluating the derivatives at $\tilde{z}=1$ and solving M-1 simultaneous equations for $\left.\frac{\partial \beta^{i-1}(\tilde{z})}{\partial z_j}\right|_{\tilde{z}=1}$ for $j \neq i-1$.

The values of these derivatives may then be substituted into the simultaneous equations generated from the M-1 fold differentiation of each of the M-1 equations obtained from the first differentiation. The resultant set of M(M-1)/2 simultaneous equations may be solved for the M(M-1)/2 second partial derivatives. Since it is desired that M be large in order to approximate the mean wait time in the continuous patroling problem, the above process of differentiation is overwhelming. In the next chapter, an efficient procedure for formulating and solving the required equations, when M is arbitrarily large, is presented. An approximate solution to the highway patrol problem is obtained and compared to a Monte Carlo solution to the same problem.

CHAPTER 3

THE SOLUTION OF THE FIRST ENCOUNTER, FIRST SERVE AND THE FIRST DISABLED, FIRST SERVE HIGHWAY AID PROBLEMS USING THE THEORY OF QUEUES

3.1 Introduction

In Chapter 3 two important highway aid dispatching problems will be solved using the theory of queues. In particular, an approximate solution of the continuous first encounter, first serve highway patrol problem described in Chapter 2 will be derived. Then the exact solution to the aid dispatch problem in which the patrol vehicle renders aid to vehicles in the sequence in which they break down will be presented. In the latter problem, it will be assumed that as soon as a vehicle becomes disabled, an aid vehicle is immediately dispatched, i.e. the highway maintains a perfect detection system. It will be shown that when this assumption is relaxed, the time between breakdowns detected by the system is no longer exponentially distributed and the arrival process of the isomorphic queue can not be assumed to be Poisson.

3.2 Solution of the First Encounter, First Serve Aid Dispatch Policy

In this section, an algorithm is derived for formulating and sequentially solving the two sets of simultaneous equations required to obtain the mean waiting time of a disabled vehicle for the first encounter, first serve aid dispatching system described in Chapter 2. More precisely, a systematic procedure for formulating a sequential set of linear matrix equations which are easily programmed on a digital computer is developed for evaluating the first and second partial derivatives of $\dot{\beta}^{i}(\tilde{z})$ when the number of highway sections, M, is arbitrary. Then only the memory capacity of the digital computer limits one's ability to obtain the expected wait time for any M. The $\lim_{M\to\infty} E[\text{waiting time}]$ represents the solution to the continuous highway patrol problem.

3.2.1 The Linear Matrix Equation for the Determination of the First Partial Derivative of $\dot{\beta}^{i}(\tilde{z})$

Since it is assumed that vehicles become disabled with a uniform spatial distribution around the highway loop, without any loss in generality the mean wait time for the first section will be obtained.

For section 1, Eq. (2-37) becomes

$$\mathcal{V}^{1}(s) = \beta^{M}(z_1, 1, \ldots 1)\Big|_{z_1 = 1 - sM/\lambda} C(s). \tag{3-1}$$

In order to obtain the moments of the intervisit time it is evident from Eq. (3-1) that $\left.\frac{\partial\beta^M(\tilde{z})}{\partial z_j}\right|_{\tilde{z}=1}$ and $\left.\frac{\partial^2\beta^M(\tilde{z})}{\partial z_p\partial z_j}\right|_{\tilde{z}=1}$ for $j, p < M$ must be obtained. It is convenient to rewrite Eqs. (2-18), (2-19) and (2-21) as

$$\begin{aligned} h_1^M &= \tilde{g}^M(z_1,\ldots,z_{M-1}), \\ h_2^M &= \tilde{g}^{M-1}(z_1,\ldots,z_{M-2},h_1^M), \\ &\vdots \\ h_M^M &= \tilde{g}^1(h_{M-1}^M,\ldots,h_1^M), \end{aligned} \tag{3-2}$$

$$\begin{aligned} f_1^M(\tilde{z}) &= (z_1,\ldots,z_{M-1},h_1^M), \\ &\vdots \\ f_M^M(\tilde{z}) &= (h_M^M,\ldots,h_1^M), \end{aligned} \tag{3-3}$$

and

$$\beta^M(\tilde{z}) = \beta^M[f_M^M(\tilde{z})]\,\tilde{C}\left[\sum_{j=1}^{M} f_j^M(\tilde{z})\right]. \tag{3-4}$$

To obtain the M-1 set of simultaneous equations for the solution of $\left.\frac{\partial\beta^M(\tilde{z})}{\partial z_1}\right|_{\tilde{z}=1}$, Eq. (3-4) is differentiated with respect to $z_j, j<M$,

$$\frac{\partial\beta^M(\tilde{z})}{\partial z_j} = \frac{\partial\beta^M[f_M^M(\tilde{z})]}{\partial z_j}\,\tilde{C}\left[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})\right] + \beta^M[f_M^M(\tilde{z})]\,\frac{\partial\tilde{C}\left[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})\right]}{\partial z_j}. \tag{3-5}$$

From Eqs. (3-2) and (3-3) it may be found

$$\frac{\partial\beta^M[f_M^M(\tilde{z})]}{\partial z_j} = \frac{\partial\beta^M[h_M^M,\ldots,h_1^M]}{\partial z_j} = \sum_{i=1}^{M-1}\frac{\partial\beta^M[f_M^M(\tilde{z})]}{\partial h_{M-i+1}^M}\,\frac{\partial h_{M-i+1}^M}{\partial z_j}, \tag{3-6}$$

and

$$\frac{\partial \tilde{c}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial z_j} = \frac{\partial \tilde{C}[(z_1,\ldots,z_{M-2},h_1^M)+\cdots+(h_M^M,\ldots,h_1^M)]}{\partial z_j}$$

$$= \frac{\partial \tilde{c}[(M-1)z_1+h_M^M,(M-2)z_2+2h_{M-1}^M,\ldots,0z_M+Mh_1^M]}{\partial z_j} \tag{3-7}$$

$$= \frac{\partial \tilde{c}[\omega_1,\ldots,\omega_M]}{\partial z_j}$$

$$= \sum_{k=1}^{M} \frac{\partial \tilde{c}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial \omega_k}\left[(M-k)U(k-j)+k\frac{\partial h_{M-k+1}^M}{\partial z_j}\right],$$

where $U(n)=\begin{cases}1 & n=0,\\ 0 & \text{elsewhere,}\end{cases}$ and $\omega_k = kh_{M-k+1}^M+(M-k)z_k$.

Since $h_i^M\Big|_{\tilde{z}=1}=1$ for all i, it follows that

$$\beta^M[f_M^M(\tilde{z})]\Big|_{\tilde{z}=1}=1,\quad \tilde{C}\left[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})\right]\Big|_{\tilde{z}=1}=1,\quad \frac{\partial \beta^M[f_M^M(\tilde{z})]}{\partial h_{M-i+1}^M}\Big|_{\tilde{z}=1}=\frac{\partial \beta^M(\tilde{z})}{\partial z_i}\Big|_{\tilde{z}=1},$$

and

$$\frac{\partial \tilde{c}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial \omega_i}\Big|_{\tilde{z}=1} = \frac{\partial \tilde{c}(\tilde{z})}{\partial z_i}\Big|_{\tilde{z}=1}.$$

Evaluating Eqs. (3-6) and (3-7) at $\tilde{z}=1$ and substituting them into Eq. (3-8) with $\tilde{z}=1$, the set of M-1 simultaneous equations solvable for $\frac{\partial \beta^M(\tilde{z})}{\partial z_j}\Big|_{\tilde{z}=1}$ for all $j \neq M$ is obtained

$$\frac{\partial \beta^M(\tilde{z})}{\partial z_j}\Big|_{\tilde{z}=1} = \sum_{i=1}^{M-1}\frac{\partial \beta^M(\tilde{z})}{\partial z_i}\Big|_{\tilde{z}=1}\frac{\partial h_{M-i+1}^M}{\partial z_j}\Big|_{\tilde{z}=1} \tag{3-8}$$

$$+\sum_{k=1}^{M}\frac{\partial \tilde{c}(\tilde{z})}{\partial z_k}\Big|_{\tilde{z}=1}\left[(M-k)U(k-j)+k\frac{\partial h_{M-k+1}^M}{\partial z_j}\Big|_{\tilde{z}=1}\right].$$

From Eq. (2-10) $\left.\frac{\partial \tilde{C}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1}$ may be obtained as

$$\left.\frac{\partial \tilde{C}(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} = \frac{\lambda D}{M^2 V} = \eta \text{ for all } i, \tag{3-9}$$

and the values of $\left.\frac{\partial h^M_{M-i+1}}{\partial z_j}\right|_{\tilde{z}=1}$ for all $j \leq M-1$,

$i \leq M$ may be found from Eqs. (3-4) and (2-15) as follows:

From Eq. (2-15),

$$\left.\frac{\partial h^M_1}{\partial z_j}\right|_{\tilde{z}=1} = \left.\frac{\partial \tilde{g}^M(z_1,\ldots,z_{M-1})}{\partial z_j}\right|_{\tilde{z}=1} = \frac{\lambda T_F/M}{1-\lambda T_F/M} = \gamma \text{ for } j < M-1. \tag{3-10}$$

and therefore from Eq. (3-4)

$$\left.\frac{\partial h^M_2}{\partial z_j}\right|_{\tilde{z}=1} = \begin{cases} \left.\frac{\partial \tilde{g}^{M-1}[f^M_2(\tilde{z})]}{\partial z_j}\right|_{\tilde{z}=1} + \left.\frac{\partial \tilde{g}^{M-1}[f^M_2(\tilde{z})]}{\partial z_M}\right|_{\tilde{z}=1} \left.\frac{\partial h_1}{\partial z_j}\right|_{\tilde{z}=1}, & \text{for } j < M-1, \\ \left.\frac{\partial \tilde{g}^{M-1}[f^M_2(\tilde{z})]}{\partial z_M}\right|_{\tilde{z}=1} \left.\frac{\partial h^M_1}{\partial z_j}\right|_{\tilde{z}=1}, & \text{for } j = M-1. \end{cases}$$

From Eqs. (2-15) and (3-10) it follows that

$$\left.\frac{\partial h^M_2}{\partial z_j}\right|_{\tilde{z}=1} = \begin{cases} \gamma + \gamma^2, & \text{for } j < M-1, \\ \gamma^2, & \text{for } j = M-1. \end{cases} \tag{3-11}$$

Continuing in this fashion, a sequential set of equations for evaluating $\left.\frac{\partial h^M_\ell}{\partial z_j}\right|_{\tilde{z}=1}$ may be generated,

$$\left.\frac{\partial h^M_\ell}{\partial z_j}\right|_{\tilde{z}=1} = \gamma\left[\phi(j-M+\ell-1) + \sum_{k=1}^{\ell-1} \left.\frac{\partial h^M_k}{\partial z_j}\right|_{\tilde{z}=1}\right], \tag{3-12}$$

for all $j \leq M-1$, $\ell \leq M$,

where

$$\phi(n) = \begin{cases} 1 & n < 0 , \\ 0 & n \geq 0 . \end{cases} \tag{3-13}$$

In order to formulate the algorithm in matrix form, an M-1 x M $\underline{H}$ matrix whose elements are

$$h_{j\ell} = \left. \frac{\partial h_\ell^M}{\partial z_j} \right|_{\tilde{z}=1} = \gamma \left[\phi(j-M+\ell-1) + \sum_{k=1}^{\ell-1} h_{jk} \right] , \tag{3-14}$$

is defined.

After the elements of the $\underline{H}$ matrix are obtained, the elements of an M-1 column matrix $\underline{C}$, defined as

$$c_i = \eta \sum_{k=1}^{M} \left[k\, h_{i,M-k+1} + (M-k) U(k-i) \right] , \tag{3-15}$$

are obtained. Finally, an M-1 column matrix $\underline{B}$ with elements

$$b_j = \left. \frac{\partial \beta^M(\tilde{z})}{\partial z_j} \right|_{\tilde{z}=1} , \tag{3-16}$$

and an M-1 square matrix $\underline{A}$ with elements

$$a_{ij} = h_{i,M-j+1} , \tag{3-17}$$

are defined. From Eq. (3-8) and the matrix definitions given by Eqs. (3-14), (3-15), (3-16), and (3-17) it follows that

$$\underline{B} = \underline{A}\ \underline{B} + \underline{C} . \tag{3-18}$$

Example for the Case M = 2

When M=2, the matrix Eq. (3-18) becomes

$$(b_1) = (a_{11})(b_1) + (c_1) , \tag{3-19}$$

where $a_{11} = h_{12}$ and $c_1 = \eta\,(h_{12} + 2h_{11} + 1)$,

and $h_{11} = \left. \frac{\partial h_1^2}{\partial z_1} \right|_{z_1=1} = \gamma$, $h_{12} = \left. \frac{\partial h_2^2}{\partial z_1} \right|_{z_1=1} = \gamma^2$.

When Eq. (3-19) is solved for b_1, the solution is

$$\left.\frac{\partial \beta^2(z_1)}{\partial z_1}\right|_{z_1=1} = \frac{\eta(1+\gamma)^2}{1-\gamma^2}, \tag{3-20}$$

where

$$\gamma = \frac{\lambda T_F/M}{1-\lambda T_F/M} \text{ and } \eta = \frac{\lambda D}{M^2 V}.$$

3.2.2 The Linear Matrix Equation for the Determination of the Second Partial Derivative of $\beta^i(\tilde{z})$

In order to obtain the second partial derivatives $\left.\frac{\partial^2 \beta^M(\tilde{z})}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}$, j,p< M, Eq. (3-5) is differentiated with respect to z_p, p< M and $\tilde{z}$ at 1,

$$\left.\frac{\partial^2 \beta^M(\tilde{z})}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} = \left.\frac{\partial^2 \beta^M[f_M^M(\tilde{z})]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} + \left.\frac{\partial^2 \beta^M[f_M^M(\tilde{z})]}{\partial z_j}\right|_{\tilde{z}=1} \left.\frac{\partial \tilde{C}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial z_p}\right|_{\tilde{z}=1}$$

$$+ \left.\frac{\partial \beta^M[f_M^M(\tilde{z})]}{\partial z_p}\right|_{\tilde{z}=1} \left.\frac{\partial \tilde{C}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial z_j}\right|_{\tilde{z}=1} + \left.\frac{\partial^2 C[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}. \tag{3-21}$$

In a manner similar to the derivation of Eqs. (3-6) through (3-12) the first term on the right side of Eq. (3-21) is found to be

$$\left.\frac{\partial^2 \beta^M[f_M^M(\tilde{z})]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} = \sum_{i=1}^{M-1}\sum_{k=1}^{M-1} \left.\frac{\partial^2 \beta^M(\tilde{z})}{\partial z_k \partial z_i}\right|_{\tilde{z}=1} \left.\frac{\partial h^M_{M-k+1}}{\partial z_p}\right|_{\tilde{z}=1} \left.\frac{\partial h^M_{M-i+1}}{\partial z_j}\right|_{\tilde{z}=1}$$

$$+ \sum_{i=1}^{M-1} \left.\frac{\partial \beta^M(\tilde{z})}{\partial z_i}\right|_{\tilde{z}=1} \left.\frac{\partial^2 h^M_{M-i+1}}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}, \tag{3-22}$$

where the fact that $\left.\frac{\partial^2 \beta^M[f_M^M(\tilde{z})]}{\partial h_{M-k+1}^M \partial h_{M-i+1}^M}\right|_{\tilde{z}=1} = \left.\frac{\partial^2 \beta^M(\tilde{z})}{\partial z_k \partial z_i}\right|_{\tilde{z}=1}$ has been used. The values of $\left.\frac{\partial^2 h_\ell^M}{\partial z_n \partial z_j}\right|_{\tilde{z}=1}$ in Eq. (3-22) may be obtained from the following two sequential sets of equations:

$$\left.\frac{\partial^2 h_\ell^M}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} = \left.\frac{\partial^2 \tilde{g}^{M-\ell+1}(z_1,\ldots,z_{M-\ell},h_{\ell-1}^M,\ldots,h_1^M)}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} \phi(j-M+\ell+1)$$
$$+ \sum_{k=1}^{\ell-1}\left\{ \left.\frac{\partial^2 \tilde{g}^{M-\ell+1}(z_1,\ldots,z_{M-\ell},h_{\ell-1}^M,\ldots,h_1^M)}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} \left.\frac{\partial h_k^M}{\partial z_j}\right|_{\tilde{z}=1} \right. \tag{3-23}$$
$$\left. + \gamma^2 \left.\frac{\partial^2 h_k^M}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} \right\} ,$$

and

$$\left.\frac{\partial^2 \tilde{g}^i(z_1,\ldots,z_{i-1},h_{M-i}^M,\ldots,h_1^M)}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} = \Theta\left\{\phi(n-1) + \sum_{\ell=1}^{M-i} \left.\frac{\partial h_\ell^M}{\partial z_n}\right|_{\tilde{z}=1}\right\} , \tag{3-24}$$

where from Eq. (2-15)

$$\Theta = \left.\frac{\partial^2 \tilde{g}^i(z_1,\ldots,z_{i-1},h_{M-i}^M,\ldots,h_1^M)}{\partial h_{M-k+1}^M \partial z_j}\right|_{\tilde{z}=1} = \left.\frac{\partial^2 \tilde{g}^i(z_1,\ldots,z_{i-1},z_{i+1},\ldots z_M)}{\partial z_k \partial z_j}\right|_{\tilde{z}=1} \tag{3-25}$$
$$= \frac{(\lambda/M)^2 E(s^2)}{(1-\lambda T_F/M)^3} .$$

The values $\left.\frac{\partial^2 \tilde{c}[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}$ in Eq. (3-21) are obtained from Eq. (3-7) as

$$\left.\frac{\partial^2 \tilde{c}\left[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})\right]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} = \eta \sum_{k=1}^{M} k \left.\frac{\partial^2 h_{M-k+1}^M}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}$$

$$+ \eta^2 \sum_{k=1}^{M} \sum_{\ell=1}^{M} \left\{ k \left.\frac{\partial h_{M-k+1}^M}{\partial z_j}\right|_{\tilde{z}=1} + (M-k) U(k-j) \right\} \left[\ell \left.\frac{\partial h_{M-\ell+1}^M}{\partial z_p}\right|_{\tilde{z}=1} + (M-\ell) U(\ell-p) \right] \Big\}, \quad (3\text{-}26)$$

where from Eqs. (2-10) and (3-24) it may be seen that

$$\left.\frac{\partial^2 \tilde{c}\left[\sum_{\ell=1}^{M} f_\ell^M(\tilde{z})\right]}{\partial \omega_p \partial \omega_j}\right|_{\tilde{z}=1} = \left.\frac{\partial^2 \hat{c}(\tilde{z})}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} = \left[\frac{\lambda D}{M^2 V}\right]^2 = \eta^2. \quad (3\text{-}27)$$

An M x M-1 matrix $\underline{G}$ is defined as

$$g_{in} = \left.\frac{\partial^2 \tilde{g}^i\left[f_{M-i+1}^M(\tilde{z})\right]}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} = \Theta\left\{\phi(n-i) + \sum_{\ell=1}^{M-i} h_{n\ell}\right\}, \quad (3\text{-}28)$$

the M-1 x M-1 x M set $\underline{H}'$ as

$$h'_{nj\ell} = \left.\frac{\partial^2 h_\ell^M}{\partial z_n \partial z_j}\right|_{\tilde{z}=1} = g_{M-\ell+1,n}\, \phi(j-M+\ell-1) + \sum_{k=1}^{\ell-1} \left(g_{M-\ell+1,n} h_{jk} + \gamma h'_{njk}\right), \quad (3\text{-}29)$$

the M-1 x M-1 matrix $\underline{C}'$ as

$$c'_{nj} = c_n c_j + \eta \sum_{k=1}^{M} k\, h'_{nj,M-k+1} , \quad (3\text{-}30)$$

and the M-1 x M-1 matrix $\underline{B}'$ as

$$b'_{pj} = \left.\frac{\partial^2 \beta^M(\tilde{z})}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} . \quad (3\text{-}31)$$

Eq. (3-21) may be rewritten in terms of the matrix definitions given in Eqs. (3-28) through (3-31) as

$$b'_{pj} = \sum_{i=1}^{M-1}\sum_{k=1}^{M-1} b'_{ki}\, h_{p,M-k+1}\, h_{j,M-i+1} + \sum_{i=1}^{M-1} b_i\, h'_{p,j,M-i+1} + c_p \sum_{i=1}^{M-1} b_i\, h_{j,M-i+1} + c_j \sum_{i=1}^{M-1} b_i\, h_{p,M-i+1} + c'_{pj}\,. \quad (3\text{-}32)$$

Since $\left.\dfrac{\partial^2 \beta^M(\tilde{z})}{\partial z_p \partial z_j}\right|_{\tilde{z}=1} = \left.\dfrac{\partial^2 \beta^M(\tilde{z})}{\partial z_j \partial z_p}\right|_{\tilde{z}=1}$, Eq. (3-22) may be rewritten as

$$b'_{pj} = \sum_{k=1}^{M-1} b'_{kk}\, h_{p,M-k+1}\, h_{j,M-k+1} + \sum_{i=1}^{M-1}\sum_{k=i+1}^{M-1} b'_{ik}\left[h_{p,M-k+1}\, h_{j,M-i+1} + h_{j,M-k+1}\, h_{p,M-i+1}\right] + \sum_{i=1}^{M-1} b_i\, h'_{p,j,M-i+1} + c_p \sum_{i=1}^{M-1} b_i\, h_{j,M-i+1} + c_j \sum_{i=1}^{M-1} b_i\, h_{p,M-i+1} + c'_{pj}\,. \quad (3\text{-}33)$$

Eq. (3-33) may be greatly simplified by transforming the upper triangle of the matrix $\underline{B}'$ into the (M-1) M/2 column matrix $\underline{D}$ as

$$b'_{pj} = d_{(p-1)(M-1-p/2)+j} \quad \text{for } p \le j \le M-1. \quad (3\text{-}34)$$

Additionally, the (M-1)M/2 square matrix $\underline{R}$ is defined as

$$r_{(p-1)(M-1-p/2)+j,\,(i-1)(M-1-i/2)+k} = h_{p,M-k+1}\, h_{j,M-i+1} + h_{j,M-k+1}\, h_{p,M-i+1}\, \Psi(i-k), \quad (3\text{-}35)$$

where $\Psi(n) = \begin{cases} 1 & \text{elsewhere,} \\ 0 & n=0, \end{cases}$ and the (M-1)M/2 column matrix, $\underline{T}$, as

$$t_{(p-1)(M-1-p/2)+j} = \sum_{i=1}^{M-1} b_i\, h'_{p,j,M-i+1} + c_p \sum_{i=1}^{M-1} b_i\, h_{j,M-i+1} + c_j \sum_{i=1}^{M-1} b_i\, h_{p,M-i+1} + c'_{pj}\,. \quad (3\text{-}36)$$

Eq. (3-23) may now be formulated in terms of matrices, $\underline{D}$, $\underline{R}$ and $\underline{T}$ as

$$\underline{D} = \underline{R}\ \underline{D} + \underline{T}\ . \tag{3-37}$$

<u>Example for the Case M=2</u>

When M=2, the matrix Eq. (3-37) becomes

$$(d_1) = (r_{11})(d_1) + (t_1),$$

where $r_{11} = h_{12}^2$, $t_1 = b_1 h'_{112} + 2c_1 b_1 h_{12} + c'_{11}$

and $c'_{11} = c_1^2 + \eta(h'_{111} + 2h'_{112})$, $h'_{111} = \Theta$, $h'_{112} = \Theta[\rho^2 + \rho]$.

solving for $d_1 = \left.\frac{\partial^2 \beta^2(z_1)}{\partial z_1^2}\right|_{z=1}$, the solution is

$$\left.\frac{\partial^2 \beta^2(z_1)}{\partial z_1^2}\right|_{z_1=1} = \frac{\Theta\eta(1+\rho)^2(\rho^2+\rho) + 2\eta\rho^2(1+\rho)^4}{(1-\rho^2)(1-\rho^4)} \tag{3-38}$$

$$+ \frac{\eta^2[(\rho^2+1)^2 + 4\rho(\rho^2+1) + 4\rho^2] + \eta\Theta[\rho^2+\rho+2]}{(1-\rho^4)},$$

where

$$\Theta = \frac{(\lambda/M)^2 E(s^2)}{(1-\lambda T_F/M)^3}, \quad \eta = \frac{\lambda D}{M^2 V}, \quad \rho = \frac{\lambda T_F/M}{1-\lambda T_F/M}.$$

<u>3.2.3 Algorithm for Obtaining the Mean Waitimg Time</u>

In order to calculate the value of the mean waiting time for a given number of sections, M, the following procedure should be used:

(1) Calculate the first partial derivatives of the elements of the vector functions, h_i^M, evaluated at $\tilde{z}=1$ using Eq. (3-14).

(2) Calculate the first partial derivatives of $\tilde{C}\left[\sum_{\ell=1}^{M} f_{\ell}^{M}(\tilde{z})\right]$ evaluated at $\tilde{z}=1$. These derivatives are found by substituting the values obtained in step (1) into Eq. (3-15).

(3) After forming the matrices $\underline{A}$ and $\underline{C}$, the M-1 values of the first partial derivatives of $\beta^{M}(\tilde{z})$ are obtained from the solution of the matrix Eq. (3-18).

(4) Calculate the second partial derivatives of the elements of the vector functions, h_{i}^{M} , and $\tilde{C}\left[\sum_{\ell=1}^{M} f_{\ell}^{M}(\tilde{z})\right]$ evaluated at $\tilde{z}=1$. The second partial derivatives of h_{i}^{M} are found by substituting the values of the first partial derivatives of the elements of the vector functions obtained in step (1) into the pair of sequential Eqs. (3-23) and (3-24). Then using the values of the second partial derivatives of the elements of the vector functions, the values of the first partial derivatives of $\tilde{C}\left[\sum_{\ell=1}^{M} f_{\ell}^{M}(\tilde{z})\right]$ obtained in step (2) may be substituted into Eq. (3-26) to obtain $\left.\frac{\partial^2 \tilde{C}\left[\sum_{\ell=1}^{M} f_{\ell}^{M}(\tilde{z})\right]}{\partial z_p \partial z_j}\right|_{\tilde{z}=1}$.

(5) Form the matrices $\underline{R}$ and $\underline{T}$ from the values obtained in steps (1) - (4) and then solve the matrix Eq. (3-37) to determine the second partial derivative $\left.\frac{\partial^2 \beta^{M}(\tilde{z})}{\partial z_1^2}\right|_{\tilde{z}=1}$.

(6) After determining the value of the second moment of the intervisit time

$$E\left[v^2\right] = \left.\frac{d^2 V^{1}(s)}{ds^2}\right|_{s=0} = \left.\frac{\partial^2 \beta^{M}(\tilde{z})}{\partial z_1^2}\right|_{\tilde{z}=1}\left(\frac{M}{\lambda}\right)^2 + 2\left.\frac{\partial \beta^{M}(\tilde{z})}{\partial z_1}\right|_{\tilde{z}=1}\left(\frac{D}{\lambda V}\right) + \left(\frac{D}{MV}\right)^2,$$

from the values of $\left.\frac{\partial \beta^{M}(\tilde{z})}{\partial z_1}\right|_{\tilde{z}=1}$ and $\left.\frac{\partial^2 \beta^{M}(\tilde{z})}{\partial z_1^2}\right|_{\tilde{z}=1}$, the value of the mean waiting time is found by substituting $E\left[v^2\right]$ into Eq. (2-4).

3.2.4 Comparison of Mean Waiting Time Using Large M with the Results from a Monte Carlo Simulation

The expected waiting time versus M, computed using the algorithm of the previous section, is shown in Fig. 3-1. When the traffic intensity, $\rho=\lambda T_F$, is less than or equal to 0.75, the expected waiting time approaches its asymptotic value; this asymptotic value for each ρ corresponds to the exact solution of the highway patrol problem. When $\rho>.75$ a solution for $M>25$ is required in order to obtain an expected waiting time close to its asymptotic value. When M=25, a graph of the expected waiting time versus ρ is shown in Fig. 3-2.

An independent Monte Carlo simulation study was performed for the highway patrol problem. From Table 3-1 comparison may be made between the approximate expected population mean waiting time obtained using the above algorithm, with M=25, and the sample mean waiting time obtained from five replications of the Monte Carlo simulation. It is noted that when $\lambda<3.$, the sectioned loop expected waiting time is within 8.1 percent of the sample mean waiting time obtained by replicating the Monte Carlo simulation.

At very high values of λ , and thus ρ, the expected waiting time for M=25 becomes a poor approximation of the mean in the highway patrol problem. Furthermore, the sample mean obtained by replicating the Monte Carlo simulation has a large variance when ρ approaches 1. These facts explain the growing discrepancy in the two columns of Table 3-1 as λ increases.

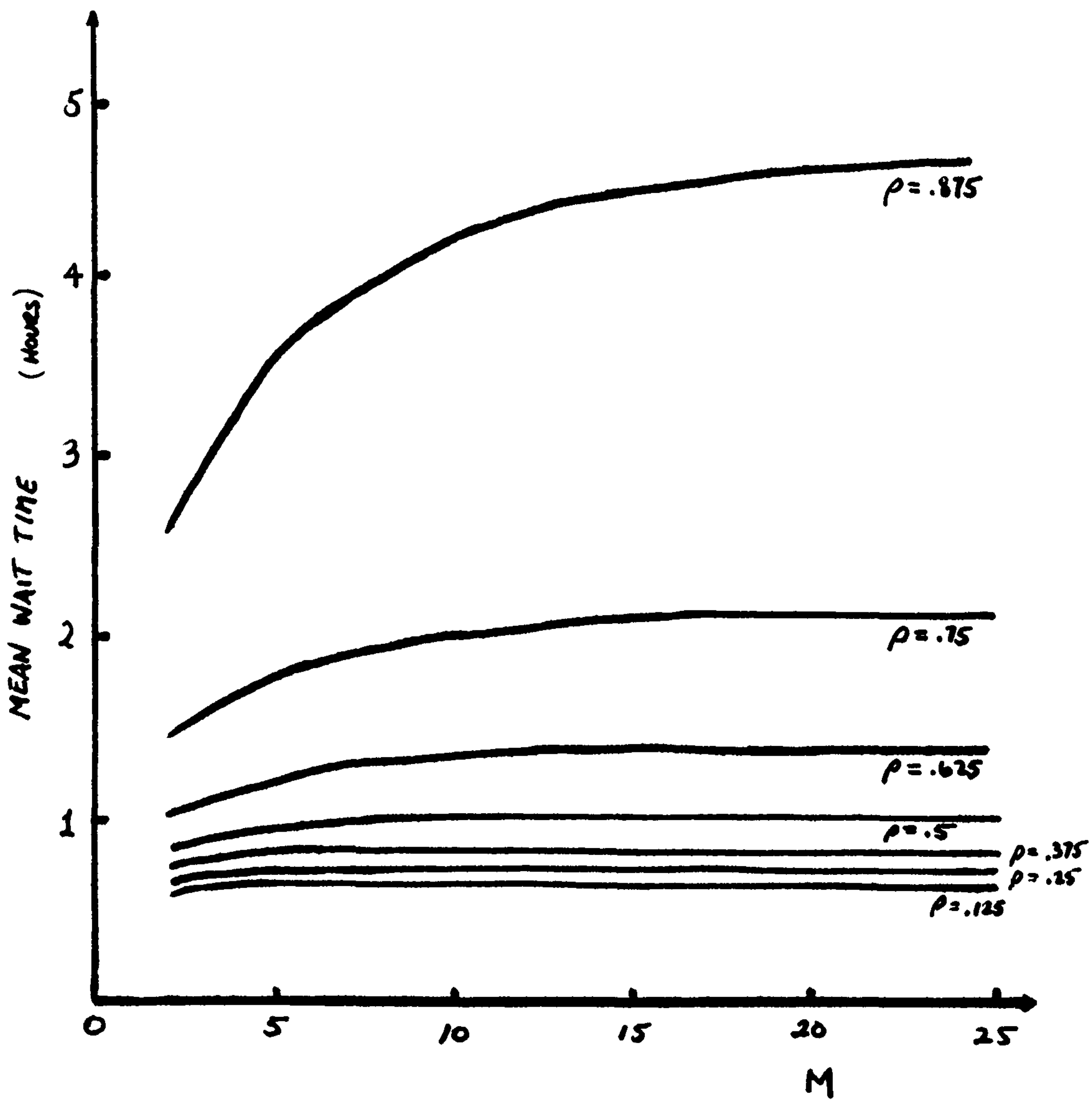


Fig. 3-1 The Mean Waiting Time vs. M

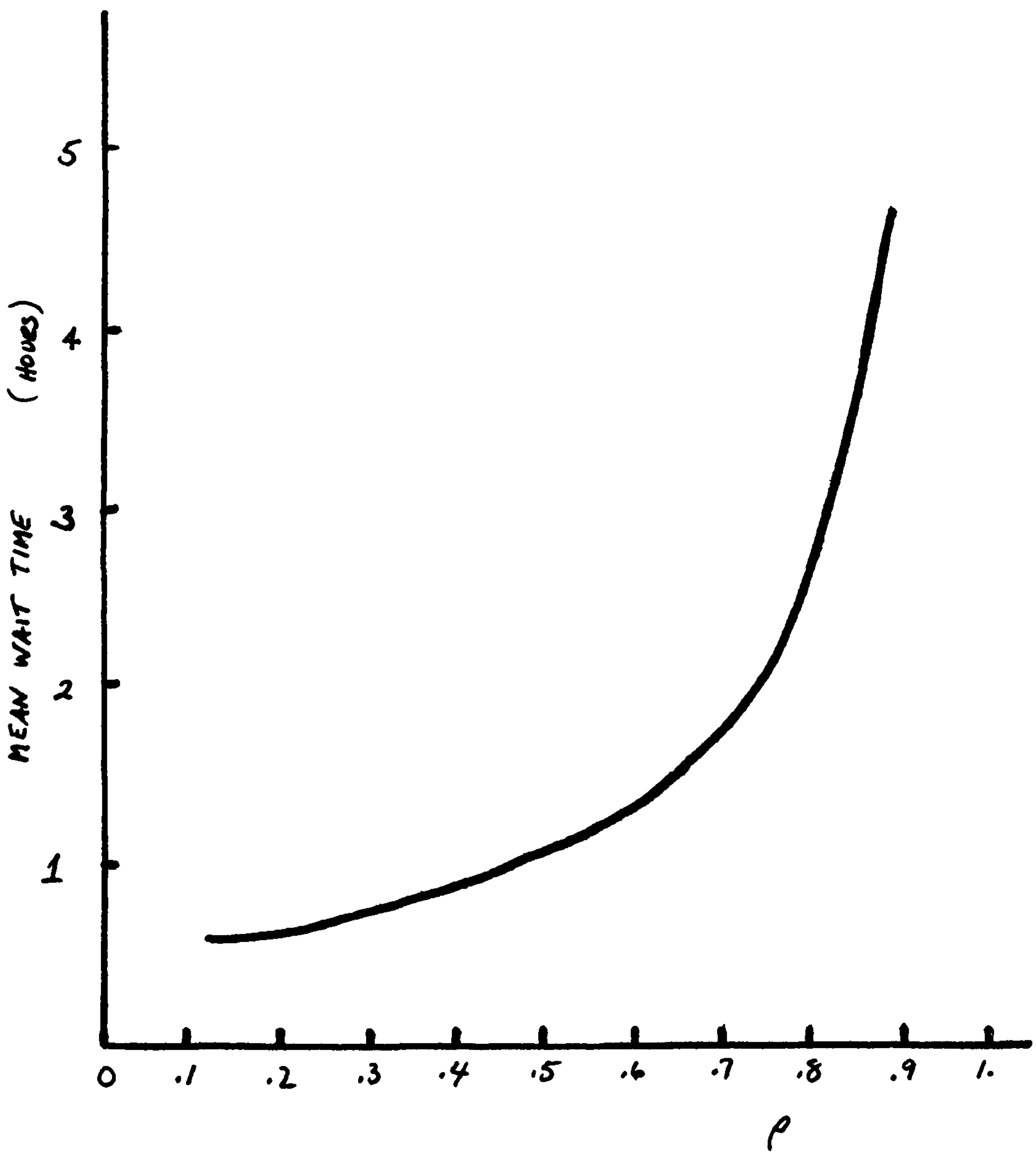


Fig. 3-2 The Mean Waiting Time vs. Traffic Intensity

Table 3-1 Comparison of Average Waiting Times for First Encounter, First Serve Highway Patrol Problem

λ (Veh/hr)	Expected Waiting Time, M=25 (hr)	Sample Waiting Time, Simulation (hr)
0.5	0.6477733	0.6477737
1.0	0.7365002	0.7350950
1.5	0.8659560	0.8619171
2.0	1.070370	1.053026
2.5	1.432507	1.382990
3.0	2.209306	2.031024
3.5	4.719639	4.131753

It is interesting to note that the mean waiting time for the sectioned loop approaches from below the mean waiting time of the continuous loop. This fact may be explained by comparing the number of disabled vehicles serviced per section traveled by a sectioned loop patrol vehicle to the number serviced per section traveled by a continuous loop patrol vehicle. In the continuous case, a certain percentage of those incidents which occur in the section in which the patrol vehicle is presently serving are not serviced until it returns to that section; that is, all those incidents in the section whose breakdown positions are upstream of the patrol vehicle's position will not be serviced. However, in the sectioned loop case, all of the vehicles that break down in the section in which the patrol vehicle is serving will be serviced before it leaves the section.

Therefore, for any number of sections, the mean waiting time of the sectioned loop will be less than the mean waiting time of the continuous loop. As the number of sections increases, the number of the disabled vehicles not serviced per section traveled by the continuous loop patrol vehicle diminishes and the mean waiting time of the sectioned loop approaches the mean waiting time of the continuous loop. For example, in the continuous loop case, assuming the patrol vehicle spends zero time at each incident, then the probability that within a section an incident occurs upstream from the patrol vehicle during the time the patrol vehicle spends in the section is 1/2. Since the average number of incidents that occur in a section during the time the patrol vehicle is in the section is $\frac{\lambda}{M}\left(\frac{D}{VM}\right)$, and the average number of incidents not serviced per section traveled by the continuous loop patrol vehicle is $\frac{\lambda D}{2M^2V}$.

3.3 Solution of a First Disabled First Serve Highway Aid Problem Using M/G/1 Queuing Theory

In this section the results of the standard M/G/1 queuing theory are applied in solving a first disabled first serve highway aid problem. It is assumed that vehicles break down according to a Poisson time process with parameter λ , and their positions of breakdown are uniformly distributed about the length of highway. A single patrol vehicle renders aid to the disabled vehicles in the sequence in which they break down. The patrol vehicle cruises the highway loop with constant speed V, and spends an average time T_{f_1} , from the distribution $F_s(t)$, with each vehicle.

The M/G/1 queuing problem[1] is described by a Poisson customer arrival process, a general service process, one server, and the order of service first come, first serve. It may be seen that the first disabled, first serve highway aid problem is isomorphic to the M/G/1 queuing problem by considering the temporal Poisson breakdown process of the disabled vehicles, the queuing arrival process, the concatenation of the times spent by the aid vehicle traveling to and servicing a disabled vehicle, the queuing service process and the patrol vehicle, the single server.

The probability distribution of the service time may be obtained as follows: The service time of any disabled vehicle, t_s , is given by

$$t_s = t_c + t_f , \tag{3-39}$$

where t_c is the time spent by the aid vehicle traveling to the incident and t_f is the time spent fixing it. If the length of the highway loop is D, then it may be seen that the traveling time is

$$t_c = \begin{cases} \frac{D + X_v - X_t}{V} , & X_v < X_t , \\ \frac{X_v - X_t}{V} , & X_v \geq X_t \end{cases} \tag{3-40}$$

where X_v is the position of the disabled vehicle and X_t is the position of the patrol vehicle when it begins the service. Since a vehicle may break down anywhere along the loop, both X_v and X_t are uniformly distributed between 0-D. Upon transforming the variables X_v and X_t to t_1 and t_2, where

$$t_1 = \frac{D + X_v - X_t}{V} , \quad for\ X_v < X_t , \tag{3-41}$$

and

$$t_2 = \frac{X_v - X_t}{V} , \quad for\ X_v \geq X_t , \tag{3-42}$$

it may be seen that the probability density functions for t_1 and t_2 are

$$f_{t_1}(t) = \begin{cases} \left(\frac{V}{D}\right)^2 t , & 0 \leq t \leq \frac{D}{V} \text{ or } X_v < X_t , \\ \left(\frac{V}{D}\right)^2 \left(\frac{2D}{V} - t\right) , & \frac{D}{V} < t \leq \frac{2D}{V} \text{ or } X_v \geq X_t , \end{cases} \tag{3-43}$$

and

$$f_{t_2}(t) = \begin{cases} \left(\frac{V}{D}\right)^2 \left(\frac{D}{V} - t\right) , & 0 \leq t \leq \frac{D}{V} \text{ or } X_v \geq X_t , \\ \left(\frac{V}{D}\right)^2 \left(\frac{D}{V} + t\right) , & -\frac{D}{V} \leq t \leq 0 \text{ or } X_v < X_t , \end{cases} \tag{3-44}$$

respectively. In terms of t_1 and t_2 the probability density functions of t_c is given as

$$f_{t_c}(t) = P_r\{t \leq t_c \leq t+dt\} = P_r\{t \leq t_1 \leq t+dt \text{ and } t < \tfrac{D}{V}\} + P_r\{t \leq t_2 \leq t+dt \text{ and } t \geq 0\}. \tag{3-45}$$

Therefore, from Eqs. (3-43) and (3-44), Eq. (3-45) becomes

$$\begin{aligned} f_{t_c}(t) &= \left(\frac{V}{D}\right)^2 t + \left(\frac{V}{D}\right)^2\left(\frac{D}{V} - t\right) \\ &= \left(\frac{V}{D}\right)^2\left(\frac{D}{V}\right) = \frac{V}{D}, \quad 0 \leq t \leq \frac{D}{V}, \end{aligned} \tag{3-46}$$

that is, the traveling time spent by the aid vehicle is also uniformly distributed.

From Eqs. (3-39) and (3-46) and using the fact that t_c and t_f are independent random variables, the first, second and third central moments of the service time may be seen to be

$$t_{s_1} = \frac{1}{2}\frac{D}{V} + T_{f_1}, \tag{3-47}$$

$$t_{s_2} = \frac{1}{3}\left(\frac{D}{V}\right)^3 + T_{f_2} + \frac{1}{2}\frac{D}{V}T_{f_1}, \tag{3-48}$$

and

$$t_{s_3} = \frac{1}{4}\left(\frac{D}{V}\right)^3 + T_{f_3} + \frac{3}{2}T_{f_2}\frac{D}{V} + T_{f_1}\left(\frac{D}{V}\right)^2, \tag{3-49}$$

respectively, where T_{f_1}, T_{f_2}, and T_{f_3} are the first, second and third central moments of the time spent by the patrol vehicle servicing the disabled vehicle.

From M/G/1 queuing theory,[1] the first and second central moments of the waiting time distributions of the disabled vehicle are

$$W_1 = t_{s_1} + \frac{\lambda t_{s_2}}{2(1-\lambda t_{s_1})}, \qquad (3\text{-}50)$$

and

$$W_2 = t_{s_2} + \frac{\lambda t_{s_1} t_{s_2}}{1-\lambda t_{s_1}} + \frac{\lambda t_{s_3}}{3(1-\lambda t_{s_1})} + \frac{\lambda^2 t_{s_2}^2}{2(1-\lambda t_{s_1})^2}, \qquad (3\text{-}51)$$

for $\lambda t_{s_1} < 1$.

In Table 3-2, these quantities are listed for various values of the breakdown rate. The estimates of the first and second moments of the waiting time distribution obtained from an independent Monte Carlo simulation of this highway patrol problem, using five replications, are also presented in Table 3-2. It may be seen that the estimated values compare favorably to the theoretical ones.

From Tables 3-1 and 3-2, it may be concluded that the first encounter, first serve aid dispatching policy is preferable to the first disabled, first serve aid dispatching policy since the former policy yields lower mean waiting times than the latter for the same traffic conditions (i.e. the same incident rates).

Table 3-2 Comparison of the First and Second Central Moments for the First Disabled, First Serve Highway Patrol Problem

λ (Veh/hr)	Traffic Intensity = λt_{s_1}	Mean Wait Time (hr)		Mean Square Wait Time $(hr)^2$	
		Theoretical	Estimated	Theoretical	Estimated
.5	.29167	.7165	.7132	.6301	.6215
1.0	.5833	1.0361	1.0334	1.5262	1.5251
1.5	.875	2.8472	2.9437	14.3221	14.7114

3.4 The Arrival Process Assuming Imperfect Detection

In the previous two sections, it was assumed that the highway maintains a perfect detection system. With the above assumption and the fact that vehicles are assumed to break down according to a Poisson time process, the resultant isomorphic queuing arrival process may be considered to be Poisson. However, when the perfect detection system assumption is relaxed, the resultant arrival process is no longer Poisson. This fact may be seen by calculating the probability distribution of the time between disabled vehicle detections, (i.e. the queuing interarrival time) and showing that it is not exponential.*

Vehicles break down according to a Poisson time process with parameter λ. Since it is assumed that the position of the breakdown is uniformly distributed between two detectors, the time interval between breakdown and detection, the detection interval, is also uniformly distributed. With no loss in generality, the probability density function of the detection interval of the ith disabled vehicle may be given as

$$f_{t_D^i}(t) = 1/T_D , \quad 0 < t < T_D \text{ seconds.}$$

The time between disabled vehicle detections is calculated as follows: Assuming that vehicle i becomes disabled at time t_B^i and that the system takes t_D^i seconds

*It is well known that the distribution of the interarrival time of a Poisson time process is exponential.[2] If the interarrival time distribution is not exponential, then the arrival process will not be Poisson.

to detect it, the time difference between successive vehicle's detection times, $t_{i,i+1}$, may be calculated as

$$\begin{aligned} t_{i,i+1} &= t_B^{i+1} + t_D^{i+1} - (t_B^i + t_D^i) \\ &= (t_B^{i+1} - t_B^i) + (t_D^{i+1} - t_D^i) . \end{aligned}$$

The time between disabled vehicle detections, i.e. the isomorphic interarrival time, t_I, may be found as

$$t_I = |t_{i,i+1}| .$$

In the above, the absolute sign is required since it may be possible that the $i+1^{th}$ disabled vehicle will be detected by the system before the i^{th} disabled vehicle. Since the quantity $t_B^{i+1} - t_B^i$ is distributed exponentially with parameter $1/\lambda$, (because of the assumed Poisson breakdown process), the probability density function of t_I may be determined as

$$f_{t_I}(t) = \begin{cases} \frac{1}{T_D}\left(2 - \frac{2t}{T_D} + \frac{2e^{-\lambda T_D}\cosh(\lambda t) - 2e^{-\lambda t}}{\lambda T_D}\right), & 0 < t < T_D, \\ \frac{2e^{-\lambda t}(\cosh(\lambda T_D) - 1)}{\lambda T_D^2}, & t > T_D. \end{cases}$$

It is obvious from the above that with the relaxation of the perfect detection system assumption, the isomorphic interarrival time distribution is no longer exponential and therefore, the assumption of a Poisson arrival process is inapplicable.

CHAPTER 4

THE DESIGN OF THE MONTE CARLO COMPUTER SIMULATION

4.1 Introduction

The problems dealt with in Chapter 3 were simplified versions of highway aid dispatch problems. When practical system conditions are considered, the isomorphic queuing problems have no solutions. For example, the speed of the aid vehicle is actually a function of the number of disabled vehicles awaiting service. For the temporal policy discussed in Section 3.3, this leads to a service time distribution dependent on the queue length. Indeed, an analytic solution of this aid dispatch problem would be desirable.

Since it is desired that competing dispatch policies be evaluated for practical system conditions, an experimental technique must be employed. The implementation of an accurate data gathering system on existing highways for obtaining information on proposed aid dispatch systems is highly impractical. The effort is not only costly in dollars but in work hours as well. However, with the advent of high speed digital computers, such systems can be approximately modeled and simulated on the computer; thereby avoiding a great quantity of painstaking and costly work.

It has been suggested that the great value of a simulation lies in the fact that this method of experimentation is the only one which can achieve "perfect homogeneity of experimental medium".[1] The use of a computer allows the experimentor the advantage of subjecting alternative policies to the same stochastic samples (in this case times and positions of incidents) and thereby "sharpens the contrast between alternatives" by eliminating one source of statistical variation.

4.2 A General Description of the Activity-Scanning Program Design

Computer simulations deal with systems that consist of collections of objects called entities. For the highway aid dispatching system, the entities are the highway, the aid vehicles, and the disabled vehicles. Entities, in general, are characterized by descriptors or attributes. For example, the attributes of the aid vehicles could be their position, speed, and mode of service. In Table 4-1, these three entities are listed with their attributes for a typical aid dispatching system.

The state of an entity's attribute changes only at discrete moments in time called events. Since no change occurs in the time between events, the simulation program is designed to move the system from one event to another. This next event approach is common to all modern computer simulation programming languages.[2] In Table 4-2 the events for a typical aid dispatching system are described.

The computer programming language used for all simulation programs discussed in this study is FORTRAN IV. FORTRAN IV is more flexible than most modern computer simulation languages, i.e. GPSS, SIMSCRIPT. The actual simulation program with a detailed explanation of the entities, their attributes, events, and flow charts is presented in the Appendix. However, a general discussion of the program superstructure is now presented.

The discrete event model building technique used for this study is similar to the activity scanning technique

Table 4-1 The Entities and Their Attributes
For a Typical Aid Dispatch Policy

Entity	Attributes
Aid Vehicles	Highway position, speed; service mode.
Disabled Vehicles	Time of breakdown; position of breakdown; vehicle mode; time required for service.
Highway	Total number of aid vehicles; number of aid vehicles in each service mode category; length of the highway; number of detectors; total number of disabled vehicles; number of disabled vehicles in each vehicle mode category.

Table 4-2 The Events for a Typical Aid Dispatching Policy

Event	Description
Breakdown	At this time a disabled vehicle is created by the program.
Detection	At this time a disabled vehicle is detected by the system. An aid vehicle is dispatched from the garage when available.
Arrival	At this time an aid vehicle arrives to service a disabled vehicle.
Departure	At this time an aid vehicle completes service of a disabled vehicle and then departs from the scene of the incident. The disabled vehicle just serviced is now destroyed by the program.
Return to Garage	At this time an aid vehicle returns to the garage and awaits further orders.

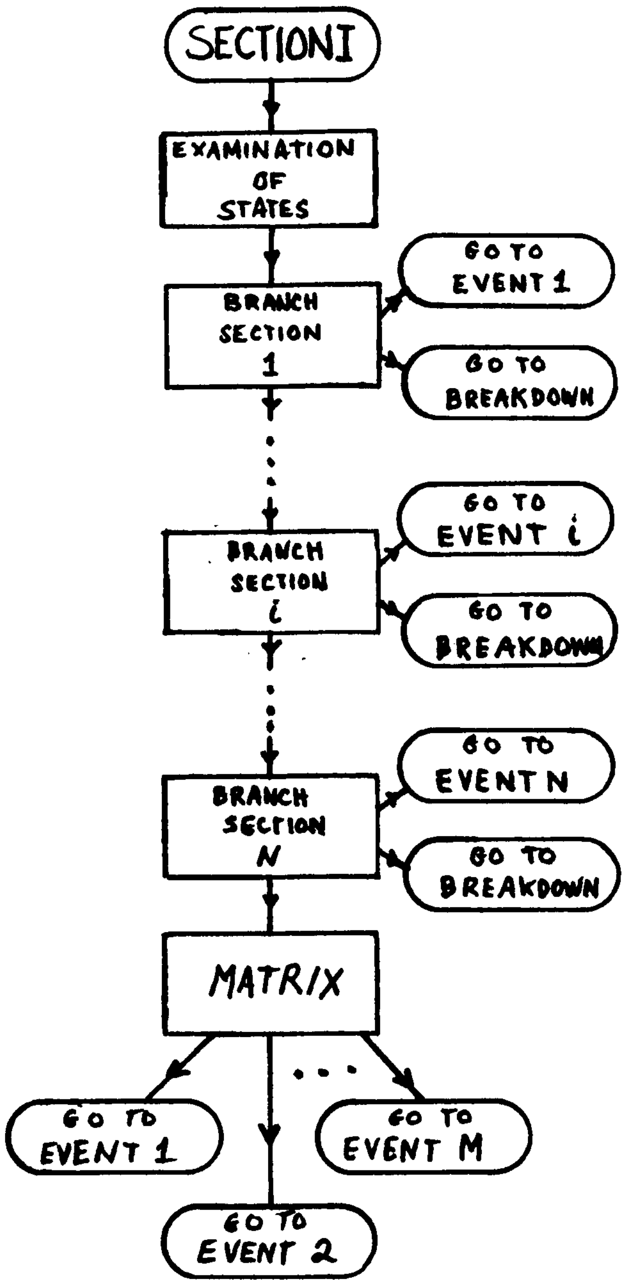
described in Fishman.[2] An activity is a set of operations that changesthe state of an entity's attributes. For example, the repairing of a disabled vehicle is an activity and it occurs between the time at which an aid vehicle arrives at the scene of an incident and the time at which the aid vehicle departs from the scene. Each time an event occurs, the activity scanning approach reviews all of the activities to determine which can be begun or terminated. This study has developed a new approach for scanning the simulation activities that may be applied in general to any simulation employing the activity scanning modeling technique. By examining the status of the entities' attributes, a set of possible events that either commence or terminate an activity is found. After choosing the next event from this set, the computer logic updates the simulation to the time of occurrence of this event and the scanning procedure is repeated.

Each simulation program consists of two sections. Section I contains the logic that determines the next event and Section II consists of the event routines where the changes of state for all appropriate attributes are made for each event in the simulation. Each time an event routine has been executed, control is transferred to Section I where the attributes are again examined to determine a new set of possible next events.

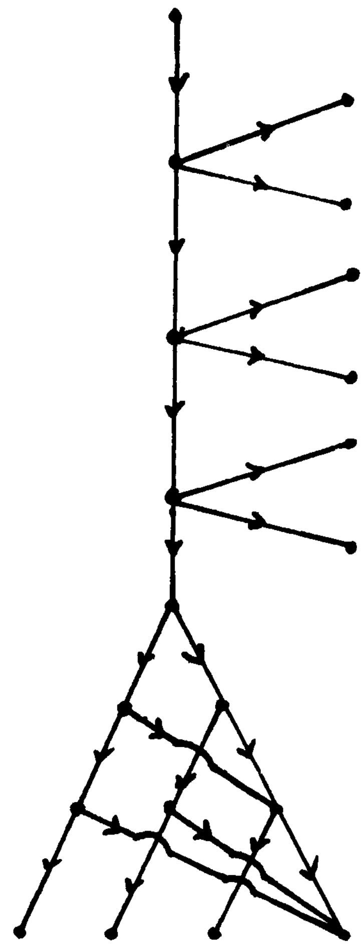
The logic flow chart of Section I can be considered to be a directed single path or tree which contains a series of points or vertices where two unconnected branches emanate. This series of vertices or double branch sections leads to the crown of the tree. The crown or matrix is comprised of an interconnected system of directed paths. Each path of the matrix terminates at the end of an unconnected branch (see Fig. 4-1). When the program flow has proceeded to the end of any of the unconnected branches, the next event has been determined and control is transferred to the proper event routine in Section II.

There exists a double branch section for each type of vehicle mode. The vehicle mode is the state of a disabled vehicle's progress in the system. For a typical aid dispatching policy, the various vehicle mode types are undetected, detected for service, and being serviced. The design of a typical double branch section is illustrated in Fig. 4-2. When a disabled vehicle is in mode i, the next event to take place for this vehicle is event i. $EVNT_i$ is defined as the computer simulation variable that stores the time of occurrence of the next event i. Examples of such events are detection, arrival, and departure. The logic first determines if all disabled vehicles presently on the highway are in mode i. If this is true, then the only possible next event is event i and the routine to determine the value of $EVNT_i$ is executed. The only event that can preempt event i is breakdown since vehicle breakdowns can always occur.* After the logic checks whether or

*If the number of available aid vehicles is greater than unity, the event return to garage becomes another contender to preempt event i.



a) Logic Flow Chart for N vehicle modes and M events.



b) Graphical representation of Logic Flow Chart for 3 vehicle modes and 4 events.

Fig. 4-1 Logic Flow Chart of Section I and its Graphical Representation

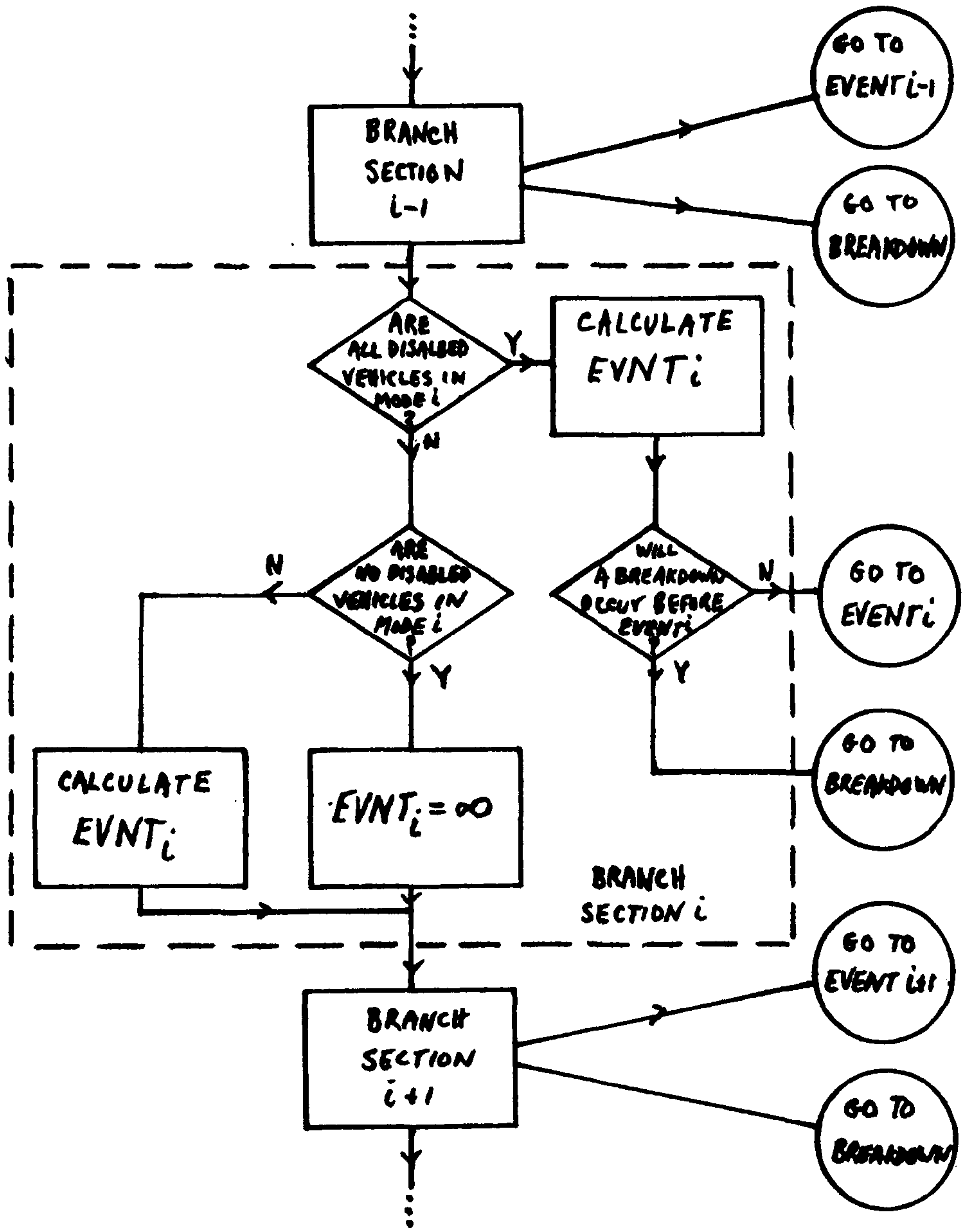


Fig. 4-2 A Typical Branch Section

not a preemption is possible, the flow proceeds to either of the ends of the branches of the double branch section and control is transferred to the proper event routine in Section II. When not all the vehicles presently on the highway are in mode i, the logic determines if there are no disabled vehicles presently on the highway in mode i. If true, then event i is an impossible next event and the program sets $EVNT_i$ to infinity. The flow then proceeds to the next branch section. If some of the disabled vehicles are in mode i, the above result is false and event i is one of the possible next events. From the set of all mode i disabled vehicles, the value of $EVNT_i$ is then calculated and the next double branch section is executed. This structure simplifies programming efforts since a great deal of parallel logic may be avoided. If control does not pass to either of the ends of the branches in the last double branch section, then the matrix section is executed. The size of a matrix is determined by its number of unconnected path ends and is equal to the total number of events that describe the simulation state changes. Fig. 4-3 illustrates a four event matrix. In the matrix, the values of $EVNT_i$ for i=1,2,3,4 are systematically compared to obtain the smallest $EVNT_i$ value. When this has occurred, the flow has reached a branch end of the matrix and control is then transferred to event in in Section II. If event j is an impossible next event, then its branch end will never be reached.

Section II contains the event routines. For each event

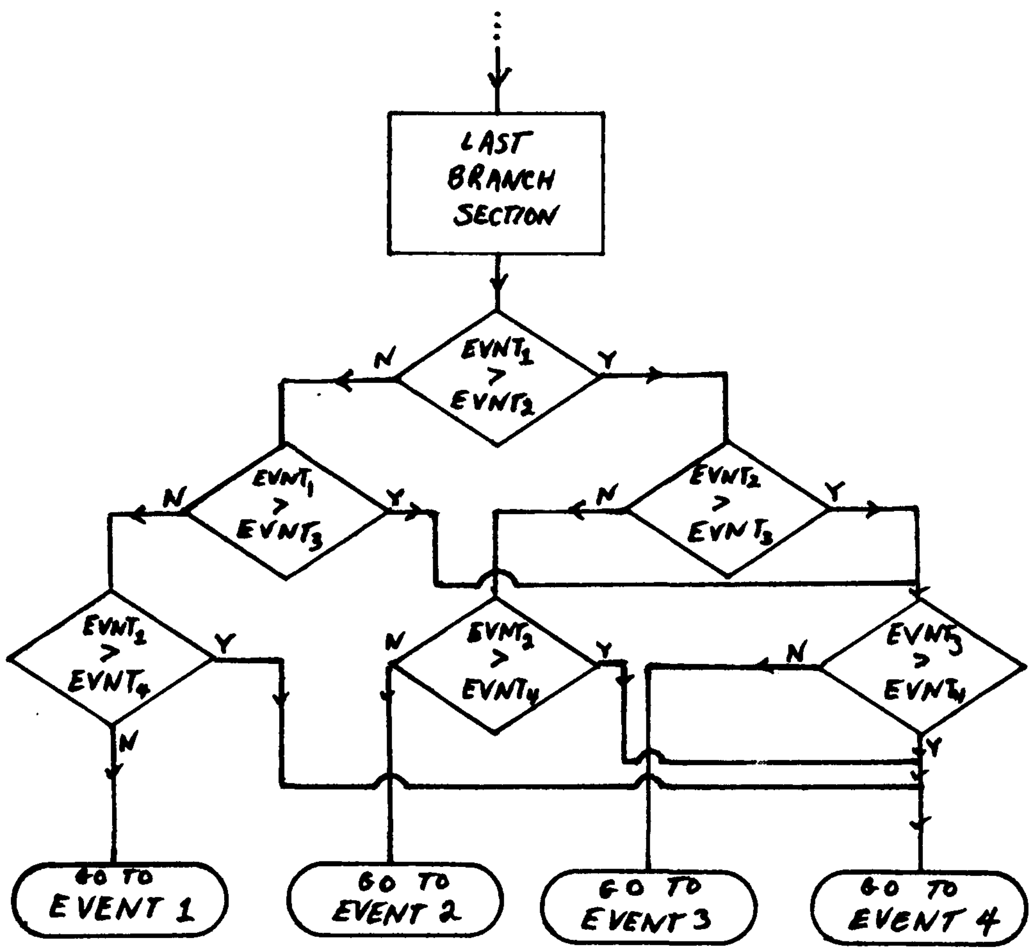


Fig. 4-3 Matrix of Size 4

in the simulation, a subprogram is written in which the attributes of the appropriate entities and the simulation clock are updated. Event routines may do other jobs such as the calculation of waiting time and queue length statistics and the time of occurrence of future events. For example, in Fig. 4-4, the flow chart of the event routine Detection is illustrated.

In general, simulation entities may be divided up into three groups - the servers, the customers, and the system. For the aid dispatching problems they are aid vehicles, the disabled vehicles, and the highway. Usually for very complicated systems, a customer's progress in the system can be described by states or modes. To apply this method of activity scanning, a double branch section similar to the one described above must be designed for each customer mode. The logic in each section determines whether or not the event (or events) associated with the customer mode is a possible next event.* In more complicated systems, the states of progress of the servers may also be needed to decide whether or not an event is a possible next event. For example, in the double branch section designed for the vehicle mode "detected for service", the availability of the aid vehicles must also be checked to determine whether the event Arrival is a possible next event. The simulation program is easily completed upon the designing of the appropriate matrix section and event routines.

*The breakdown event for aid dispatching problems is isomorphic to the more general customer arrival event.

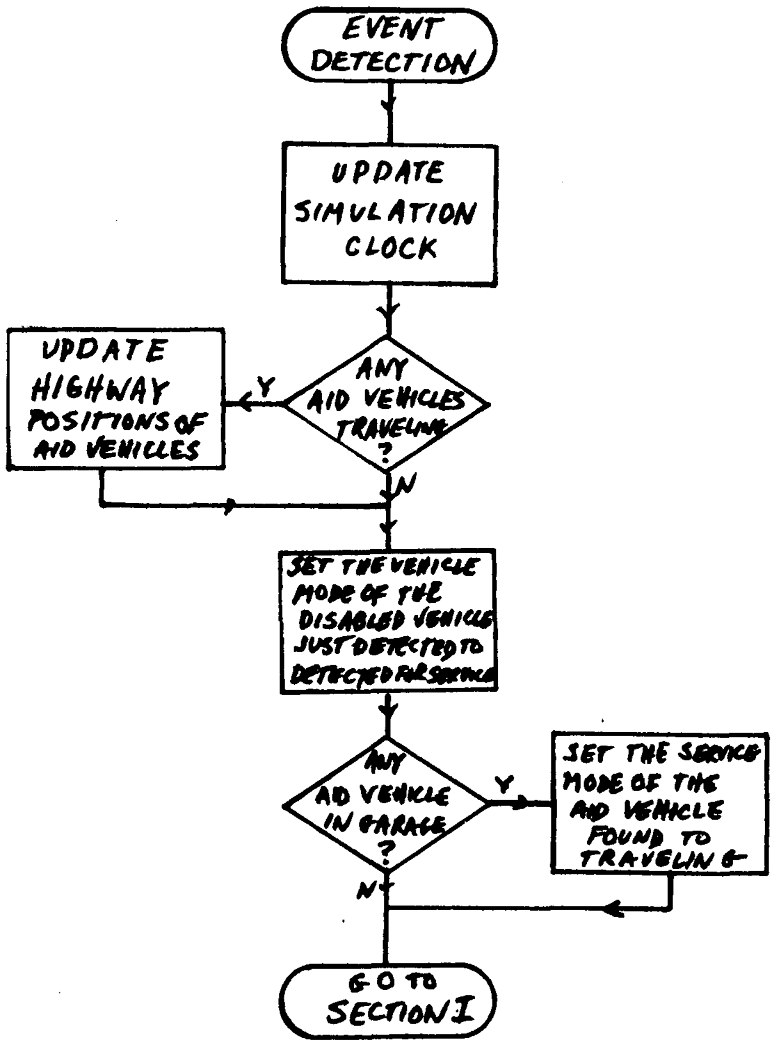


Fig. 4-4 Flow Diagram of the Event Routine DETECTION

4.3 Discussion of Simulation Design and Statistical Analysis

Before any simulation study may be run, decisions on how to design the experiment must be made. In this section the following design problems are discussed: whether to replicate the experiments, whether and when to truncate the warm-up (transient) period, what the value of the initial conditions are, and how long the simulation should be run. The discussions only propose rule of thumb solutions since the general solutions to these problems depend on the type of process simulated. The highway aid dispatch system analyzed herein can be considered to be a very highly complicated queuing process, whereas most of the research[2,3,4,5,9] done in the above areas deal with very simple, well known processes.

The focus of these discussions will be concerned with estimating an unknown parameter of the process, θ, using some function, $\hat{\theta}(\tilde{X})$ of the samples, $\tilde{X}=\{X_1, X_2, \ldots, X_T\}$, generated by the simulation. The figure of merit generally used to assess the goodness of the estimator is the mean square error, $E[(\hat{\theta}(\tilde{X})-\theta)^2]$, of the estimator. The best estimator of θ is, therefore, the one which yields the smallest mean square error. It may be easily shown that

$$E[(\hat{\theta}(\tilde{X})-\theta)^2] = Var[\hat{\theta}(\tilde{X})] + (B[\hat{\theta}(\tilde{X})])^2,$$

where $Var[\hat{\theta}(\tilde{X})]$ is the variance and $B[\hat{\theta}(\tilde{X})] = E[\hat{\theta}(\tilde{X})]-\theta$ is the bias of the estimator, $\hat{\theta}(\tilde{X})$. Usually, $\hat{\theta}(\tilde{X})$ is a function of the number of samples, T, generated by the simulation, $\hat{\theta}_T(\tilde{X})$. If it can be shown that

$$\lim_{T\to\infty} E[(\hat{\theta}_T(\tilde{X})-\theta)^2] = 0,$$

then the estimator is considered consistent. This implies that $\lim_{T\to\infty} \mathrm{Var}[\hat{\theta}_T(\tilde{x})] = 0$ and that either $B_T[\hat{\theta}_T(\tilde{x})] = 0$ or $\lim_{T\to\infty} B[\hat{\theta}_T(\tilde{x})] = 0$. For example, it is well known that the sample average, $\bar{x} = \frac{1}{T}\sum_{\tau=1}^{T} x_\tau$, is a consistent estimator of the mean of a process that generates independent samples.

Definitions of a covariance stationary process and its spectrum proceed the major discussions of this section.

4.3.1 Definitions of a Covariance Stationary Process and Its Spectrum

A stochastic discrete time process, defined by the ordered set of random variables $\{X_t\}$ for t=0,±1,±2,..., is covariance stationary provided that its mean,

$$\mu_t = E[X_t] = \int_{-\infty}^{\infty} x\, f_{x_t}(x)\, dx = \mu, \tag{4-1}$$

is independent of time and its auto covariance function,

$$\begin{aligned}\gamma_{xx}(t_1, t_2) &= E[(x_{t_1}-\mu)(x_{t_2}-\mu)] \\ &= \gamma_{xx}(k), \quad k = 0, \pm1, \pm2, \ldots,\end{aligned} \tag{4-2}$$

is only a function of the time difference, $k=t_2-t_1$. Associated with this process is a power spectral density, hereby referred to as the spectrum,

$$\Gamma_{xx}(f) = \sum_{k=-\infty}^{\infty} \gamma_{xx}(k)\, e^{-j2\pi kf}, \quad -1/2 \le f \le 1/2 . \tag{4-3}$$

The auto covariance function and the spectrum are a Fourier transform pair, thus,

$$\gamma_{xx}(k) = \int_{-1/2}^{1/2} \Gamma_{xx}(f)\, e^{+j2\pi fk}\, df, \quad k=0,\pm1,\pm2,\ldots, \tag{4-4}$$

and therefore, $\Gamma_{xx}(f)df$ represents the incremental variance of the process, $\sigma^2_{x_t}$, that is distributed over the frequency band $f, f+df,$

$$\gamma_{xx}(0) = \sigma_X^2 = \int_{-1/2}^{1/2} \Gamma_{xx}(f)\,df. \qquad (4\text{-}5)$$

Since the study is only concerned with aid dispatch systems that attain some form of steady state or equilibrium, then any time series generated by the simulation asymptotically approaches a discrete covariance stationery process. For example, $\{X_t\}$ may represent the wait time of the t^{th} disabled vehicle or, alternatively, the number of disabled vehicles waiting for service at time t.

Definitions (4-1) through (4-5) will be useful in deciding whether to replicate experiments and when to stop the simulation run.

4.3.2 Discussion of Whether to Replicate a Simulation Experiment

In general, a process $\{X_t\}$ has an autocovariance function, $\gamma_{xx}(t_1,t_2)$, which is non-zero for $t_1 \neq t_2$. For example, in any queuing process, the wait time of a customer usually depends on the waiting time of the customers that have arrived previously. For this more general process, it is no longer true that the unbiased estimator of the mean, $\bar{X} = \frac{1}{T}\sum_{t=1}^{T} X_t$, is consistent since

$$\lim_{T\to\infty} \mathrm{VAR}(\bar{X}) = \lim_{T\to\infty} \frac{1}{T^2}\sum_{t_1=1}^{T}\sum_{t_2=1}^{T} \gamma_{xx}(t_1,t_2), \qquad (4\text{-}6)$$

need not approach zero. This problem may be avoided if the mean is estimated from an average of sample means generated from independent replications of the simulation. If $\bar{X}_{T_i}$ is the sample mean of the i^{th} replication, then

$$\bar{\bar{X}}_N = \frac{1}{N}\sum_{i=1}^{N} \bar{X}_{T_i} , \qquad (4\text{-}7)$$

is a consistent estimator of the mean,

However, if a process is covariance stationary, then a consistent estimator for the mean may be obtained without replication. For a covariance stationary process, Eq. (4-6) becomes

$$V_{AR}(\bar{X}) = \left\{\frac{1}{T}\left[\gamma_{xx}(0) + 2\sum_{K=1}^{T-1}(1-K/T)\,\gamma_{xx}(K)\right]\right\}. \qquad (4\text{-}8)$$

From Eq. (4-3) in Section 4.3.1, the limiting value of $T\,Var(\bar{X})$ becomes*

$$\lim_{T\to\infty} T\,Var(\bar{X}) = \Gamma_{xx}(0)\ , \qquad (4\text{-}9)$$

which implies that $\lim_{T\to\infty} Var(\bar{X}) = 0$. Since $\bar{X}$ is an unbiased estimator of the mean, then the sample mean is consistent and the covariance stationary process is ergodic in the mean.

4.3.3 Discussion On Whether To Truncate The Data

Since a time series generated by a simulation exhibits a warm-up or non-stationary transient period prior to reaching equilibrium, it has been suggested[1] that the collection of data for estimating population quantities should begin after this warm-up period has elapsed. The selection of how much data to discard depends on the process being simulated, which, in general, is unknown.

In reference (3), Fishman examines the estimation of the mean of an asymptotic covariance stationary autoregressive process, $\{X_t\}$, given below as

*When a process is covariance stationary, it is implied that $\gamma_{xx}(K)$ must be bounded. In particular, it is assumed that $\gamma_{xx}(K) \lesssim C\alpha^{|K|}$ where $0<\alpha<1$. This assumption is very reasonable for stable queuing processes.[2]

$$X_t - \mu = \alpha\,(X_{t-1} - \mu) + \epsilon_t\,,\ 0 < \alpha < 1,$$

where $\mu = E[\{X_t\}]$ and $\{\epsilon_t\}$ is a sequence of independent, identically distributed random variables, such that $E[\{\epsilon_t\}] = 0$, $Var[\{\epsilon_t\}] = \sigma^2$, and $\gamma_{\epsilon_{t_1}\epsilon_{t_2}}(t_1, t_2) = 0$ for $t_1 \neq t_2$. Fishman shows that the truncated estimator of the mean,

$$\bar{X}_{n,K} = \frac{1}{n-K} \sum_{t=K+1}^{n} X_t\,, \tag{4-10}$$

has mean square error given by

$$E[(\bar{X}_{n,K} - \mu)^2 / X_0] = \frac{\sigma^2}{(n-K)(1-\alpha)^2} \left\{ 1 - \frac{\alpha}{(n-K)} \left[\frac{2(1-\alpha^{n-K})}{1-\alpha^2} + \frac{\alpha^{2K+1}(1-\alpha^{n-K})^2}{(1-\alpha^2)} \right] + \frac{(X_0 - \mu)^2 \alpha\, (\alpha^K - \alpha^n)^2}{\sigma^2} \right\}. \tag{4-11}$$

Furthermore, upon comparing the mean square error of $\bar{X}_{n,0}$ to $\bar{X}_{n,K^*}$, where K^* is chosen to "eliminate" the warm-up period, it is concluded that it would be undesirable to truncate the data (i.e. $\bar{X}_{n,0}$ has a smaller mean square error than $\bar{X}_{n,K^*}$).

Blomquist[4] makes a stronger statement that for any first come, first serve single server queuing system, the mean square error of the estimator of the mean wait time is minimum for truncation point k=0, providing that the coefficient of variance of the wait time process is greater than one. In particular, Blomquist shows that the M/G/1 and GI/M/1 queuing systems satisfy this condition.

In general, an aid dispatch system is more complicated than an autoregressive process and a first come, first serve queuing process; however, the conclusions of the above two studies provide justification for not truncating the data. This conclusion is also very convenient since the problem of determining how much data to discard is avoided.

4.3.4 Discussion Of The Determination Of Initial Conditions

In reference (1) it is conjectured that beginning the simulation at "reasonable" starting conditions will diminish the time required to reach equilibrium. Furthermore, Eq. (4-11) shows that the mean square error of the estimator of the sample mean of an autoregressive process is minimum for $X_0 = \mu$. This will lead an experimentor to choose $X_0 = \mu$ as a starting condition. However, a very startling and counter-intuitive result was developed by Madansky[5] with respect to the effect of initial conditions on the queue length for an M/M/1 queue. Using the last observation of the queue length time series, X_T , as the estimator of the mean, Madansky shows that there exists a $\mathcal{T}$ such that for $T > \mathcal{T}$ the mean square error of the estimator is minimum when $X_0 = 0$. The same result also holds for the average queue length taken from N independent replications of a simulation.

Although for this study there is more interest in determining the average wait time rather than the average queue length, Madansky's result is very useful since it is well known that the average queue length and average wait time are related.[6] It is felt that since an aid dispatch system behaves more like the M/M/1 system than the autoregressive system, and that starting the simulation at $X_0 = \mu$ requires a knowledge of the mean which is usually unknown, the choice $X_0 = 0$ is highly desirable.

4.3.5 Discussion on Determination of End Conditions

In Section 4.3.1 it was stated that the spectrum of a covariance stationary process is the Fourier transform of the autocovariance function of the process. When the process is in a transient state (i.e., before the effects of initial conditions have diminished), the process is certainly not covariance stationary and any spectral estimate based on the sample autocovariances will not be satisfactory. The procedure, described below, for estimating the spectrum is based on the assumption that the sample has been generated from a covariance stationary process and, therefore, will not yield a good spectral estimate during the transient period. When a sample yields a good spectral estimate using this procedure, it may be inferred that estimates of the mean and variance obtained from this sample represent estimates of the respective steady state parameters. Because a sufficient amount of data must be collected in order to obtain a good spectral estimate, a criterion is therefore obtained for determining the required length of the simulation. In this section, a brief summary of the art of spectral analysis with an example is presented. In addition, further remarks on whether or not to replicate a simulation are made.

An estimator of the sample spectrum is given by

$$\bar{\Gamma}_{xx}(f) = \sum_{K=-(T-1)}^{T-1} \bar{\gamma}_{xx}(K)\, e^{-j2\pi fK}, \quad -1/2 \leq f \leq 1/2, \tag{4-12}$$

where

$$\bar{\gamma}_{xx}(K) = \frac{1}{T} \sum_{t=1}^{T-|K|} (x_t - \bar{x})(x_{t+K} - \bar{x}), \quad K = 0, \pm 1, \pm 2, \ldots, \pm(T-1), \tag{4-13}$$

is an estimator of the autocovariance function of the process. It is easy to show that

$$E[\bar{\gamma}_{xx}(K)] = \left(1-\frac{|K|}{T}\right)\gamma_{xx}(K) - \left(1+\frac{|K|}{T}\right)\operatorname{Var}\bar{X}, \qquad (4\text{-}14)$$

and when T becomes large

$$E[\bar{\gamma}_{xx}(K)] = \gamma_{xx}(K) - \operatorname{Var}\bar{X}\,. \qquad (4\text{-}15)$$

Since $\lim_{T\to\infty} \operatorname{Var}\bar{x} \to 0$, $\bar{\gamma}_{xx}(K)$ is asymptotically unbiased. To determine the variance of $\bar{\gamma}_{xx}(K)$, the covariance, $\operatorname{Cov}[\bar{\gamma}_{xx}(K_1), \bar{\gamma}_{xx}(K_2)]$, must first be determined. It may be shown that

$$\begin{aligned}
\operatorname{Cov}[\bar{\gamma}_{xx}(K_1), \bar{\gamma}_{xx}(K_2)] &= \operatorname{Cov}\left\{\left[\frac{1}{T}\sum_{t=1}^{T-|K_1|}(X_t-\bar{X})(X_{t+K_1}-\bar{X})\right], \left[\frac{1}{T}\sum_{v=1}^{T-|K_2|}(X_v-\bar{X})(X_{v+K_2}-\bar{X})\right]\right\} \\
&= \operatorname{Cov}\left\{\left[\frac{1}{T}\sum_{t=1}^{T-|K_1|}(X_t-\mu)(X_{t+K_1}-\mu)\right], \left[\frac{1}{T}\sum_{v=1}^{T-|K_2|}(X_v-\mu)(X_{v+K_2}-\mu)\right]\right\} \\
&\quad - \operatorname{Cov}\left\{\left[\left(1-\frac{|K_2|}{T}\right)(\bar{X}_v-\mu)^2\right], \left[\frac{1}{T}\sum_{t=1}^{T-|K_1|}(X_t-\mu)(X_{t+K_1}-\mu)\right]\right\} \qquad (4\text{-}16) \\
&\quad - \operatorname{Cov}\left\{\left[\left(1-\frac{|K_1|}{T}\right)(\bar{X}_t-\mu)^2\right], \left[\frac{1}{T}\sum_{v=1}^{T-|K_2|}(X_v-\mu)(X_{v+K_2}-\mu)\right]\right\} \\
&\quad + \operatorname{Cov}\left\{\left[\left(1-\frac{|K_1|}{T}\right)(\bar{X}_t-\mu)^2\right], \left[\left(1-\frac{|K_2|}{T}\right)(\bar{X}_v-\mu)^2\right]\right\}.
\end{aligned}$$

The first term on right side of Eq. (4-16) is similar to the right side of equation (5.3.15) in Jenkins and Watts.[7] There it is shown that this term asymptotically approaches zero, provided that $\{Y_t\}$ is also stationary in the 4th moment. Since the remaining terms in Eq. (4-16) are all of order four, it is conjectured that a similar approach as in Jenkins and Watts may be applied to show that these terms will also asymptotically approach zero.

For the present, however, it is assumed that T is large enough so that $\operatorname{Var}\bar{X} \simeq 0$ and the last three terms of Eq. (4-16) can be ignored.

It can be shown that the estimator of the spectrum is asymptotically unbiased, i.e. $\lim_{T\to\infty} E[\bar{\Gamma}_{xx}(f)] = \Gamma_{xx}(f)$; however, its variance unhappily does not go to zero as $T\to\infty$. In order to reduce the variance of the spectral estimates, another estimator, known as the smoothed spectral estimator, $\bar{\bar{\Gamma}}_{xx}(f)$, is introduced,

$$\bar{\bar{\Gamma}}_{xx}(f) = \sum_{k=-(M-1)}^{M-1} \omega(k)\, \bar{\gamma}_{xx}(k)\, e^{-j2\pi f k}, \quad -1/2 \le f \le 1/2, \tag{4-17}$$

where $\omega(k)$ is called the lag window and M is its truncation point. The lag window allows the weighted values of the first M lags of the sample autocovariance function to be considered in the estimation of the spectrum. Since the amount of information is reduced, the smoothed estimator will have a smaller variance than $\bar{\Gamma}_{xx}(f)$.

The properties that a lag window must satisfy are given below,

$$\begin{aligned} &1.\ \omega(0) = 1, \\ &2.\ \omega(t) = \omega(-t), \\ &3.\ \omega(t) = 0,\quad |t| \ge M,\ M < T. \end{aligned} \tag{4-18}$$

It is easy to show that

$$\bar{\bar{\Gamma}}_{xx}(f) = \int_{-1/2}^{1/2} W(g)\, \bar{\Gamma}_{xx}(f-g)\, dg, \tag{4-19}$$

where $W(f)$ is the Fourier transform of $\omega(t)$ and it is known as the spectral window. The corresponding properties that the spectral window satisfies are

$$\begin{aligned} &1.\ \int_{-\infty}^{\infty} W(f)\, df = \omega(0) = 1, \\ &2.\ W(f) = W(-f), \\ &3.\ W(f) \text{ is a slit with base width of order } 2/M. \end{aligned} \tag{4-20}$$

A list of useful windows is given in Table 4-3.

As the width, M , of the lag window decreases, the variance of the smoothed spectral estimator is decreased and, in contrast, the bias is increased. When M becomes large, the shape of the spectral window approaches a delta function and the asymptotic expected value of $\bar{\bar{\Gamma}}_{xx}(f)$ becomes

$$\lim_{T\to\infty} E\left[\bar{\bar{\Gamma}}_{xx}(f)\right] = \lim_{T\to\infty} E\left[\bar{\Gamma}_{xx}(f)\right] = \Gamma_{xx}(f) . \qquad (4\text{-}21)$$

Hence, one must compromise between bias and variance by making the mean square error as small as possible. The exact nature of the compromise depends on the degree of smoothness of $\Gamma_{xx}(f)$.

Before discussing the achievement of this compromise, the windows given in Table 4-3 will be compared. In Table 4-4, the approximate expressions for the large sample bias and variance ratio, $\frac{\mathrm{Var}\left[\bar{\bar{\Gamma}}_{xx}(f)\right]}{\mathrm{Var}\left[\bar{\Gamma}_{xx}(f)\right]}$, are given for each of the windows.[7] Another important criterion is the degree of correlation between smoothed spectral estimators separated in frequency by f_1-f_2. Jenkins and Watts[7] show that this correlation is proportional to the amount of overlap of the spectral windows centered at f_1 and f_2. Because of this, the Bartlett window is rejected since there are large side lobes in its spectral window.

In this study, the estimator of the power density spectrum uses the Tukey window. For the same value of the variance ratio, the Tukey window has a smaller bias than the Parzen window. Secondly, the Tukey window is superior because of the simple form of its lag window representation and therefore smoothed spectral component computations may be made faster.

Table 4-3 Typical Windows

Name	Lag Window	Spectral Window
Bartlett	$w(t)=\begin{cases} 1-\frac{\lvert t\rvert}{M}, & \lvert t\rvert \le M \\ 0, & \lvert t\rvert > M \end{cases}$	$W(f)= M\left(\frac{\sin \pi f M}{\pi f M}\right)^2$
Tukey	$w(t)=\begin{cases} \frac{1}{2}(1+\cos \pi t/M), & \lvert t\rvert \le M \\ 0, & \lvert t\rvert > M \end{cases}$	$W(f)= \frac{M(\sin 2\pi f M)}{2\pi f M\,(1-(2fM)^2)}$
Parzen	$w(t)=\begin{cases} 1-6(t/M)+6\left(\frac{\lvert t\rvert}{M}\right)^3, & \lvert t\rvert \le \frac{M}{2} \\ 2\left(1-\frac{\lvert t\rvert}{M}\right)^2, & M/2<\lvert t\rvert \le M \\ 0, & \lvert t\rvert > M \end{cases}$	$W(f)= 3M\left(\frac{\sin \pi f M/2}{\pi f M/2}\right)^4$

Table 4-4 Properties of Windows

Name	Asymptotic Bias	Variance Ratio= $Var\ \bar{\bar{\Gamma}}_{xx}(f)/Var\ \bar{\Gamma}_{xx}(f)$
Bartlett	$1/M \sum_{-\infty}^{\infty} -\lvert K\rvert \, \gamma_{xx}(K)\, e^{-j2\pi fK}$	$.667\ M/T$
Tukey	$\pi^2/4M^2 \sum_{-\infty}^{\infty} -K^2 \gamma_{xx}(K)\, e^{-j2\pi fK}$	$.75\ M/T$
Parzen	$6/M^2 \sum_{-\infty}^{\infty} -K^2 \gamma_{xx}(K)\, e^{-j2\pi fK}$	$.539\ M/T$

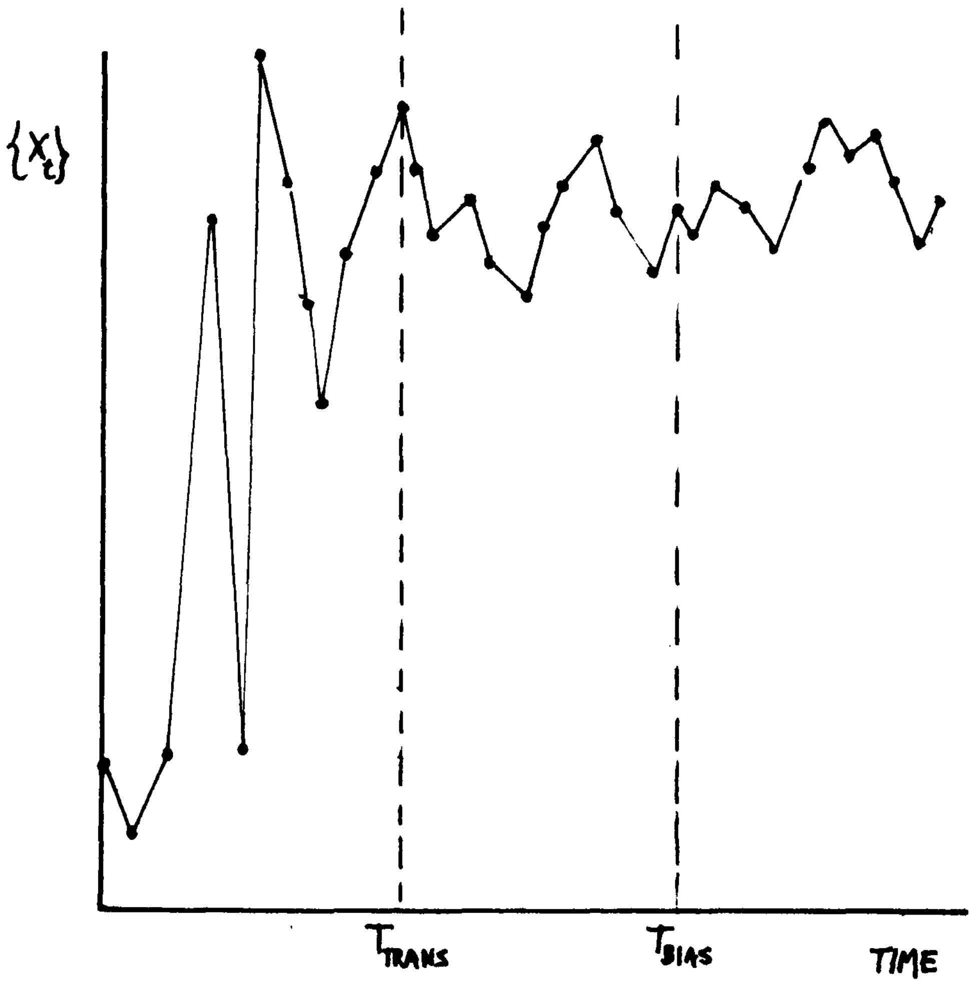
The procedure for estimating the spectrum is known as window closing. As the lag window is closed (i.e. the value of M is decreased), the variance of the estimator decreases and the spectral estimate, in general, converges to a stable value. Any further decrease in M distorts the shape of the estimate because of the increased bias. It is possible that one of the following three situations may occur. The first, called ideal window closing, is characterized by no major changes occurring in the sample spectrum after a large reduction in M. When the estimate suddenly converges as small values of M are reached, the intermediate condition of window closing has occurred. From Eqs. (4-15) and (4-17) it may be shown that

$$E[\bar{\bar{\Gamma}}_{xx}(f)] \cong \Gamma_{xx}(f) + B_w(f) - \mathrm{Var}\,\bar{X}\; W(f), \qquad (4\text{-}22)$$

where $B_w(f)$ is the large sample asymptotic window bias given in Table 4-4. A great deal of detail in the actual spectrum may be missed, but the basic form of the spectrum is preserved. This is probably due to an increase in bias due to estimating the process mean with the sample mean; as seen in Eq. (4-22) when $\mathrm{Var}\,\bar{X} \neq 0$, as is the case when the sample record is not very large (the intermediate condition), the smoothed spectral estimator possesses an additional bias term.

Finally, when the window closing procedure indicates that the spectral estimates are not converging to any sort of stable value (as M decreases), the situation is considered poor. In this case, the trouble may be due to any one of the following: First, the length of the sample record is such that the $Var\,\bar{X}$ is so large that increasing M, i.e. decreasing $B_W(f)$ has little effect in unmasking the true spectrum. Secondly, the process has not reached a level of equilibrium, i.e. steady state. In Fig. 4-5 it may be seen that these causes of spectral bias are not unrelated. When the record length, T, is less than the time at which the process reaches equilibrium, T_{TRANS}, poor spectral estimates are caused by the lack of stationarity of $\{X_t\}$; that is, estimating the spectrum using the sample autocovariances is unsatisfactory. When T is greater than T_{TRANS} (i.e., the process has reached a level of stability) but less than the time at which the $Var\,\bar{X}$ ceases to introduce bias in Eq. (4-22), T_{BIAS}, the large bias of the spectral estimator corrupts the analysis. This effect is shown in the example that follows this section. However, the latter condition may not be disjoint from the former condition, since the transition from the unstable period to the large bias period is always smooth.

It is because of this last situation, that a set of experiments, using various record lengths, can determine the minimum record size, $\mathcal{T}$, needed to achieve a good estimate of the spectrum. The value of the record size which does not permit the procedure to fall into the poor spectral analysis category is the sufficient sample record size, $\mathcal{T}$. Since a good estimate of the power spectrum will have been obtained using the sample autocovariances, the process may be considered to be covariance stationary and



$T_{TRANS} \triangleq$ The time at which $\{X_t\}$ reaches equilibrium.

$T_{BIAS} \triangleq$ The time at which $VAR\,\bar{X}$ ceases to introduce bias.

Fig. 4-5 A Typical Sample of the Stochastic Process $\{X_t\}$

any estimates of the mean and variance using a sample of size equal or greater than $\mathcal{T}$ will represent steady state estimates. For any $T > \mathcal{T}$ the window closing procedure will yield a better estimate since the variance of the smoothed spectral estimators are all inversely proportional to T .

For large values of T the window closing procedure also provides the experimentor with an estimate of the variance of the sample mean, as seen from Eq. (4-9).

In Section 4.3.2 it was shown that there is no need to replicate a covariance stationary process. Since an estimate of the variance of the mean may be obtained from an estimate of the spectrum at f=0, confidence intervals for the population mean may be calculated from a single run. However, when a change in the input parameters of a simulation are made, the autocovariance structure of the output time series changes and new values of $\mathcal{T}$ and M must be obtained for a good spectral estimate. Rather than reevaluating $\mathcal{T}$ for each parameter change, the minimum value of record size that should be used is the $\mathcal{T}$ obtained for the most strongly autocorrelated process in the study. In this way, the experimentor is assured that $\mathcal{T}$ will be adequate for every experiment in the study.

Since the window closing procedure is an empirical technique, the range of values of M that achieves the best compromise between the bias and variance of the smooth spectral estimator will be different, in general, for each parameter change. Therefore, the window closing must be applied for every experiment in the study. This is inefficient and it may be argued that the use of spectral analysis to estimate the confidence limits of the mean for every experiment in the study is more time consuming than estimating these confidence limits from the values of the sample means obtained from identical independent replications of the simulation with record length $T \geq \mathcal{T}$ (see Section 4.3.2 Eq. [4-7]). This latter procedure is the one employed since it is simpler and can be completely automated as part of the simulation program.

The use of spectral analysis for estimating $\mathrm{Var}\,\bar{X}$ may be unsatisfactory. Since $W(0) > |W(f)|$ for $f \neq 0$, the bias of the spectral estimator (Eq. [4-22]), is largest at f=0. Therefore, for moderate values of T, the estimation of $\Gamma_{xx}(0)$, i.e., $T\,\mathrm{Var}\,\bar{X}$, is always biased. Duket[9] shows that using independent, identically distributed replications for estimation of the variance of the mean queue size of an M/M/1 queue is far superior to using the spectral estimates from one long run.

<u>Example: The Spectral Analysis of a First Encounter, First Serve and a First Disabled, First Serve Aid Dispatching Problem.</u>

To illustrate the procedure of window closing, the spectrum of the wait time squared process of the disabled vehicles was analyzed for the first encounter, first serve and first disabled, first serve aid dispatch priorities described in Chapter 2. The traffic intensity for the systems were .75 and .583333, respectively and, therefore, the process was considered to be rather highly autocorrelated. Each of the systems were simulated until 1000 observations of the wait time squared were generated. The spectral estimates were calculated using a Tukey window.

In Fig. 4-6 the three smoothed sample spectrum estimates of the first encounter, first serve policy are drawn corresponding to truncation points 400, 200, and 100 lags. Since the spectrum of a highly auto correlated process approaches a delta function centered at f=0, most of the interesting detail may be found in the first 0.1 cycles per lag. For M=400 lags, the estimate exhibits a highly oscillatory nature due to high variance. As M is reduced, the variance ratio becomes smaller and the estimate becomes smoother. When M =100, the height of the peaks at f=0 seems to be underestimated and reducing M would only produce more distortion in the estimate. Since only one good, smooth estimate, M=200 lags, can be obtained as the window closing procedure passes from high variance estimates to distorted ones, this experiment falls into the intermediate category.

A similar conclusion may be drawn when the analysis is repeated for 500 observations. Only when M =154 lags can a smooth estimate that preserves the basic form of the spectrum be obtained (see Fig. 4-7).

A significant change in the results of the experiment occurs when the analysis is made for 250 observations, Fig. 4-8. The spectral estimates do not converge to the

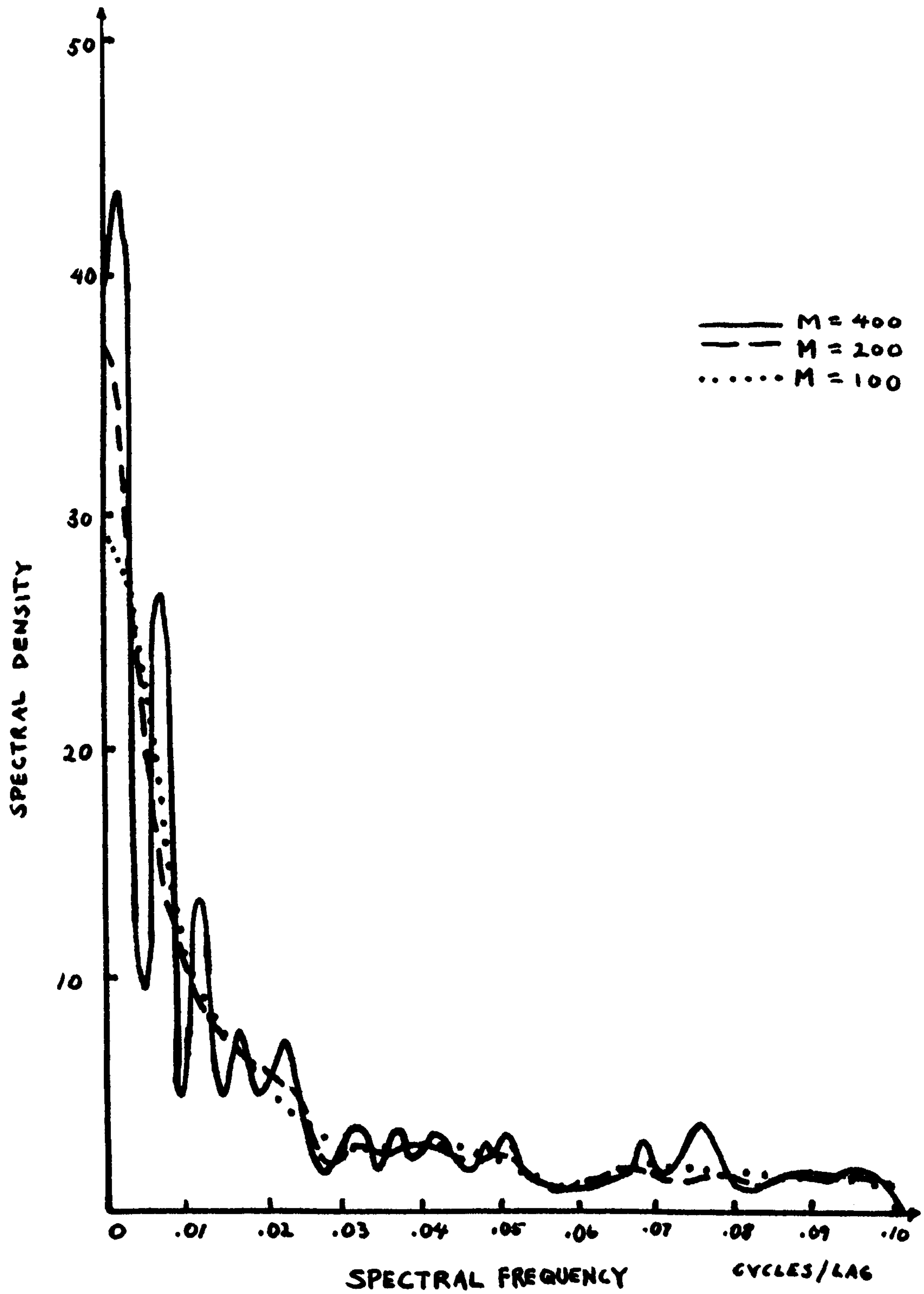


Fig. 4-6 Spectral Estimates of the First Encounter, First Serve Policy (N=1000)

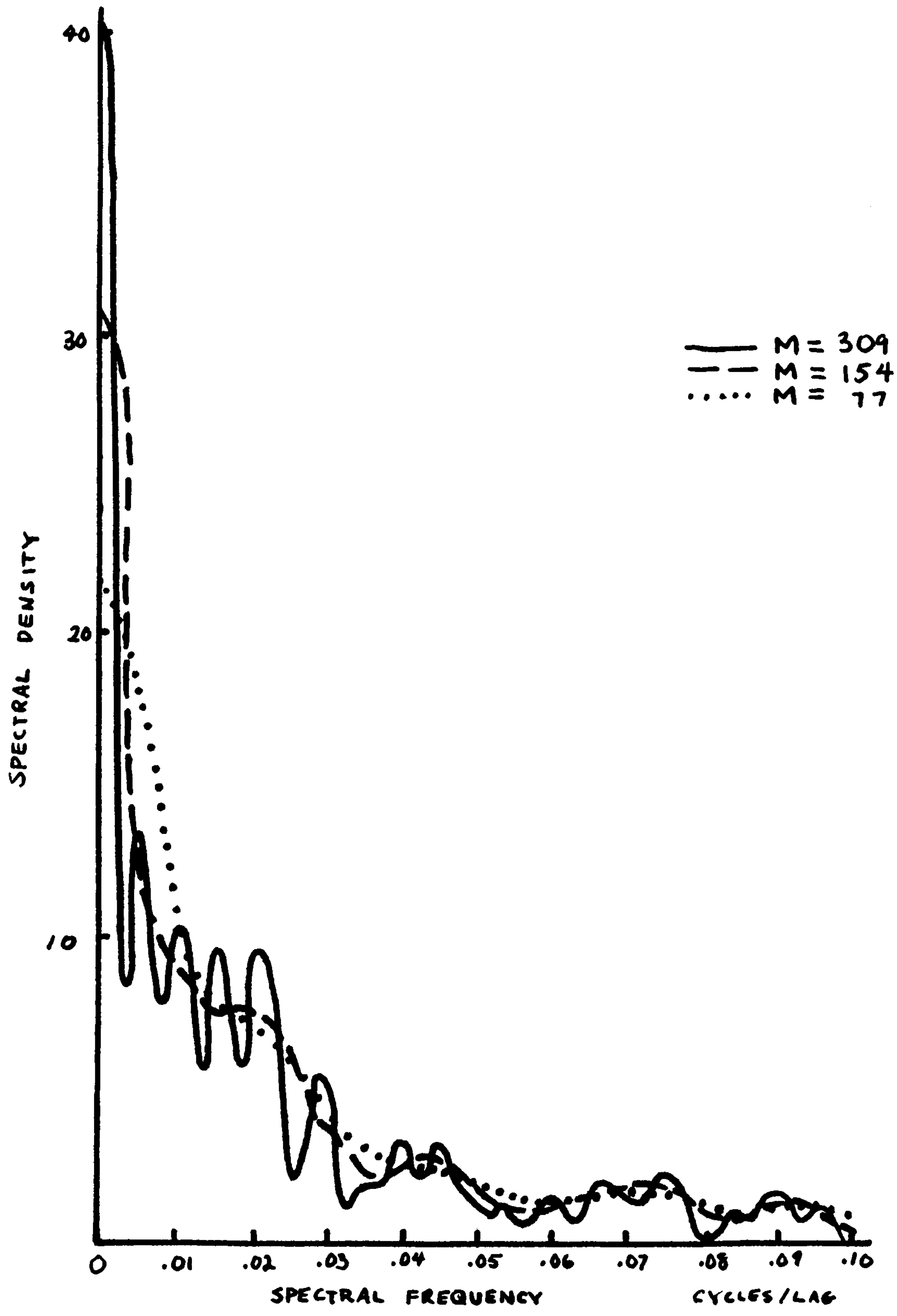


Fig. 4-7 Spectral Estimates of the First Encounter, First Serve Policy (N=500)

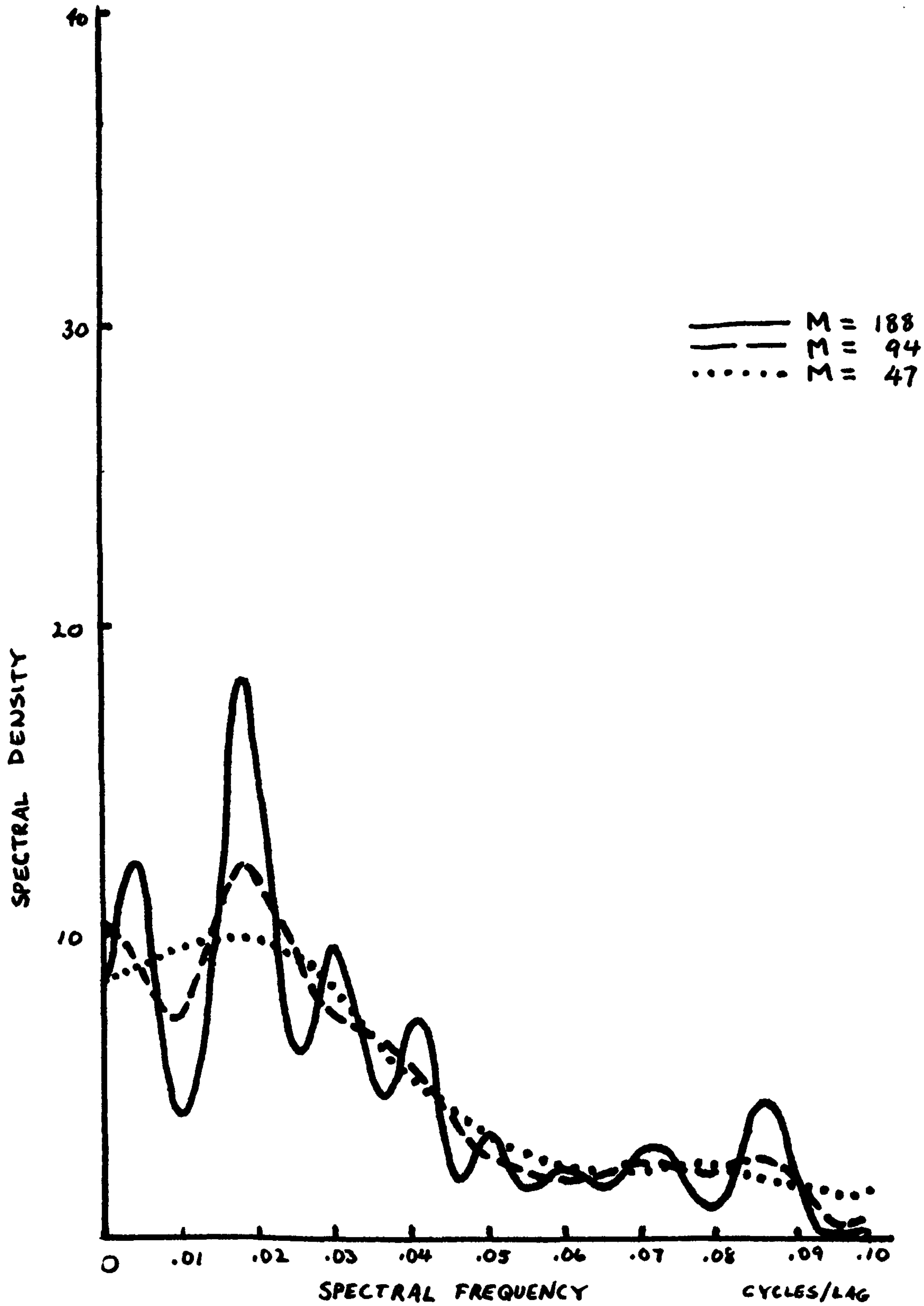


Fig. 4-8 Spectral Estimates of First Encounter, First Serve Policy (N=250)

Table 4-5 The Estimation of the Variance of the Sample Mean Square Wait Time for a First Encounter First Serve Policy

Sample Size=1000 $\overline{W^2}$ =2.058116 (hours)^2 $\bar{\gamma}_{W^2,W^2}(0)$ =1.929223 (hours)^4

M	$\bar{\bar{\Gamma}}_{W^2,W^2}(0)/\bar{\gamma}_{W^2,W^2}(0)$	$Var(\overline{W^2})$ (hours)^4
400	37.19003	.0358739
200	37.52313	.0361952
100	28.79642	.0277773

Sample Size=500 $\overline{W^2}$ =2.255945 (hours)^2 $\bar{\gamma}_{W^2,W^2}(0)$ =2.380833 (hours)^4

M	$\bar{\bar{\Gamma}}_{W^2,W^2}(0)/\bar{\gamma}_{W^2,W^2}(0)$	$Var(\overline{W^2})$ (hours)^4
309	41.19669	.0980824
154	30.81824	.073373
77	21.43210	.0510262

Sample Size=250 $\overline{W^2}$ =1.763113 (hours)^2 $\bar{\gamma}_{W^2,W^2}(0)$ =1.138336 (hours)^4

M	$\bar{\bar{\Gamma}}_{W^2,W^2}(0)/\bar{\gamma}_{W^2,W^2}(0)$	$Var(\overline{W^2})$ (hours)^4
94	10.2389	.0233104
47	8.81762	.0200748
23	9.42618	.0214603

general shape exhibited by the previous experiments. This is probably because spectral windows with slit width greater than 2/250 are too wide to estimate the narrow peak at f=0. Since the results of the previous experiment are satisfactory, the minimum record length is $\mathcal{T}$=500. In Table 4-5 the estimates of the variance of the sample mean square wait time are listed. It is noted that these values are greatly underestimated for $\mathcal{T}$=250.

A similar set of experiments were made for the first disabled, first serve policy, Figs. 4-9, 4-10, and 4-11 and Table 4-6, and the result $\mathcal{T}$=500 compares favorably.

It may also be noted that in both sets of experiments, the estimate of $Var[\overline{W^2}]$ tends to increase as the sample size decreases (i.e., the bias of the spectral estimator increases - see Figs. 4-6, 4-7, 4-9, and 4-10). Therefore, as seen by Eq. (4-22), the bias of the spectral estimator will increase as the sample size is reduced.

4.3.6 Summary of Monte Carlo Simulation Design Procedure

The simulation design procedure used throughout this study can be summarized by the following four rules:

1. Use the initial condition $\underline{X}_0 = 0$, that is an initially empty queue and idle servers, for every simulation run.

2. Do not exclude or truncate the warm-up period when estimating population parameters.

3. To determine the end condition, $\mathcal{T}$, apply the procedure of window closing to a pilot run for a strongly

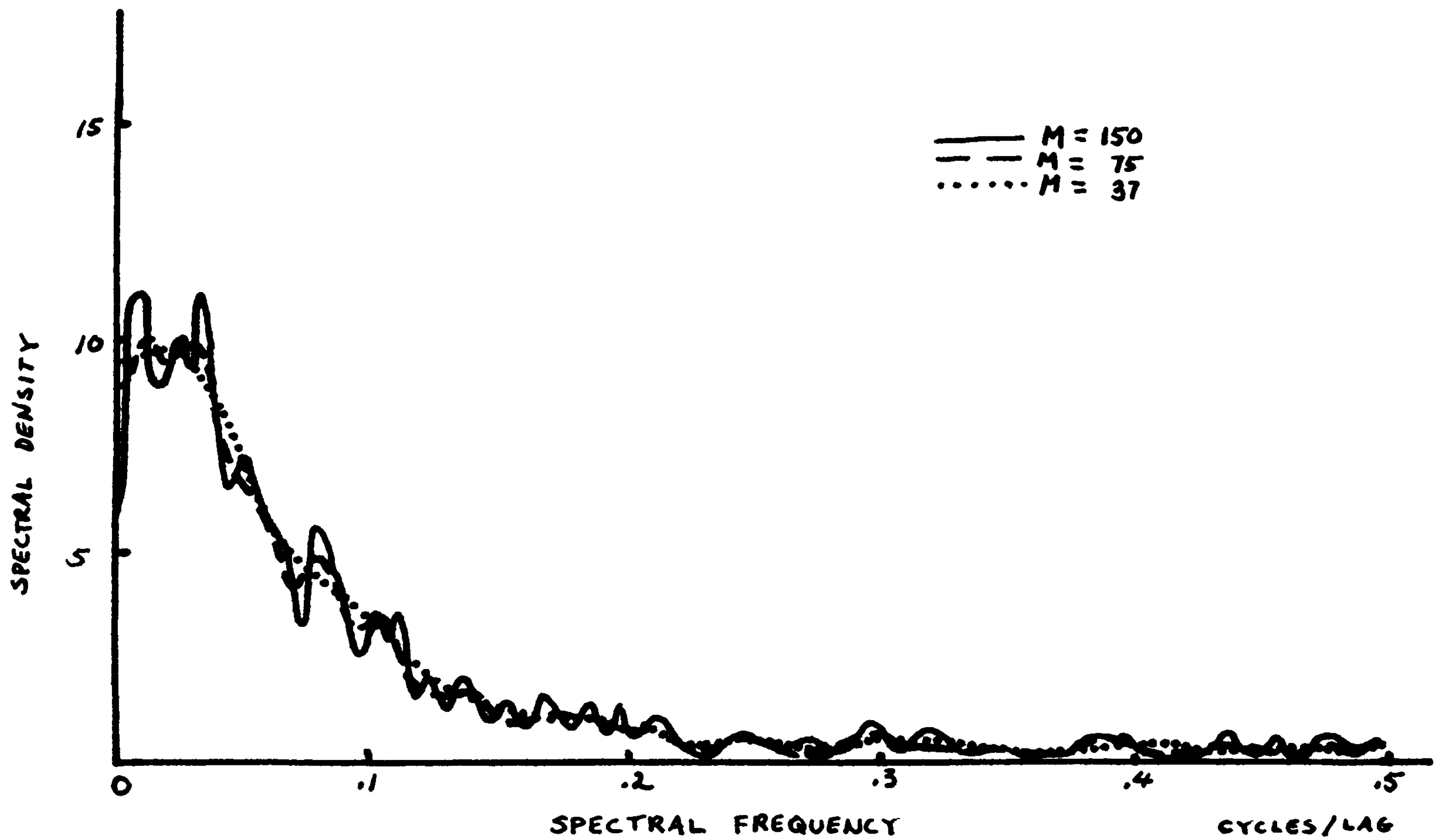


Fig. 4-9 Spectral Estimates of First Disabled, First Serve Policy
(N=1000)

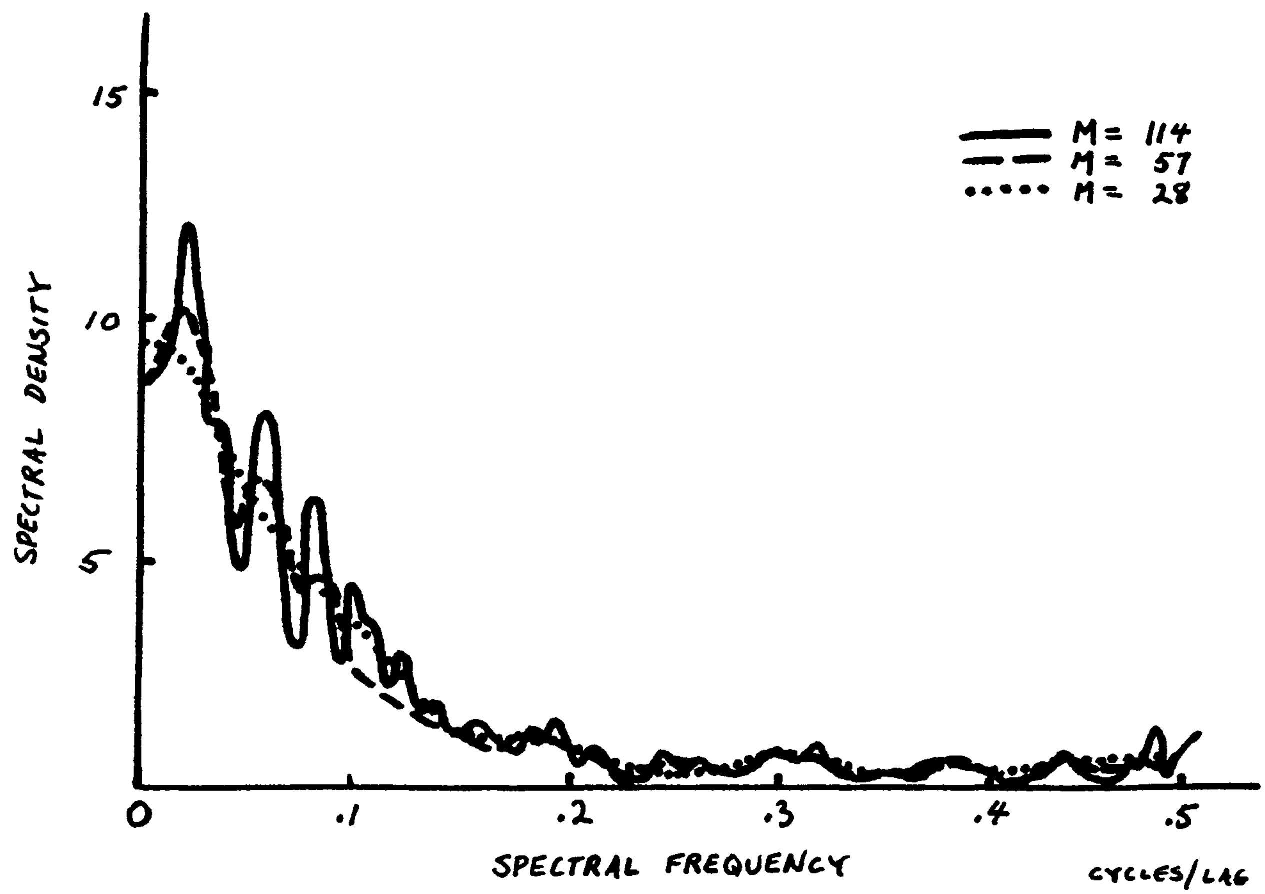


Fig. 4-10 Spectral Estimates of First Disabled, First Serve Policy (N=500)

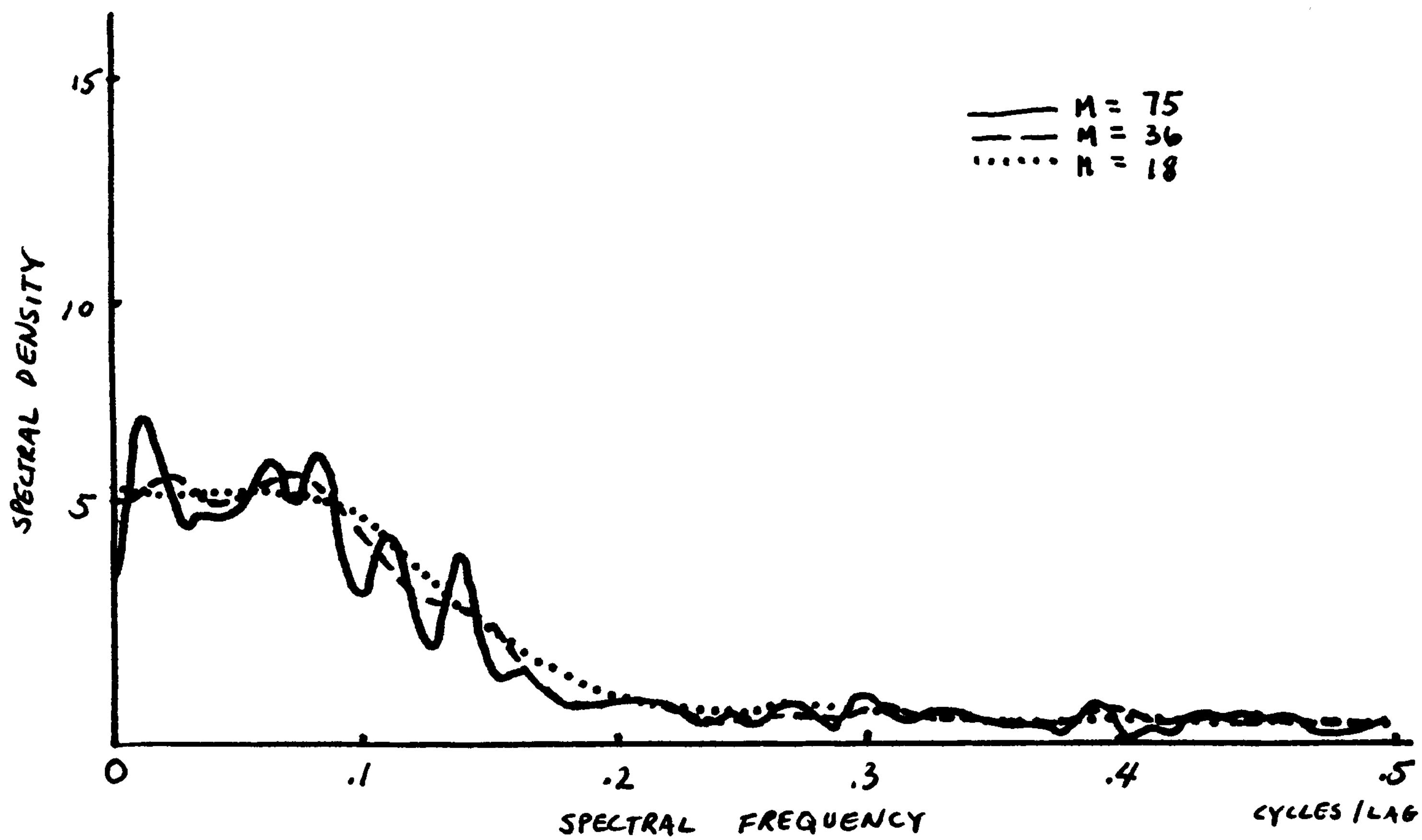


Fig. 4-11 Spectral Estimates of First Disabled, First Serve Policy (N=250)

Table 4-6 The Estimation of the Variance of the Sample Mean Square Wait Time for a First Disabled First Serve Policy

Sample Size=1000 $\overline{W^2}$ =1.818123 (hours)^2 $\bar{\gamma}_{w^2,w^2}(0)$ =4.628511 (hours)^4

M	$\bar{\bar{\Gamma}}_{w^2,w^2}(0)/\bar{\gamma}_{w^2,w^2}(0)$	$Var(\overline{W^2})$ (hours)^4
150	6.330753	.0146509
75	8.696325	.0201255
37	9.489573	.0219612

Sample Size=500 $\overline{W^2}$ =1.922242 (hours)^2 $\bar{\gamma}_{w^2,w^2}(0)$ =4.889652 (hours)^4

M	$\bar{\bar{\Gamma}}_{w^2,w^2}(0)/\bar{\gamma}_{w^2,w^2}(0)$	$Var(\overline{W^2})$ (hours)^4
114	8.826933	.0431606
57	8.811129	.0430833
28	9.558805	.0467392

Sample Size=250 $\overline{W^2}$ =1.514319 (hours)^2 $\bar{\gamma}_{w^2,w^2}(0)$ =2.29952 (hours)^4

M	$\bar{\bar{\Gamma}}_{w^2,w^2}(0)/\bar{\gamma}_{w^2,w^2}(0)$	$Var(\overline{W^2})$ (hours)^4
75	3.580971	.016469
36	5.609095	.0257964
18	5.794876	.0266508

autocorrelated process in the study.

4. Using the above rules, generate identical independent replications of the simulation for each parameter change.

CHAPTER 5

ANALYSIS OF HIGHWAY AID DISPATCH SYSTEMS USING MONTE CARLO SIMULATION

5.1 Introduction

In this chapter various aid dispatch systems are simulated and their performance compared. The major effort and intent of this simulation study is to gain those insights which will enable highway engineers to design more efficient aid dispatching algorithms. As previously discussed in Chapter 1, the speedy removal of highway incidents greatly reduces highway congestion. Therefore, the proper choice of an aid dispatch system improves traffic flow and yields a safer level of service.

The main focus of this chapter is a comparison between the conventional highway patrolling system[9] and a system which uses automatic electronic detection of disabled vehicles. The electronic detection system assumed herein is based on the Responsive Electronic Vehicular Instrumentation System, REVIS, proposed and developed by Nadan and Wiener.[1] The REVIS system and the highway patrolling system are compared according to a cost-benefit criterion. This comparison is accomplished for a single section of highway and a multi-sectioned highway for various traffic conditions using the technique of Monte Carlo simulation.

By subjecting these competing systems to the same set of input sequences (i.e. the same temporal and spatial distribution of highway incidents), the contrasts in performance between the competitors is heightened. The statistical tool used to determine a level of confidence upon which the accuracy of these contrasts may be judged is the hypothesis test for comparing the difference between means of two correlated populations. This procedure allows the experimentor to test the significance of the effects that may cause variation between policies.

The results of these simulations reveal that the REVIS system operating on a single section of highway is superior to the highway patrol system for rural traffic conditions and is comparable to it for heavier than rural traffic conditions. Secondly, the REVIS system is far superior to the highway patrol system on a multiple sectioned highway for all traffic conditions tested.

The mathematical models which describe the physical phenomena of the highway, the various aid dispatch policies used by these systems, and the performance criteria are discussed in the following section before an analysis of the simulation is presented.

5.2 Discussion of the Mathematical Models of the Highway Phenomena Assumed in the Computer Simulation

The physical phenomena of the highway described by the computer simulation program are the breakdown process of the disabled vehicles, the system detection process, the vehicle speed model and the service process. In this section, the mathematical models which generate these processes are presented.

It is assumed that incidents occur according to a Poisson time process with parameter λ, where λ represents the average rate of breakdowns. Although this model may be criticized on the grounds that actual incident rates vary, it is believed that for relatively long intervals of time, the average incident rate remains constant (e.g. at night, during off peak hours).[7] Also, since incidents are a relatively rare event, the Poisson assumption is justified. The breakdown positions of the disabled vehicles are assumed to be uniformly distributed along the length of the highway.[8] Through the use of the computer's internal random number generator and an appropriate inversion scheme, the modeling of the breakdown process is easily achievable.

Disabled vehicles are detected by either a cruising highway patrol vehicle or the electronic detection system, REVIS. When the patroling system is used, the time at which the disabled vehicle is detected, the detection time, is given as the time at which the highway patrol first encounters the incident. REVIS uses either roadside or loop detectors that are evenly spaced along the length of the highway. It is assumed that this electronic system is able to uniquely identify every vehicle that traverses the highway (i.e. REVIS is an automatic vehicle identification system). When a vehicle enters the highway, the driver receives a miniature integrated circuit transmitter bonded to the standard highway toll card. Each time a vehicle passes a detector, this device transmits the vehicle's unique code to a central computer tracking system. The tracking system then updates the highway position of this vehicle. Vehicles, therefore, "log in" to the system on the average every $DESP/V$ seconds where $DESP$ is the detector spacing and V is the time-average vehicle speed. When a vehicle has not logged in for $T = T_{MAX} > DESP/V$ seconds, the system considers that the vehicle is disabled and an aid vehicle is dispatched from the garage. If T_D is the time at which the vehicle has passed the last detector before breaking down, then its detection time, T_{DET}, is equal to $T_D + T_{MAX}$. Since the simulation program only generates disabled vehicle breakdown times, it may be shown that

$$T_D = T_B - (P_B - P_D)/V_B \quad , \qquad (5\text{-}1)$$

where T_B is the disabled vehicle's breakdown time, P_B is the disabled vehicle's highway breakdown position, P_D is the highway position of the last detector passed by the disabled vehicle, and V_B is the average speed of the vehicle prior to breakdown. The model for detecting a disabled vehicle becomes

$$T_{DET} = T_B + T_{MAX} - (P_B - P_D)/V_B \, . \qquad (5\text{-}2)$$

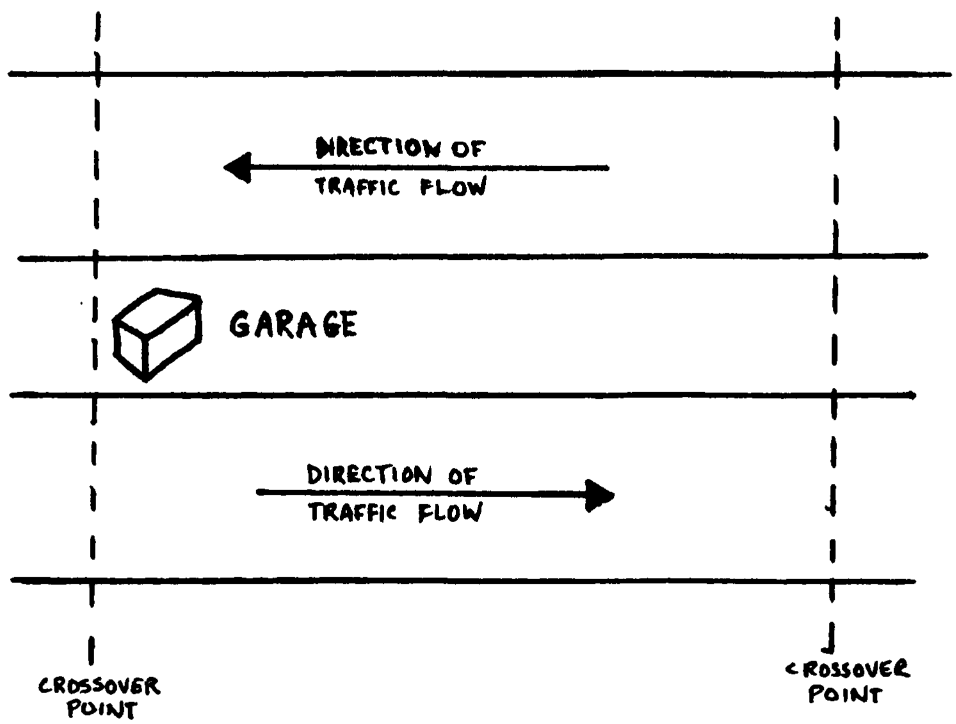
The value of T_{MAX} is chosen equal to $DESP/V_{MIN}$ where V_{MIN} is the minimum non zero time-average speed expected on the highway and is taken to be 10 mph.[2] This model is considered to be satisfactory for most light to moderately heavy traffic conditions, however, it will be shown that as traffic conditions become very heavy, the performance of the electronic detection system degenerates to a patrolling system and the usefulness of a high technology electronic detection system diminishes. To obtain a fair comparison with existing detection systems, the value of $DESP$ was taken to be 0.5 miles since present day modern superhighway detection systems, such as the Los Angeles system,[3] use detectors spaced at 1/2 mile intervals.

The detection model described above and the service model below require that the simulation generate the time-average speed of the disabled and aid vehicles which are assumed to be constant with time. Two models are considered: a model which is independent of the number of incidents on the highway, and a piecewise-linear model given by

$$V = \begin{cases} V_{MAX} - IVH\,(V_{MAX} - 10)/D\,, & V > 10, \\ 10 & V \leq 10, \end{cases} \qquad (5\text{-}3)$$

where V_{MAX} is the maximum speed of the highway, D is the length of the highway, and IVH is the actual number of disabled vehicles on the highway. This model saturates at 10 mph for one incident per mile and is independent of the position of these incidents. The sensitivity of the performance of a typical aid dispatch system is evaluated for both speed models in Section 5.5 of this chapter. There it is shown that, indeed, a system is sensitive to the choice of model.

In order to service a highway incident, an aid vehicle must first travel to the location of the incident, spend time rendering aid to the disabled vehicle, and then travel back to the garage or to the next incident. It is assumed that a single aid vehicle services a section of highway of total length, D, see Fig. 5-1. The speed of travel assumed depends on the type of speed model used. When a disabled vehicle is repaired, it returns to the normal flow of the highway traffic. In order to eliminate a source of variability in evaluating competing dispatch policies, the time to repair a disabled vehicle is assumed to be a constant.



Mileage of section in each direction of traffic flow = D/2 miles
Total mileage of section = D miles

Fig. 5-1 Representation of the Section of Highway Serviced by an Aid Vehicle

5.3 Discussion of System Performance Criteria

The performance of the aid dispatching systems will be evaluated according to a cost-benefit criterion. The cost criterion used in this study was developed by Nadan and Wiener[1] and will be outlined here for completeness. This cost criterion is based on a yearly operating cost and does not include the initial capital costs for the installation of the system. The annual cost for a highway patrol aid vehicle, C_{HP}, may be written as

$$C_{HP} = C_{FIXED\ ANNUAL} + C_{FUEL} \text{ dollars,} \qquad (5\text{-}4)$$

where $C_{FIXED\ ANNUAL}$ is a fixed annual cost of operating and maintaining (24 hours a day) a patrol vehicle, and C_{FUEL} is the fuel cost. For the purposes of this study, $C_{FIXED\ ANNUAL}$ is taken as \$90,000 and C_{FUEL} is based on \$0.50 per gallon per 10 miles or 5 cents per mile. Eq. (5-4) can be rewritten as

$$C_{HP} = 90{,}000 + .05\,(D)(T) \text{ dollars,} \qquad (5\text{-}5)$$

where D is the highway length in miles and T is the total number of trips that is made by the patrol vehicle in a year.

When the electronic detection system, REVIS, is in operation, it is assumed that private aid vehicle owners are contracted by the highway authority to provide twenty-four hours per day service. The annual cost structure assumed for a REVIS aid vehicle is, therefore,

$$C_{REVIS} = C_{ANNUAL\ CONTRACTUAL} + C_{FUEL} + C_{SERVICES} \text{ dollars,} \qquad (5\text{-}6)$$

where $C_{ANNUAL\ CONTRACTUAL}$ is the annual contractual payment made to the aid vehicle owner and $C_{SERVICES}$ is the fee paid for each service rendered. $C_{ANNUAL\ CONTRACTUAL}$ is taken to be \$15,000, the fuel costs are based on \$0.25 per mile (includes maintenance costs), and the service fee is \$3.00 per vehicle serviced. The cost for REVIS becomes

$$C_{REVIS} = 15{,}000 + .25(D)(T) + 3S \text{ dollars,} \qquad (5\text{-}7)$$

where S is the total number of services made by the aid vehicle in a year.

Historically, the analysis of customer service systems such as aid dispatch systems[8] has been concerned with determining the distribution of the number of customers on the waiting line and the distribution of the customer's time spent in the system. The quality of the system's benefit was then judged by examining the mean values of these distributions. The appeal of these quantities is that they indicate the measure of the personal discomfort to the customer (in this case the disabled motorist). Thus, the smaller they are, the better the system. It is contended that for the aid dispatch systems discussed in this study, the mean wait time is an insufficient indicator of the system benefit. For example, it is conceivable to have a dispatch policy which yields a lower mean value than another but at the cost of a wide dispersion about the mean. This policy would be of little benefit to those drivers whose wait time is at the tail of the distribution. Therefore, a good benefit criterion must include not only an indication of the average value, but also an indicator of the dispersion of the distribution, such as the variance. It is proposed by Kleinman[4] that the mean square value of the wait time distribution is a meaningful benefit criterion. The mean square wait time, $E[W^2]$ is found to be

$$E[W^2] = \mu_W^2 + \sigma_W^2, \tag{5-8}$$

where μ_W is the mean wait time and σ_W is the standard deviation of the wait time. The appeal of the mean square as a benefit criterion is that it equally emphasizes the average value and the dispersion about the average.

5.4 A Description of the Aid Dispatch Policies

The aid dispatch policies used by the highway patrol and the REVIS systems are described in this section. When the patrolling system is operative, the policy used to service disabled vehicles is first encounter, first serve. In the course of patrolling the highway, an aid vehicle will encounter disabled vehicles and will immediately service them. Upon completion of each service, the aid vehicle returns to the highway flow and resumes its patrol until another incident is encountered. It is assumed that this patrolling is maintained continuously.

Under the REVIS system, aid vehicles are only dispatched when a disabled vehicle is detected, and therefore, the system is amenable to more creative dispatching policies. This study considers three such policies. When REVIS was first proposed,[5] the spatial policy, first encounter, first serve was suggested. When more than one incident has been detected, the aid vehicle services the incident nearest to it. This policy is, obviously, most detrimental to those incidents furthest downstream from the aid vehicle, since the occupants of these vehicles are always the last to be served.

The second policy under consideration, first disabled, first serve, therefore, bases its order of service on how long each disabled vehicle has been waiting. This temporal policy dispatches the aid vehicle to the incident which has occurred first.

The third policy combines both the temporal and the spatial aspects of the previous two. This hybrid dispatch policy operates as follows: Aid vehicles are directed to service incidents according to the first encounter, first serve spatial aid dispatch policy. Associated with each disabled vehicle is a virtual breakdown highway position, which at first is equal to the actual breakdown position of the disabled vehicle. However, when a disabled vehicle has been waiting for service longer than a prescribed length of time, the threshold time, THRT, its priority for service is increased by advancing the disabled vehicle's virtual breakdown position closer to the aid vehicle. The constant rate at which the virtual breakdown position of the disabled vehicle is advanced upstream is known as the virtual vehicle speed, VVS. When the aid vehicle encounters the virtual breakdown position of a disabled vehicle, it must service this disabled vehicle next. The aid vehicle, under the hybrid policy, services disabled vehicles in the order in which it encounters the actual breakdown and virtual breakdown highway positions of the disabled vehicles.

In order for the hybrid policy to function properly, (if it were implemented) a central computer dispatch processing system must be developed to maintain and update the virtual breakdown position and waiting time of every disabled vehicle on the highway and the actual position of the aid vehicle. When the aid vehicle encounters an incident, the computer, through a communications link with the aid vehicle such as a radio or a signal light mounted on the dashboard of the aid vehicle, directs the aid vehicle to stop and service or pass by this disabled vehicle. If the temporal policy is operating, the processing system need not be as sophisticated as the above system, since all that is required for the temporal policy is that a list of the actual position of every disabled vehicle be maintained in the order in which each incident occurred. This system, however, must still maintain and update aid vehicle positions and provide a communications link to the aid vehicle driver. The spatial policy, the simplest to implement, needs no special processing system nor communications link. Only the occurrence of incidents needs to be monitored and this can easily be accomplished by an electronic detection system, such as REVIS.

A two dimensional hybrid policy space may be defined by the pair, virtual vehicle speed and threshold time, $(VVS, THRT)$ in the first quadrant of the plane since VVS and $THRT$ are equal or greater than zero. Each point in this space represents a unique aid-dispatch policy. The pure spatial and temporal policies described above are subsets of the hybrid space. The spatial policy is given by the lines (VVS, ∞) and $(0, THRT)$. The temporal policy is given by the point $(\infty, 0)$.

5.5 Analysis of the Speed Models

The sensitivity of an aid dispatching system to the speed model assumed for the aid vehicle is analyzed by determining the variation of the mean wait time of the disabled vehicles when the speed model assumed is changed. For each of the two models defined in Section 5.2 (i.e. the constant and piecewise-linear models), the highway patrol and the REVIS systems were simulated for various incident rates using the spatial aid dispatch policy outlined in Section 5.4. For each rate the simulation was replicated five times. The estimates of the mean, variance, and 95% confidence intervals of the squared wait time for these simulations are listed in Table 5-1. Figs. 5-2 and 5-3 illustrate the comparison of the two models for the highway patrol and REVIS, respectively. Since the confidence intervals of the mean squared wait time overlap for most breakdown rates, it might be concluded that the aid-dispatching systems are insensitive to the two different speed models. However, upon further analysis, it will be shown that the variation of the mean square wait time due to different speed models is, indeed, statistically significant.

The correlated t-test[11] is used for testing the difference between the mean square wait time obtained from the two speed models. Ordinarily, when testing the difference between the means of two independent populations, the standard student's t-test may be applied.[6] However, this test is quite unsatisfactory for pairwise correlated data. In Chapter 4 it is suggested that the great advantage of simulation over any

Table 5-1 The Estimates of the Mean, Variance and 95% Confidence Interval of the Squared Wait Time for Various Incident Rates and Speed Models

Aid Dispatch Policy: Highway Patrol — Speed Model: Constant

Incident Rate (Vehicles/hr)	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)
.3	.4344	.00005779	(.4238, .4450)
.9	.6180	.00008582	(.6051, .6309)
1.4	.8626	.001282	(.8129, .9123)
1.8	1.2269	.005163	(1.1272, 1.3266)
2.2	1.7819	.01627	(1.6049, 1.9589)
2.7	3.3792	.1618	(2.8209, 3.9375)

Aid Dispatch Policy: Highway Patrol — Speed Model: Piecewise-linear

Incident Rate (Vehicles/hr)	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)
.3	.4480	.00006690	(.4366, .4594)
.9	.6497	.0008033	(.6373, .6621)
1.4	.9233	.001112	(.8770, .9696)
1.8	1.3117	.006638	(1.1986, 1.4248)
2.2	2.0110	.02688	(1.7834, 2.2386)
2.7	4.0808	.3846	(3.2200, 4.9416)

Table 5-1 Continued

Aid Dispatch Policy: REVIS — Speed Model: Constant

Incident Rate (Vehicles/hr)	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)
.3	.4472	.00005447	(.4370, .4574)
.9	.6285	.0003973	(.6198, .6372)
1.4	.8800	.0006885	(.8436, .9164)
1.8	1.2262	.004701	(1.1310, 1.3214)
2.2	1.8023	.01656	(1.6237, 1.9809)
2.7	3.4195	.1756	(2.8379, 4.0011)

Aid Dispatch Policy: REVIS — Speed Model: Piecewise-linear

Incident Rate (Vehicles/hr)	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)
.3	.5051	.00005780	(.4945, .5157)
.9	.7195	.0004086	(.6914, .7476)
1.4	1.0107	.0007067	(.9738, 1.0476)
1.8	1.4149	.006018	(1.3072, 1.5226)
2.2	2.1155	.02525	(1.8949, 2.3361)
2.7	4.2753	.3678	(3.4335, 5.1171)

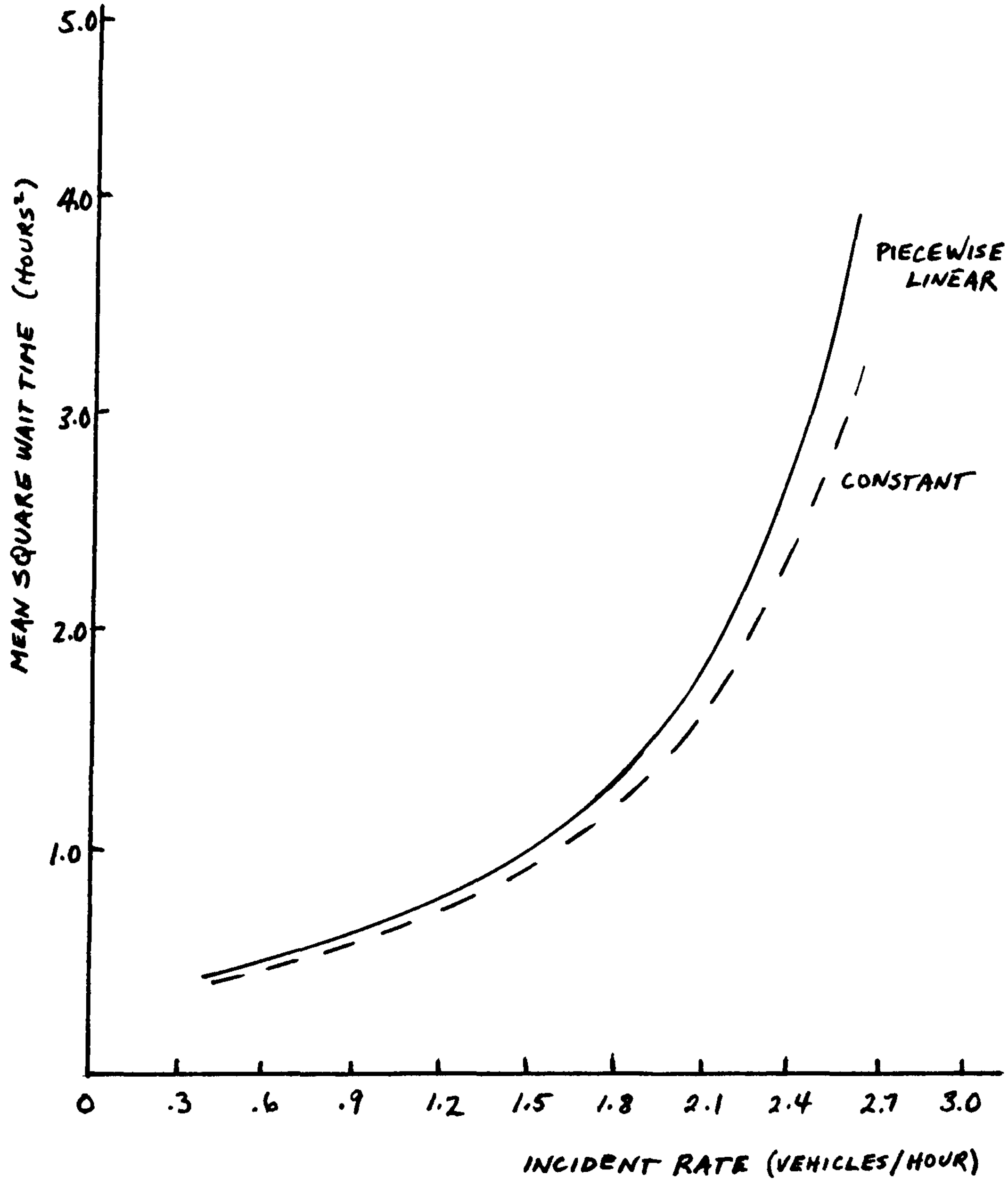


Fig. 5-2 The Estimates of the Mean Square Wait Time of the Highway Patrol Policy for Various Incident Rates and Speed Models

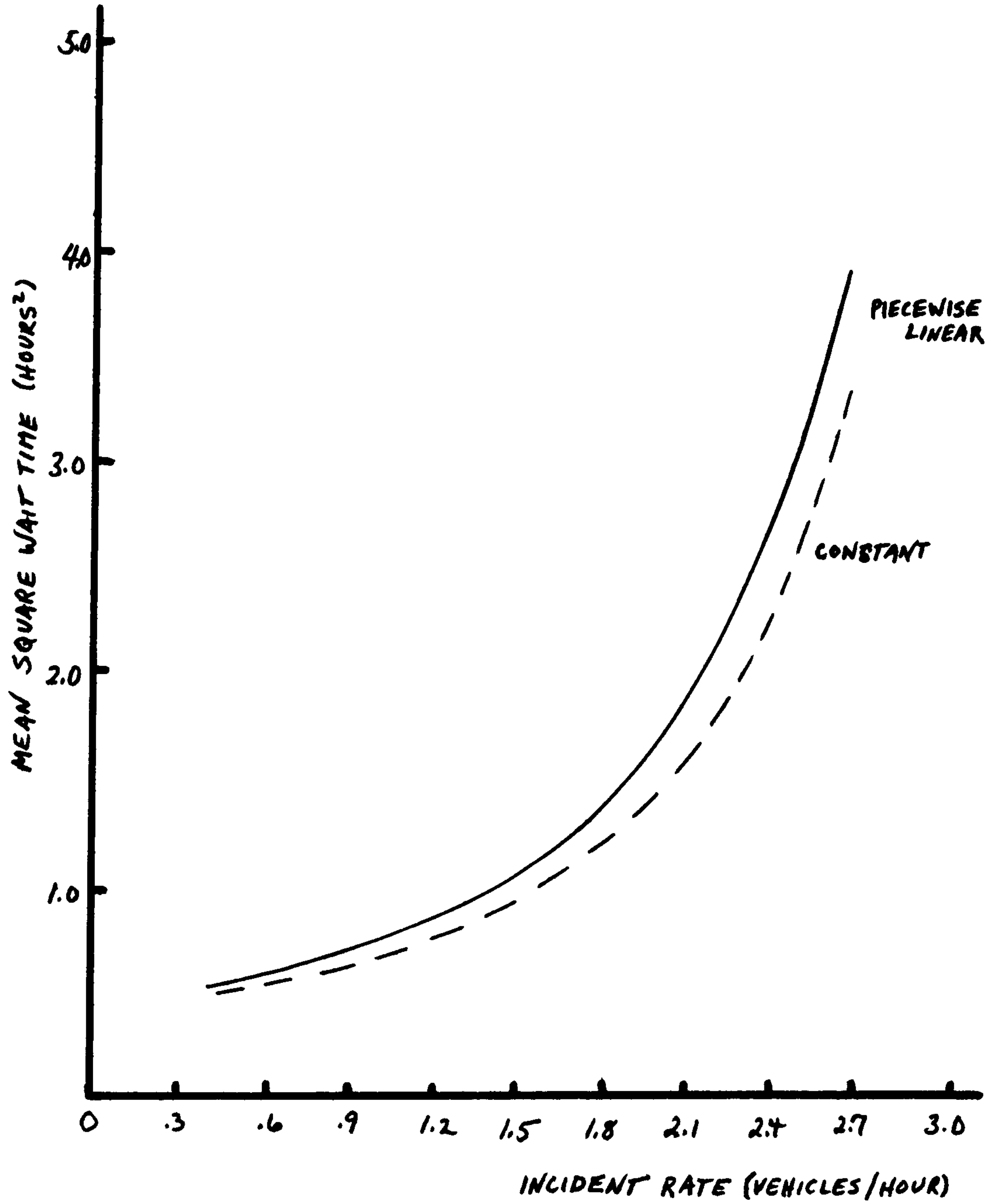


Fig. 5-3 The Estimates of the Mean Square Wait Time of the REVIS Policy for Various Incident Rates and Speed Models

other experimentation form is that competing alternatives can be subjected to the same set of input sequences. Since throughout this study competing systems were subjected to the same set of random number streams within each replication, pairwise correlation was induced between the competing alternatives. This concept is illustrated in Fig. 5-4 where alternatives A and B represent the different speed models and the outputs, A_i and B_i represent the mean square wait times due to A and B, respectively. If n replications of this experiment are made, n correlated pairs of data, (A_i, B_i), will be generated.

From these data pairs a set of independent data, Δ_i, may be formulated by subtracting $A_i - B_i$ for each pair (see Fig. 5-4). The resulting set of n points, $\{\Delta_i, i=1,2,\ldots,n\}$, are independent, identically distributed random numbers. To determine whether the effects of the alternatives A and B are null, the null hypothesis, the mean of the Δ_i population is zero, is tested using the usual student's t-test.

The statistic for determining the region for rejecting the null hypothesis is given as

$$t' = \sqrt{n(n-1)}\,\bar{\Delta} \Big/ \sqrt{\sum_{i=1}^{n} (\Delta_i - \bar{\Delta})^2} \, , \qquad (5\text{-}9)$$

where $\bar{\Delta} = \frac{1}{n} \sum_{i=1}^{n} \Delta_i$. For n=5, the number of replications for each experiment, the null hypothesis is rejected at the 95% level when the statistic t' falls outside the range (-2.776,2.776) .

The actual data and a sample calculation used for these

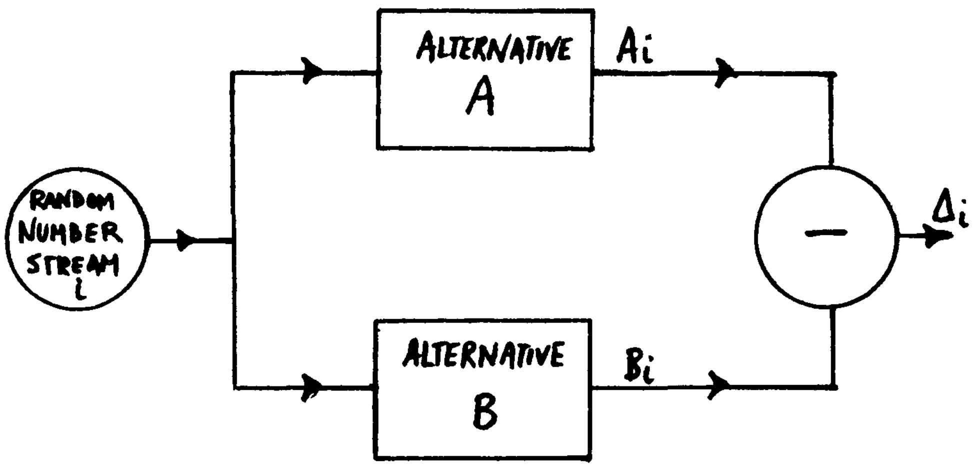


Fig. 5-4 The Technique of Formulating a Set of Independent Data From Correlated Data

tests can be found in the Appendix; however, listed in Table 5-2 are values of statistic t' for each of the twelve tests performed. It may be seen from Table 5-2 that all the values of t' for the speed models except for the highway patrol at 0.3 vehicles per hour are significant. Therefore, the hypothesis that the effect of the speed models is null is rejected. It is interesting to note that for each system the t' values exhibit a rise-decline effect as the breakdown rate increases. In Figs. 5-2 and 5-3, for increasing breakdown rate (i.e., increasing in stability) the difference between the mean squared wait time of each model increases; however, from Table 5-1 the variance of the mean increases. Therefore, although the differences between means appear to be growing, their variances are larger and the overall significance between the effects of the speed models diminishes.

From the analysis above, it is seen that the system is sensitive to the speed model assumed for the aid vehicle. Since the piecewise-linear speed model is a more realistic model than the constant model, it is used for the remainder of the simulation study.

Table 5-2 The Statistic t' for the Test of Significance of the Effects of the Aid Vehicle Speed Model on the Mean Squared Wait Time

Highway Patrol		REVIS	
Incident Rate (Vehicles/hr)	t'	Incident Rate (Vehicles/hr)	t'
.3	-2.5847	.3	-88.86*
.9	-6.4593*	.9	-33.36*
1.4	-43.597*	1.4	-133.00*
1.8	-13.495*	1.8	-29.56*
2.2	-13.88*	2.2	-22.45*
2.7	-5.386*	2.7	-9.181*

*Statistically significant of the 95% level.

5.6 Analysis of the Hybrid Space

In order to determine the most beneficial aid dispatch policy to be employed by the REVIS system or any other electronic detection system, i.e. the policy defined by the values of the threshold time and virtual vehicle speed which minimizes the mean squared wait time of the disabled vehicles, a uniform search of the hybrid plane, for various breakdown rates, was undertaken. In Figs. 5-5 through 5-9, the average mean squared wait time and the sample variance obtained from five independent, identically distributed replications of the simulation for each pair (VVS, THRT) is written upon the appropriate coordinates in the hybrid parameter plane. In order to prevent the possibility that the searching may encounter a point in the plane where the estimation of the power density spectrum of the mean square wait time will not meet the criterion established in Chapter 4 for $\mathcal{T} = 500$, all the simulations were terminated after the occurrence of 2000 incidents - a safety factor of four. For the cases where no degree of stability was reached* a star is placed at the coordinates.

For all of the incident rates simulated, it is found that the spatial policy (i.e. the lines THRT=∞ and VVS=0) yields the lowest mean squared wait time. For the lower incident rates, i.e. λ =.6, 1.2, 1.8 vehicles per hour, the minimum value of the mean squared wait time is achieved for

*To guard against excessive computer storage allocations, it was decided that when at least fifty vehicles were disabled at one time, the process was considered unstable and the simulation was terminated.

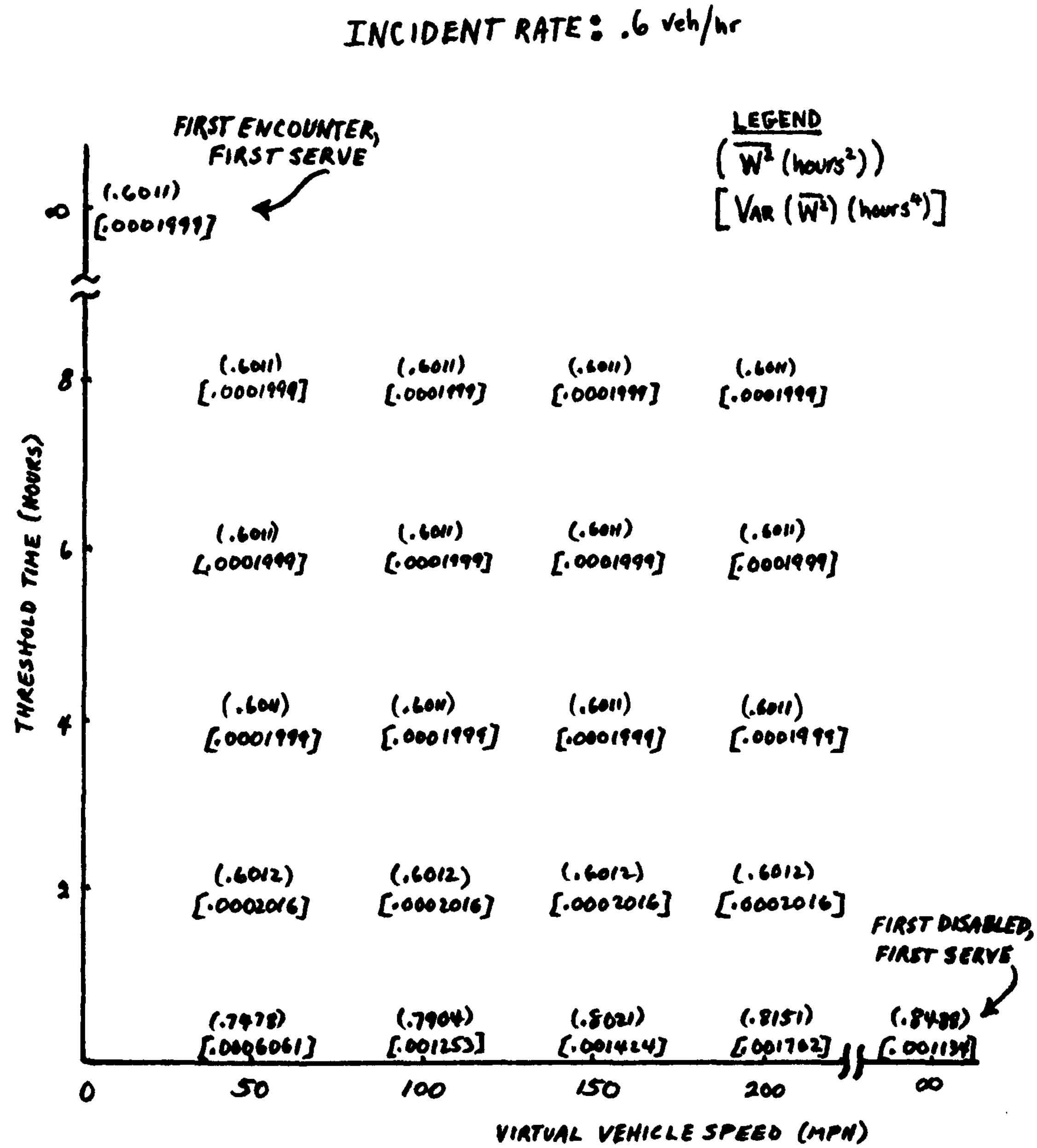


Fig. 5-5 The Estimates of the Mean Square Wait Time and Variance for the REVIS Policy Plotted in the Hybrid Space
(Incident Rate = .6 veh/hr)

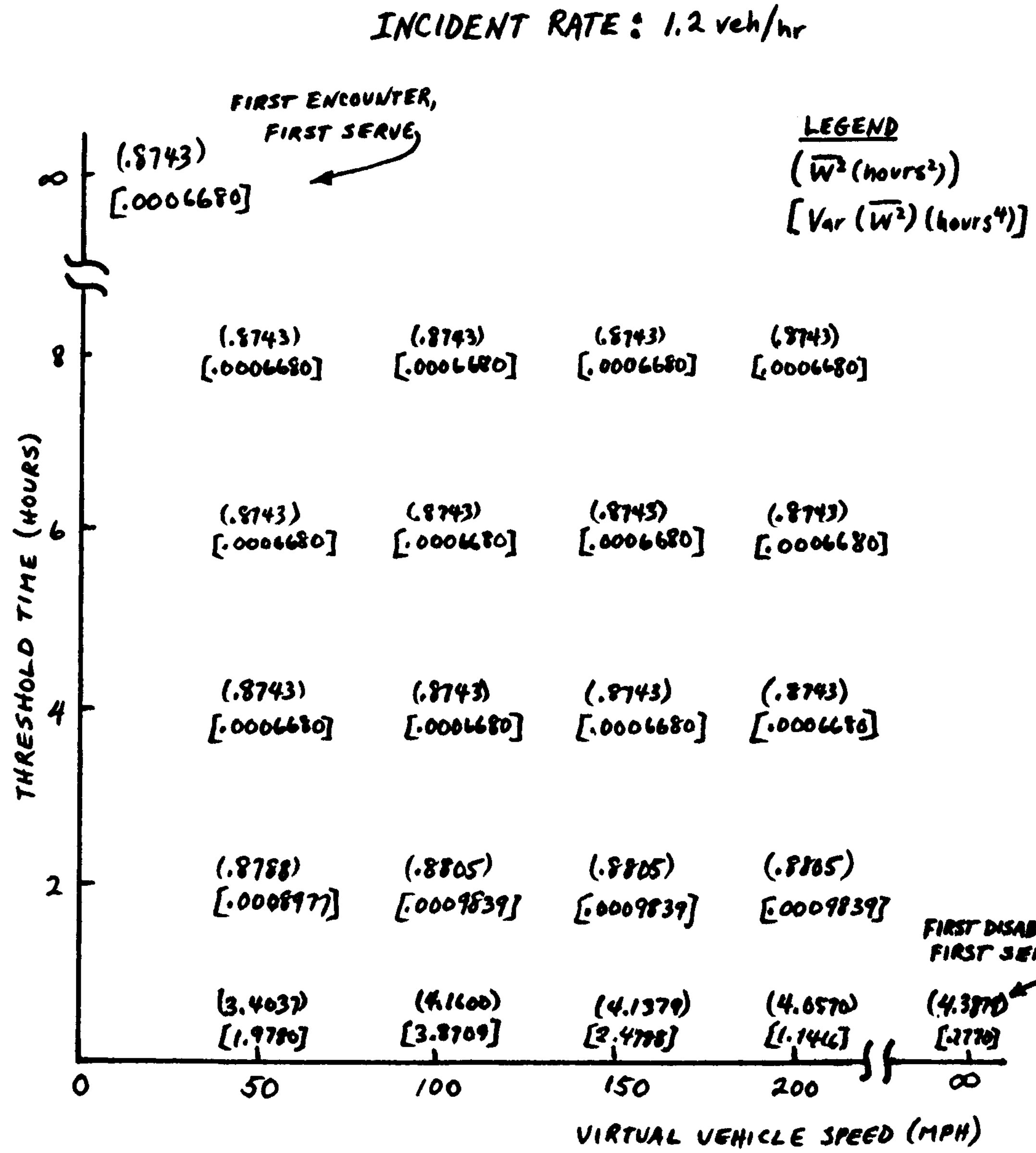


Fig. 5-6 The Estimates of the Mean Square Wait Time and its Variance for the REVIS Policy Plotted in the Hybrid Space (Incident Rate = 1.2 veh/hr)

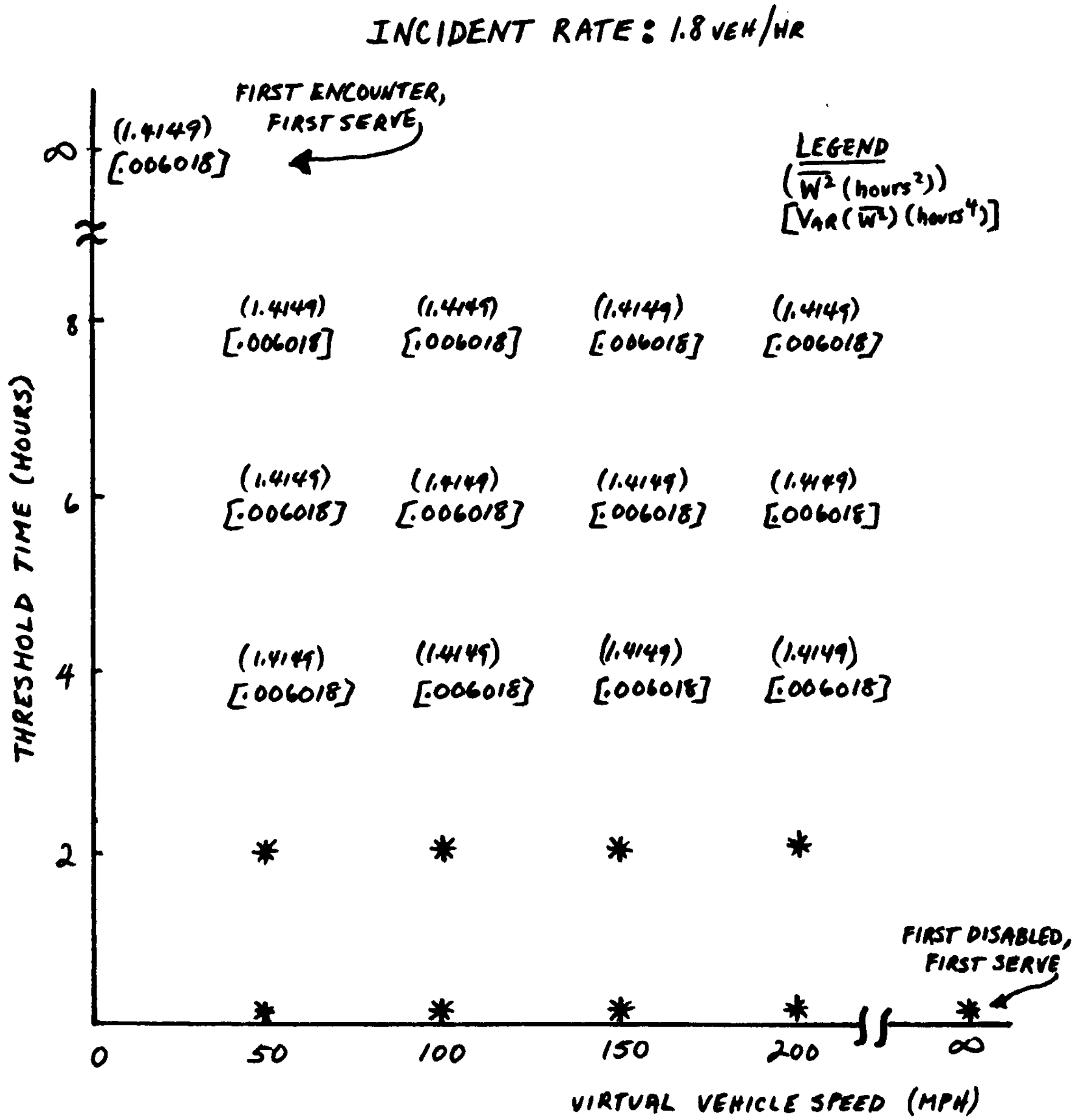


Fig. 5-7 The Estimates of the Mean Square Wait Time and its Variance for the REVIS Policy Plotted in the Hybrid Space (Incident Rate = 1.8 veh/hr)

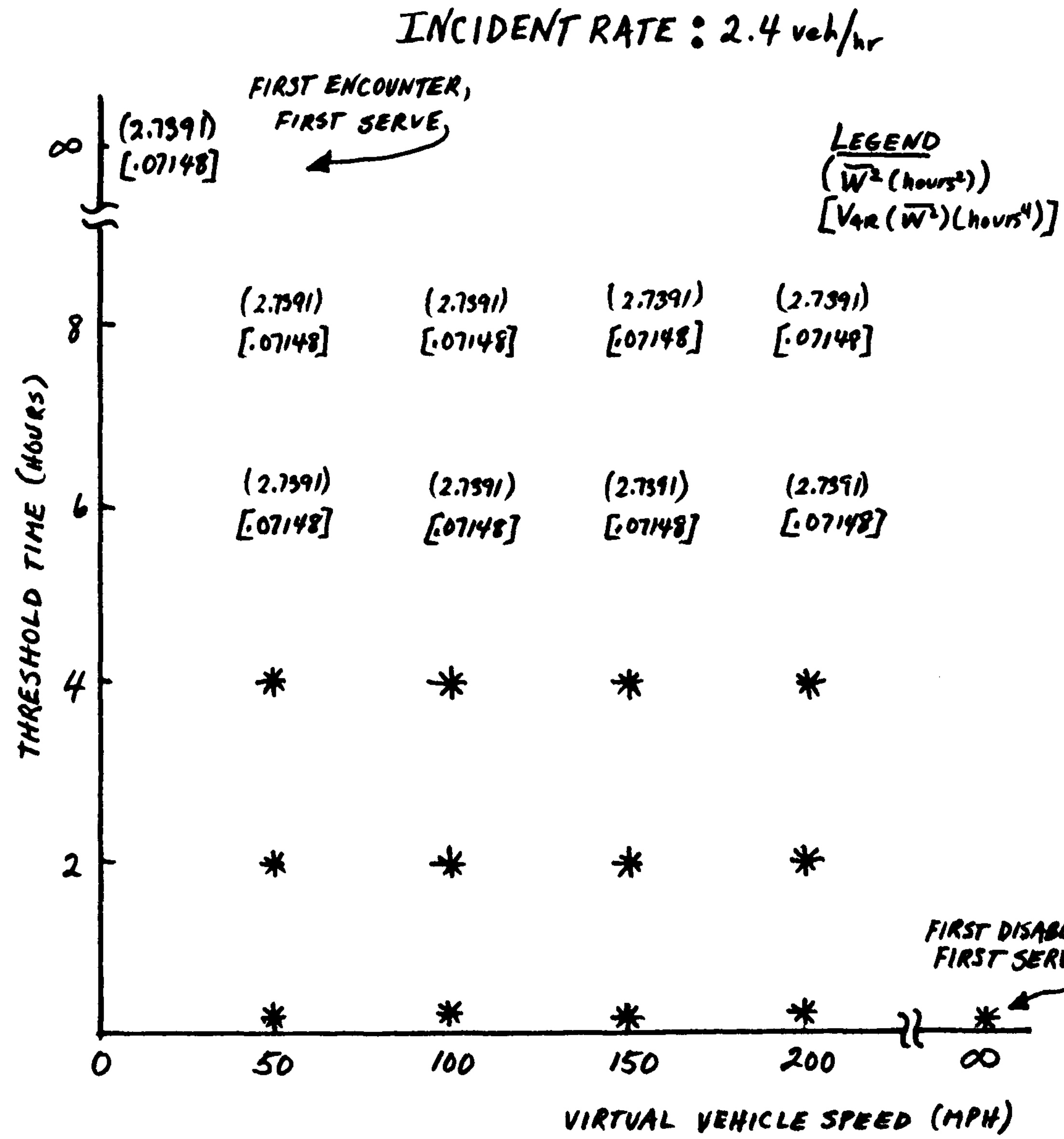


Fig. 5-8 The Estimates of the Mean Square Wait Time and its Variance for the REVIS Policy Plotted in the Hybrid Space (Incident Rate = 2.4 veh/hr)

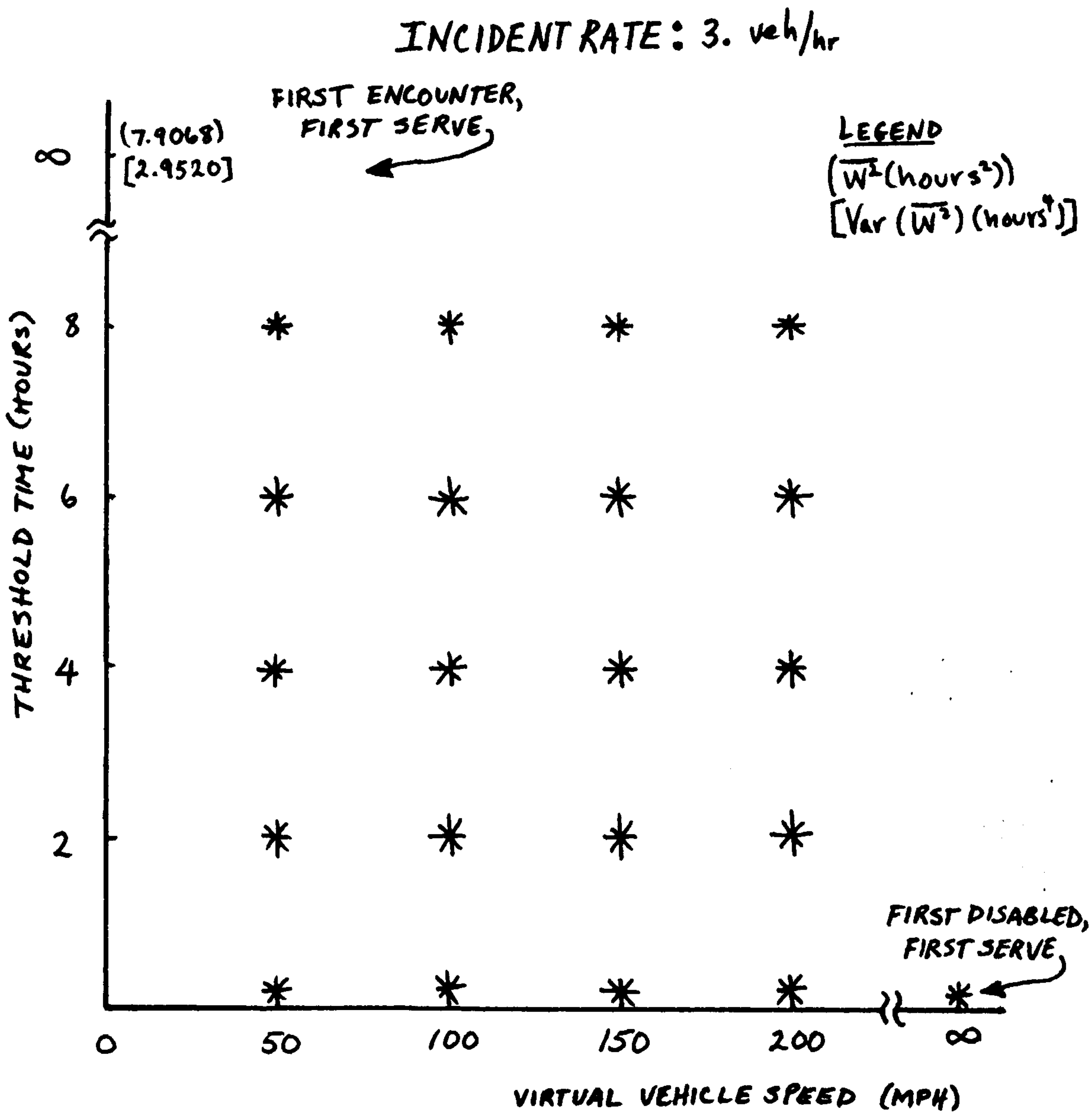


Fig. 5-9 The Estimates of the Mean Square Wait Time and its Variance for the REVIS Policy Plotted in the Hybrid Space (Incident Rate = 3 veh/hr)

all THRT > 4 hours. This occurs since for these low incident rates, no disabled vehicle has waited longer than 4 hours and, therefore, the policies with THRT > 4 hours are essentially the same as the spatial policy.

Furthermore, it may be seen that the virtual vehicle speed has no effect for THRT > 2 hours. To test this fact in general, the correlated t-test is applied to the data obtained from the experiments performed at adjacent values of virtual vehicle speed in the hybrid parameter space. In particular, since the variation of the mean square wait time is greatest along the line THRT =0, these tests are performed for each of the following adjacent points $\{(0,0),(50,0)\}$, $\{(50,0),(100,0)\}$, $\{(100,0),(150,0)\}$, $\{(150,0),(200,0)\}$, and $\{(200,0),(\infty,0)\}$ for λ equal to .6 and 1.2 vehicles per hour, respectively. In Table 5-3, the statistic t' for these tests is listed. For an incident rate of .6 vehicles per hour all the t' values are significant except the one corresponding to the 150-200 speed range; however, for λ =1.2 vehicles per hour, the results of the tests are questionable. Although there are three indications of statistical significance, two of them (the (50-100) and (200-∞) ranges) are very close to the 95% cutoff value, $\pm$2.776, and may be judged as questionable indications of significance.* Therefore, it

*These values are not significant at the 98% level since the critical region of rejection is $|t'| >$ 3.747. Secondly, these tests assume that data come from a normal population. Invoking the central limit theorem,[10] which justifies the use of the t distribution for this test, only satisfies the normality assumption approximately and therefore values of t' which fall close to the critical region may be questionable as true indications of statistical significance.

Table 5-3 The Statistic t' for the Test of Significance of the Effect of the Virtual Vehicle Speed on the Mean Square Wait Time (THRT=0)

Incident Rate = .6 Vehicles/hr

Virtual Vehicle Speed Range (mph)	t'
0 - 50	-23.78*
50 - 100	-7.519*
100 - 150	-5.0659*
150 - 200	-2.579
200 - ∞	-14.21*

Incident Rate = 1.2 Vehicles/hr

Virtual Vehicle Speed Range (mph)	t'
0 - 50	-4.051*
50 - 100	-3.001*
100 - 150	.1179
150 - 200	.254
200 - ∞	-3.1798*

*Statistically significant on the 95% level.

may be concluded that for low incident rates and low values of threshold time, the virtual vehicle speed does affect the mean square waiting time. This is of no consequence, however, since for all incident rates the spatial policy is the most beneficial policy in the hybrid parameter space. This is a very satisfactory conclusion since the spatial policy is the simplest policy to implement.

5.7 Cost-Benefit Analysis of REVIS and Highway Patrol Policies

In this section the conventional highway patrolling system and the REVIS system using the spatial policy are compared according to the cost-benefit criteria described in Section 5.3 of this chapter. For each type of incident detection system, five independent, identically distributed replications are simulated for various values of incident rates and estimates of the mean square wait time and the annual operating cost are obtained. In order to obtain an indication of the aid vehicle usage, the number of times in a year that an aid vehicle makes a complete trip around the section of highway it services is also estimated. The range of incident rates simulated is .3 vehicles per hour to 2.7 vehicles per hour. In Appendix 5.1 at the end of this chapter, it is shown that for a 40 mile section, this range corresponds to the traffic load represented by a heavy rural highway to a moderate urban highway. In Fig. 5-10, the estimated mean square wait time vs. λ is presented for the REVIS and highway patrol system, and in Table 5-4, the estimates of mean, variance, and 95% confidence intervals of the wait time squared are listed.

Although the differences between these systems seem very small, it may be seen in Table 5-5, where the results of correlated t-tests performed for each incident rate simulated are listed, that the type of incident detection system used significantly affects the mean square wait time. It is interesting to note that since the variance of the

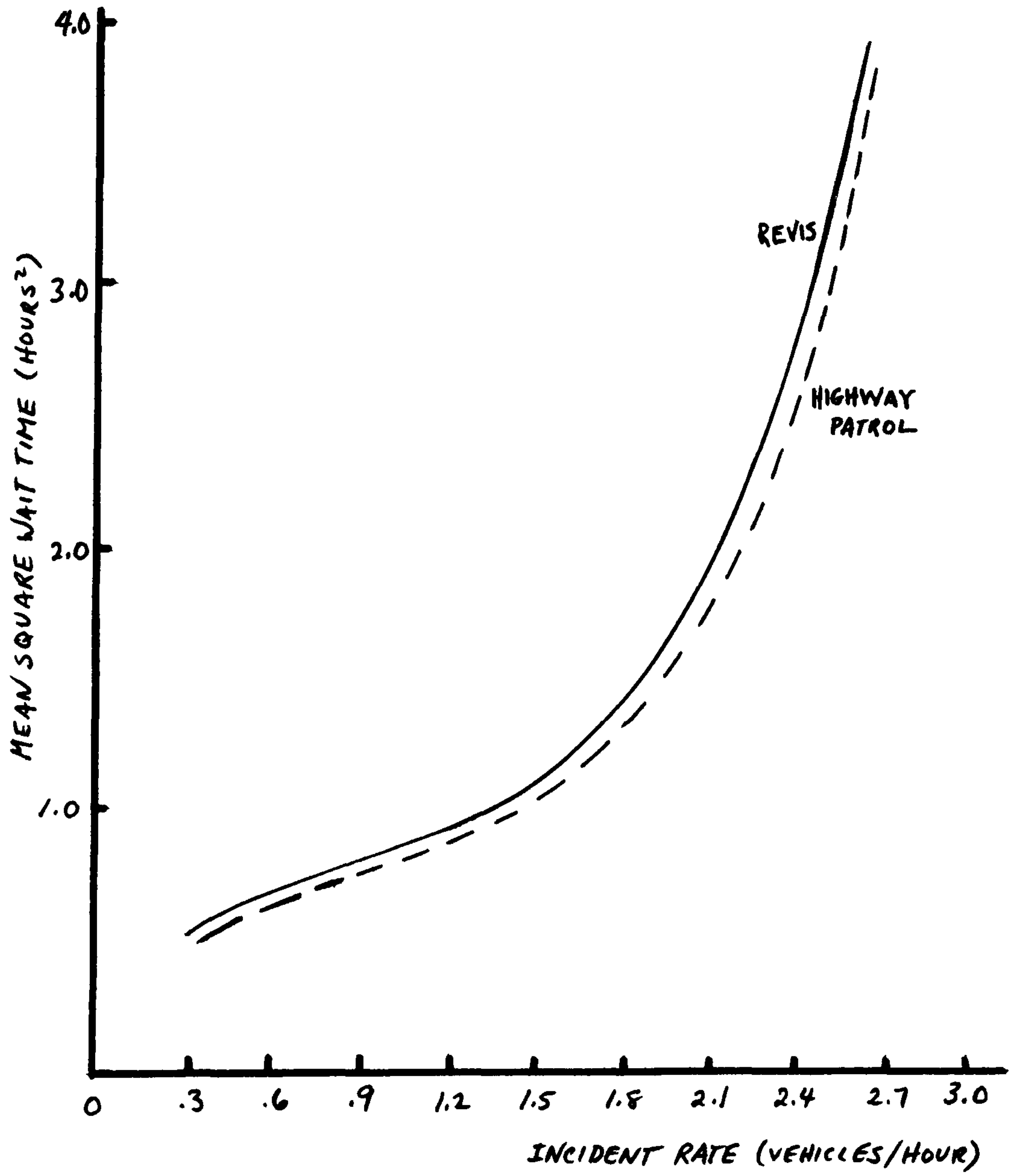


Fig. 5-10 The Estimates of the Mean Square Wait Times of the REVIS and Highway Patrol Policies for Various Incident Rates

Table 5-4 The Estimates of the Mean, Variance and 95% Confidence Interval of the Squared Wait Time for the REVIS and Highway Patrol Policies

Incident Rate Vehicles/hr	REVIS			Highway Patrol		
	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)
.3	.5156	.0000578	(.5062, .5250)	.4480	.0000669	(.4378, .4582)
.9	.7195	.0004086	(.6944, .7446)	.6497	.00008083	(.6385, .6609)
1.4	1.0107	.0007067	(.9777, 1.0437)	.9233	.001112	(.8819, .9647)
1.8	1.4149	.006018	(1.3186, 1.5112)	1.3117	.006638	(1.2106, 1.4128)
2.2	2.1155	.02525	(1.9182, 2.3128)	2.0110	.02688	(1.800, 2.2217)
2.7	4.2753	.3678	(3.5224, 5.0282)	4.0808	.3846	(3.3109, 4.8507)

Table 5-5 The Statistic t' for the Test of Significance of the Mean Square Wait Time Between the REVIS and Highway Patrol Systems

Incident Rate (Vehicles/Hr)	t'
.3	15.879*
.9	9.5602*
1.4	14.977*
1.8	26.773*
2.2	13.567*
2.7	6.388*

*Statistically significant at the 95% level.

wait time squared of each system is increasing as the breakdown rate increases, the level of significance of the variation between systems diminishes. It is conjectured that this reduction of significance is evidence that these systems are truly identical for the higher incident rates (i.e. urban traffic conditions). This effect will be more apparent when the utilization of the aid vehicles are examined. From the results presented in Fig. 5-10 and Tables 5-4 and 5-5, it is, therefore, concluded that the highway patrol will on the average yield a lower mean square wait time.

In Fig. 5-11 the estimated annual cost for the REVIS and highway patrol systems is graphed as a function of λ. The estimated mean, variance, and 95% confidence of the cost appears in Table 5-6. From Fig. 5-11, it may be seen that for incident rates greater than 1.38 vehicles per hour, corresponding to urban traffic conditions, REVIS costs more to operate than the highway patrol system. However, for rural traffic conditions, REVIS far surpasses the highway patrol system in cost performance. Therefore, it is concluded that REVIS is more favorable than the highway patrol system for rural traffic conditions and comparable to it for heavier than rural traffic conditions.

In Fig. 5-12, the estimated number of trips an aid vehicle completes in a year for the REVIS and highway patrol systems is graphed. From this graph it may be seen that the utilization of the REVIS aid vehicle approaches that of

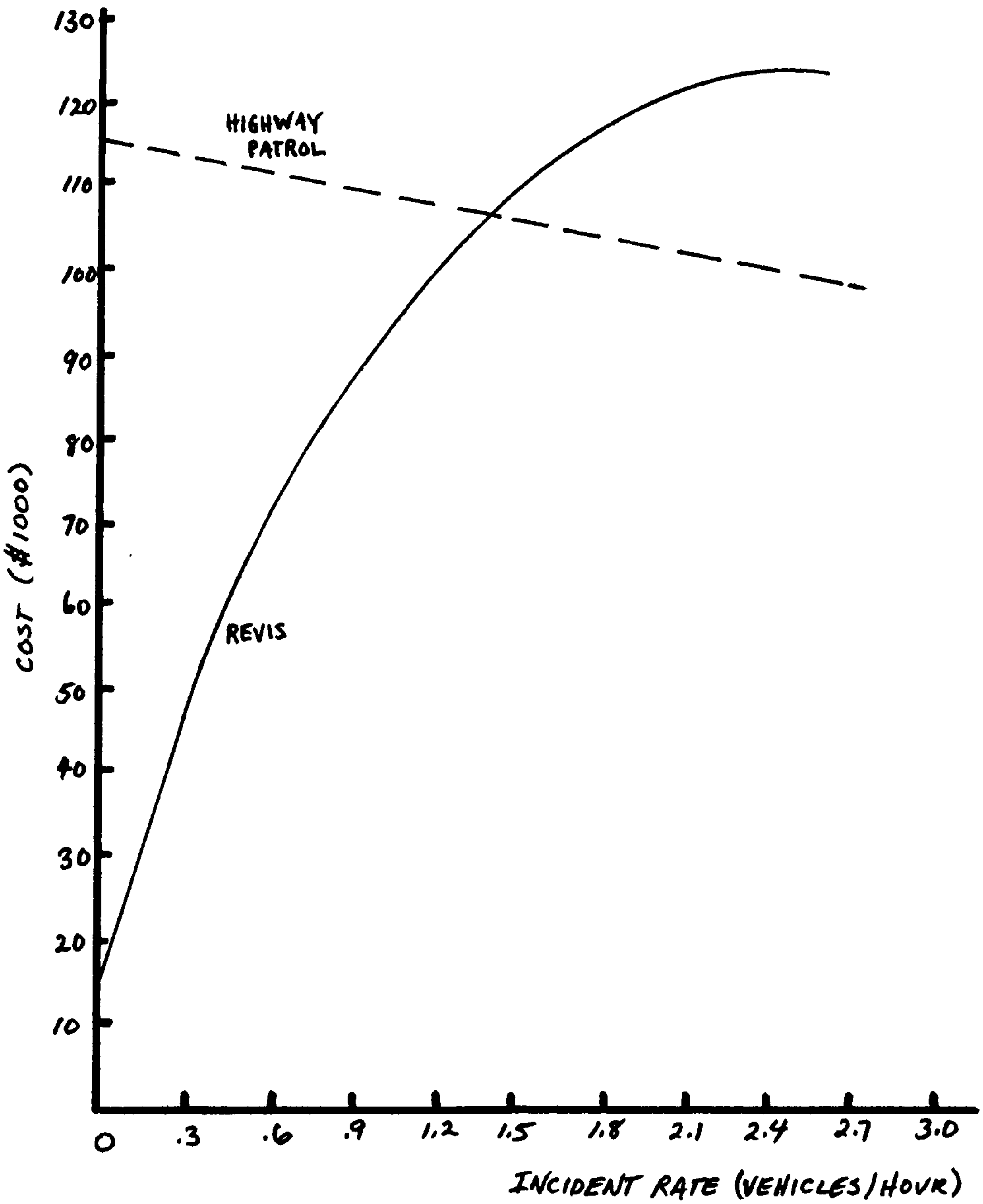


Fig. 5-11 The Estimates of the Mean Cost of the REVIS and Highway Patrol Policies for Various Incident Rates

Table 5-6 The Estimates of the Mean Variance and 95% Confidence Interval of the Cost for the REVIS and Highway Patrol Policies

Incident Rate Vehicles/hr	REVIS			Highway Patrol		
	$\bar{C}_{REVIS}$ (dollars)	$Var(\bar{C}_{REVIS})$ (dollars^2)	95% C.I. (dollars)	$\bar{C}_{HP}$ (dollars)	$Var(\bar{C}_{HP})$ (dollars^2)	95% C.I. (dollars)
.3	46245.	220719.5	(45662., 46828.)	114215.	1115.2	(114173., 114256.)
.9	88248.	206434.	(87684., 88812.)	110163.	5293.2	(110073., 110254.)
1.4	108673.	177639.8	(108149., 109196.)	106804	11110.8	(106674., 106935.)
1.8	118081.	36820.8	(117842., 118319.)	104066.	18028.8	(103899., 104232.)
2.2	122626.	9239.5	(122507., 122745.)	101340.	19678.	(101166., 101514.)
2.7	123613.	12094.0	(123476., 123750.)	97906.	18376.8	(97731., 98068.)

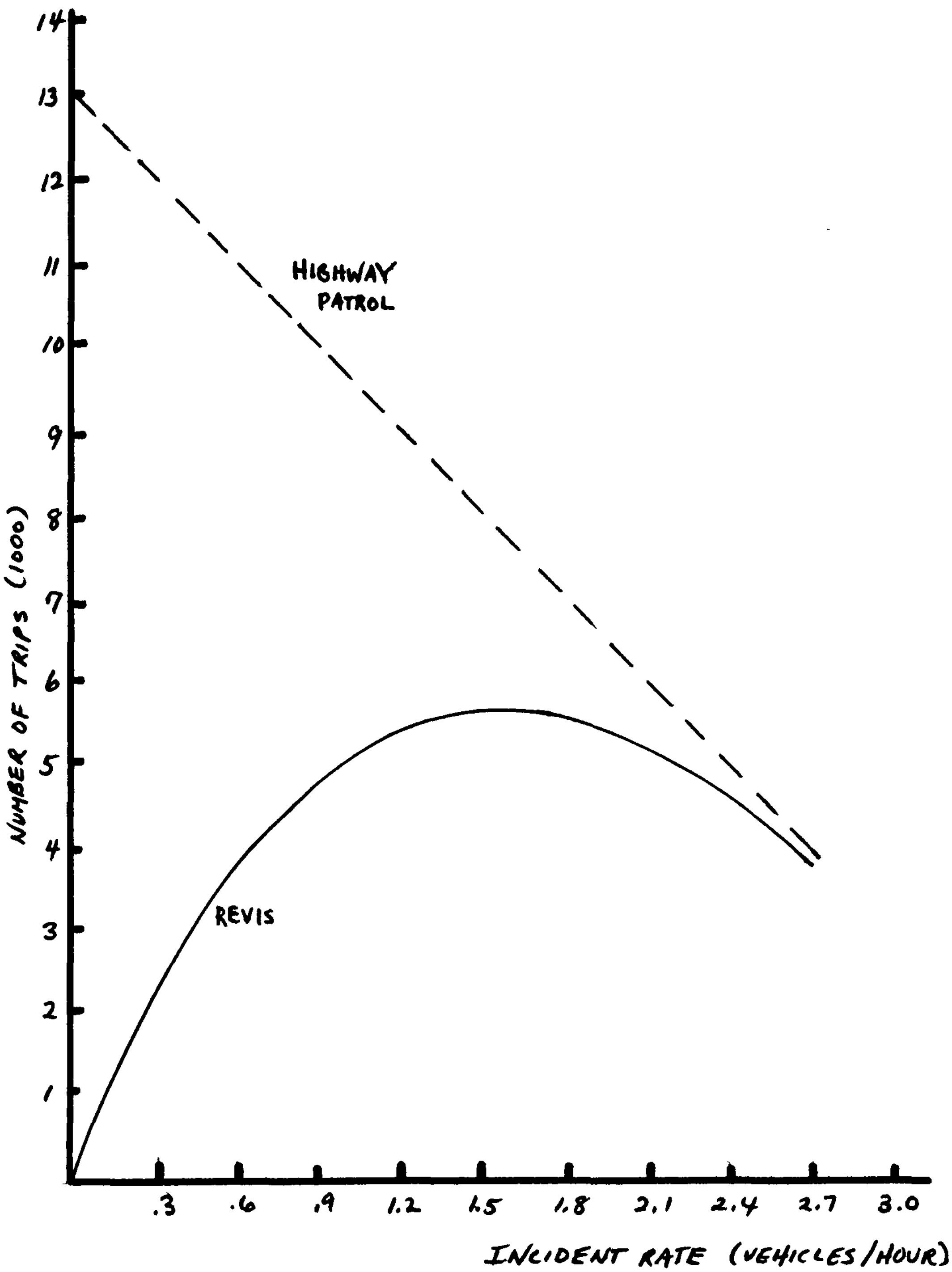


Fig. 5-12 The Estimates of the Mean Number of Trips of the REVIS and Highway Patrol Policies for Various Incident Rates

Table 5-7 The Estimates of the Mean, Variance and 95% Confidence Interval of the Number of Trips for the REVIS and Highway Patrol Policies

Incident Rate Vehicles/hr	REVIS			Highway Patrol		
	$\bar{T}$	Var($\bar{T}$)	95% C.I.	$\bar{T}$	Var($\bar{T}$)	95% C.I.
.3	2319.6	1277.3	(2275.2, 2363.9)	12107.4	278.8	(12086.7, 12128.1)
.9	4945.8	435.7	(4919.9, 4971.7)	10081.6	1323.3	(10036.4, 10126.8)
1.4	5682.	468.5	(5655.1, 5708.9)	8402.2	2777.7	(8336.8, 8467.6)
1.8	5560.2	2891.7	(5493.4, 5627)	7032.8	4507.2	(6949.5, 7116.1)
2.2	4958.8	3297.7	(4887.5, 5030.1)	5670	4919.5	(5582.9, 5757.)
2.7	3730.6	3739.3	(3654.7, 3806.5)	3949.8	4594.2	(3865.6, 4033.9)

the highway patrol vehicles as the incident rate increases (i.e. the traffic volume increases). When the utilization of the aid vehicles of each system is equal, it may be concluded that the systems are operating identically and will yield equivalent wait time distributions.

For large incident rates, it is shown in Appendix 5.2 at the end of this chapter that the difference in cost, C_D, between REVIS and the highway patrol is

$$C_D = 29{,}000 - 1000\lambda/3 \text{ dollars,} \tag{5-10}$$

where λ is the incident rate. Since this function is positive for all realistic traffic conditions* and that the usage of the REVIS vehicle approaches that of the highway patrol vehicle, for large λ, the REVIS system is operating cost-ineffective under urban traffic conditions but, as seen in Fig. 5-11, operating cost-effective for rural traffic conditions.

*From the theoretical calculation mode in Chapter 3, the breakdown rate must be less than 4 vehicles per hour in order for the wait time process to be stable. Therefore, C_D =29000-4000/3=27666.67 dollars.

5.8 Cost-Benefit Analysis of REVIS and Highway Patrol Policies - Multiple Sections

Previously it was assumed that one aid vehicle serves a single section of the highway. In order to evaluate the performance of a REVIS system operating on a more realistic multiple sectioned highway,* the following dispatch policy is proposed for the REVIS system: aid vehicles may only serve adjacent sections and operate according to the spatial policy described in Section 5.4. Since it is possible that two aid vehicles may be servicing the same section at the same time, the sections are coupled.

In Appendix 5.1 at the end of this chapter, it is shown how highway traffic conditions are related to the number of incidents per hour per mile and that heavy rural to moderate urban conditions correspond to a range of incidents from .015 to .135 vehicles per hour per mile. For the remainder of this section, it is assumed that all comparisons between the competing systems will be made for this range of traffic conditions.

In order to obtain a fair comparison of the cost-benefit performance of the REVIS multiple section system and the highway patrol system, the following two experiments were performed: For evaluating the overall highway performance, a five sectioned 100-mile highway using the REVIS system was compared to a single section 100-mile highway using six

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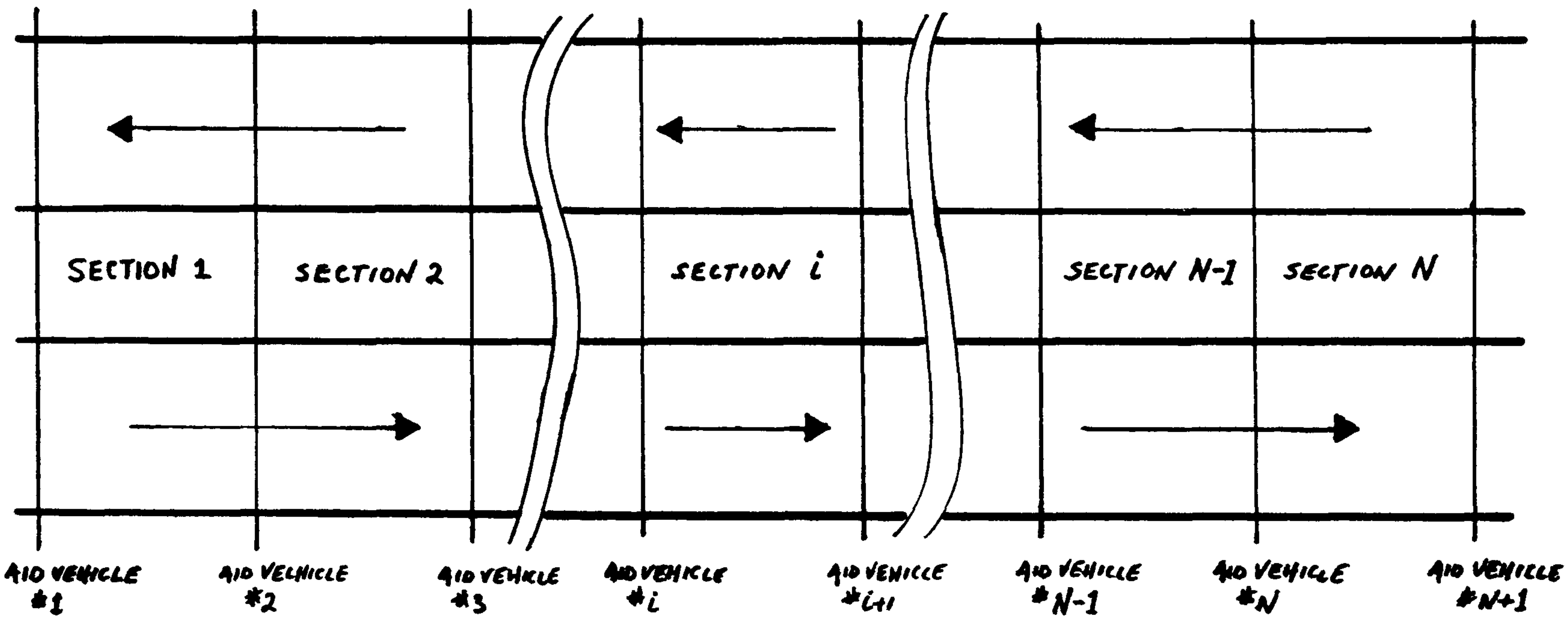
*A highway may be divided up into N sections. At the end-points of each section, there exists a traffic crossover where one aid vehicle is stationed, see Fig. 5-13.



For an N-section highway there are N+1 REVIS aid vehicles

Fig. 5-13 Representation of the Multiple Section Highway
Serviced by the REVIS System

highway patrol aid vehicles. To judge the fairness of the comparison, the number of aid vehicles per highway mile, N_v, for each system, may be calculated. From the above, it may be seen that for both systems N_v=6/100. Secondly, in order to ascertain section performance, a typical coupled REVIS section was compared to an uncoupled highway patrol section of equal length that uses a single aid vehicle. This experiment was conducted on 10, 20, and 30 mile sections. Due to symmetry and the statistical independence of incidents within each section, a REVIS aid vehicle will spend, on the average, half its time in each adjacent section it is assigned to service (for interior sections unaffected by any end effects). Therefore, the equivalent number of aid vehicles per highway mile is the same for each system.

The estimated mean, variance and the 95% confidence interval of the squared wait time, the annual cost and the total yearly mileage accumulated by the aid vehicles for the 5-sectioned REVIS system and the 6 aid vehicle highway patrol system appear in Tables 5-8, 5-9 and 5-10, respectively. Also these quantities for the two systems are graphed in Figs. 5-14, 5-15 and 5-16, respectively. From these graphs, it may be seen that the REVIS system is far superior to the highway patrol system for this range of traffic conditions. The mean square wait time of the REVIS system is on the average 18.6 percent lower than that of the highway patrol system and for all traffic conditions simulated, the REVIS system has a lower operating cost than the highway patrol.

Table 5-8 The Estimated Mean, Variance and 95% Confidence Interval for the Squared Wait Time of the REVIS - 5 Sections and Highway Patrol - 6 Aid Vehicle Policies

Incident Rate (Vehicles/hr/mile)	REVIS			Highway Patrol		
	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)
.015	.1566	.0000002009	(.1560, .1572)	.8750	.000794	(.8400, .9100)
.045	.1795	.0000003426	(.1788, .1802)	1.0320	.0007763	(.9226, 1.1414)
.075	.2071	.00000251	(.0251, .2091)	1.2604	.00140	(1.2139, 1.3069)
.105	.2425	.000002183	(.2407, .2443)	1.5588	.003199	(1.4886, 1.629)
.135	.5046	.000005165	(.5018, .5047)	1.9632	.009201	(1.8441, 2.0823)

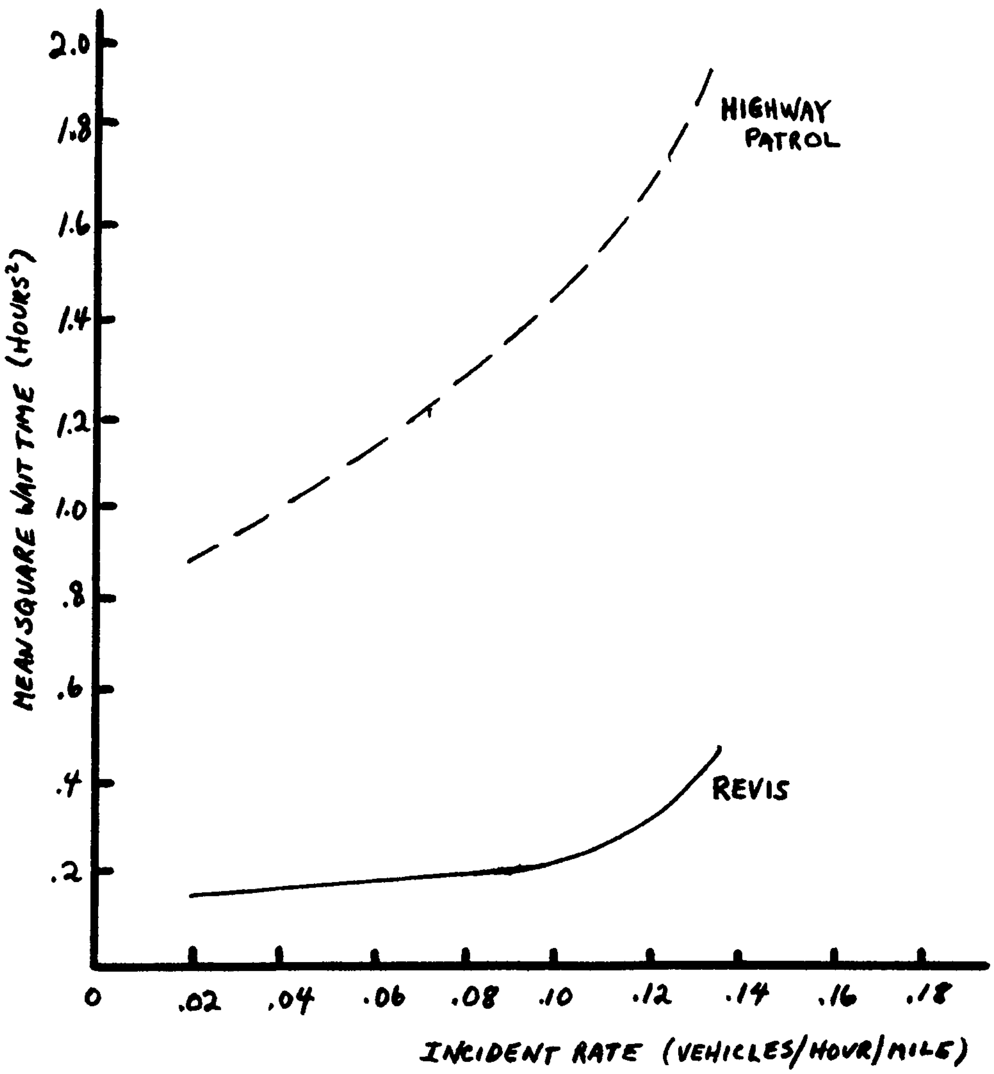


Fig. 5-14 The Estimates of the Mean Square Wait Time of the REVIS-5 Sections and Highway Patrol-6 Aid Vehicle Policies for Various Incident Rates

Table 5-9 The Estimated Mean, Variance and 95% Confidence Intervals for the Cost of the REVIS - 5 Sections and Highway Patrol - 6 Aid Vehicle Policies

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{C}_{REVIS}$ (dollars)	$Var(\bar{C}_{REVIS})$ (dollars^2)	95% C.I. (dollars)	$\bar{C}_{HP}$ (dollars)	$Var(\bar{C}_{HP})$ (dollars^2)	95% C.I. (dollars)
.015	143454.	725131.5	(142396, 144510.8)	691999	10205	(691873.6, 692124.4)
.045	249246.	2661700.	(247220.8, 251271.6)	680605	26150	(680404.2, 680805.8)
.075	350019	5754504.	(347040.9, 352997.1)	669042	27382.5	(666987.7, 691096.3)
.105	444103	9110992	(440355.7, 497850.3)	657361	32542.5	(657137., 657585.)
.135	519620	6445024	(516468.5, 522771.9)	645810	17880	(645644., 645976.)

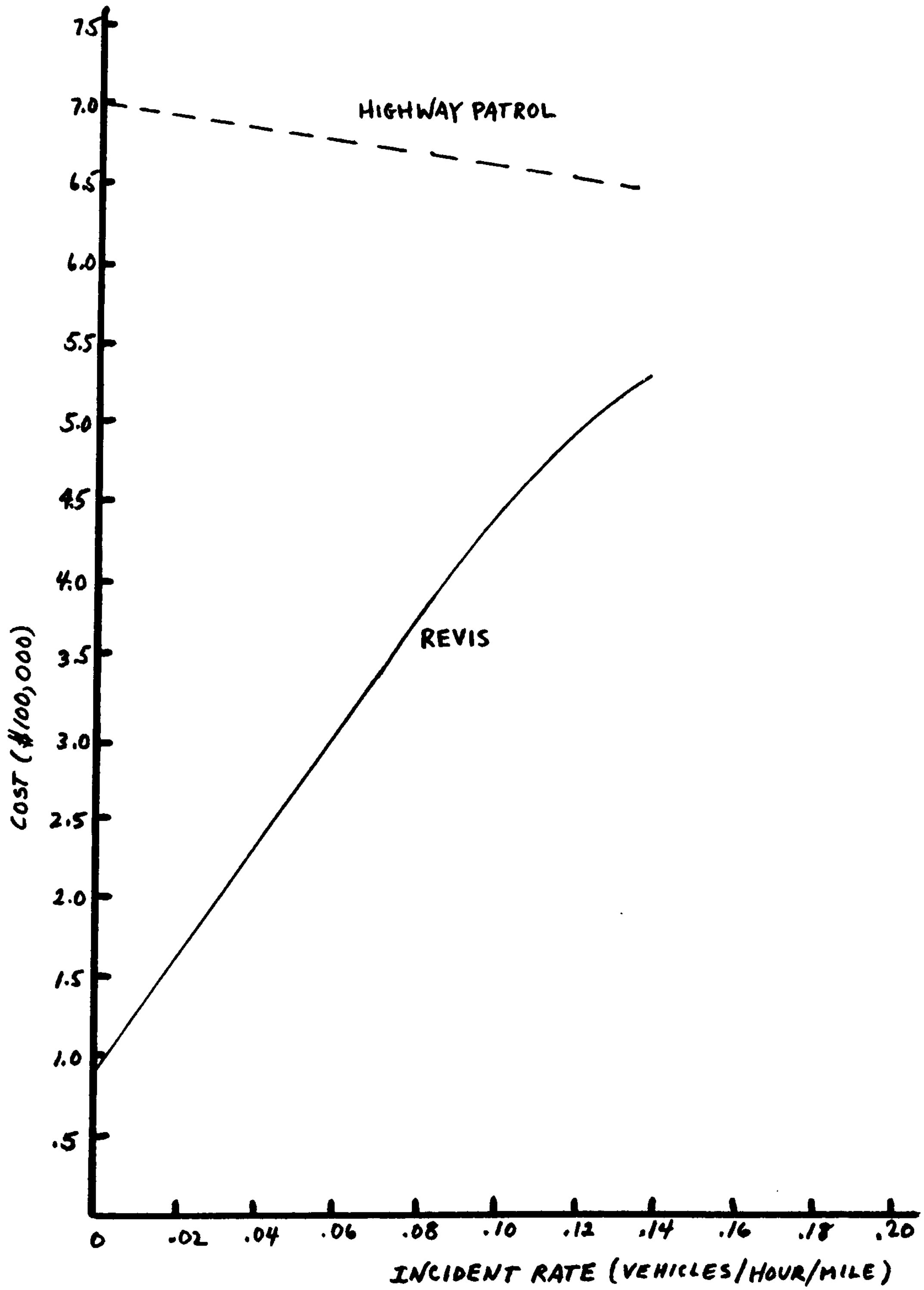


Fig. 5-15 The Estimates of the Cost of the REVIS-5 Sections and Highway Patrol-6 Aid Vehicle Policies for Various Incident Rates

Table 5-10 The Estimated Mean, Variance and 95% Confidence Intervals for the Total Yearly Mileage Accumulated by the Aid Vehicles of the REVIS - 5 Section and Highway Patrol - 6 Aid Vehicle Policies

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\overline{TYM}$ (miles)	$Var(\overline{TYM})$ (miles^2)	95% C.I. (miles)	$\overline{TYM}$ (miles)	$Var(\overline{TYM})$ (miles^2)	95% C.I. (miles)
.015	134420	4384800	(131820, 137019.6)	3039980	4082500	(3037471.6, 3042488.4)
.045	400164	169946675	(395053, 405274.7)	2812100	10460000	(2808084.9, 2816115.1)
.075	645404	31109250	(642909.6, 647898.4)	2580840	10955500	(2576730.9, 2584949.1)
.105	851628	48811750	(842954.5, 860301.5)	2347220	13017500	(2342740.8, 2351699.2)
.135	1008232	8548500	(1004603.9, 1011860.1)	2113980	7152500	(2110659.8, 2117300.2)

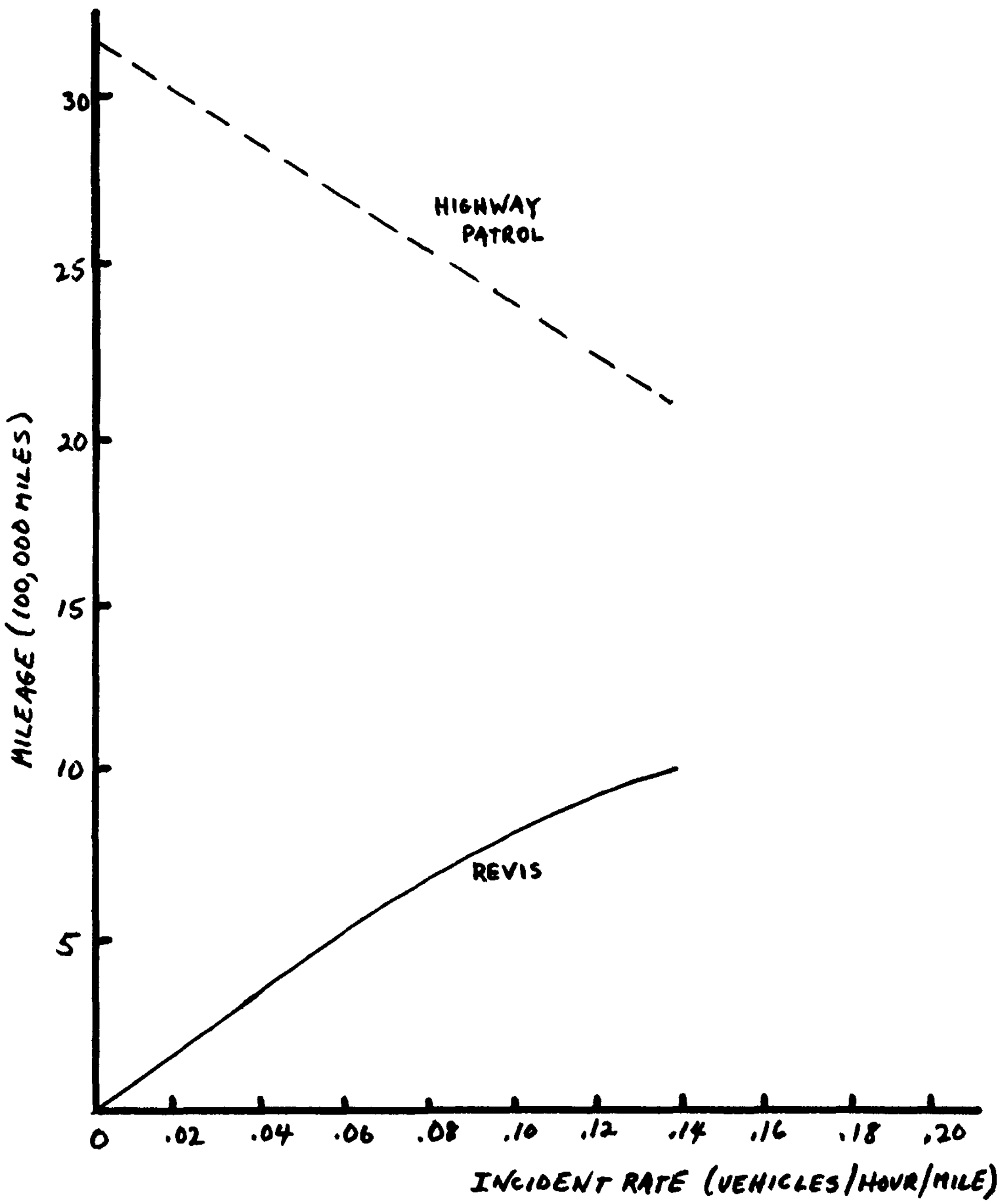


Fig. 5-16 The Estimates of the Total Yearly Mileage Accumulated by the Aid Vehicles of the REVIS-5 Section and Highway Patrol-6 Aid Vehicle Policies for Various Incident Rates

The graph of the total yearly mileage accumulated indicates that the aid vehicle utilization of both systems approaches each other as traffic conditions become very heavy. Unlike the case of the uncoupled section experiments, see Section 5.7, the operation of the REVIS system and the highway patrol system are not identical for heavy traffic conditions, however, like the uncoupled case under heavy traffic conditions, the measure of utilization of the aid vehicles for each system is similar.

Presented in Figs. 5-17 through 5-25 and Tables 5-11 through 5-19 are the results of the section performance experiment. In each case, i.e. for 10, 20, and 30 mile sections, the mean square wait time of the incidents occurring in the tenth section of a twenty section highway and the annual operating cost and total yearly mileage of the REVIS aid vehicle stationed at the tenth traffic crossover point are compared to the mean square wait time of the incidents occurring in an uncoupled highway patrol section of equal length and the annual operating cost and total yearly mileage of the sole highway patrol vehicle, respectively. In all three cases, the REVIS system yields a lower mean square wait time and lower yearly mileage than the patrol system for all traffic conditions simulated. For 10 and 20 mile sections, the annual operating costs are highest for the highway patrol vehicle; however, for the 30 mile section, the cost of the REVIS vehicle is larger than the cost of the patrol vehicle for heavier traffic conditions (i.e.

Table 5-11 The Estimated Mean, Variance and 95% Confidence Intervals for the Squared Wait Time of a 10 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)	$\overline{W^2}$ (hr^2)	$Var(\overline{W^2})$ (hr^4)	95% C.I. (hr^2)
.015	.1165	.000000231	(.1159, .1171)	.1218	.000002695	(.1198, .1238)
.045	.1207	.0000013	(.1193, .1221)	.1311	.0000006759	(.1301, .1321)
.075	.1260	.000000702	(.1256, .1264)	.1412	.000002241	(.1393, .1431)
.105	.1311	.000001419	(.1296, .1326)	.1528	.00001052	(.1488, .1568)
.135	.1372	.000001649	(.1356, .1388)	.1637	.00001265	(.1593, .1681)

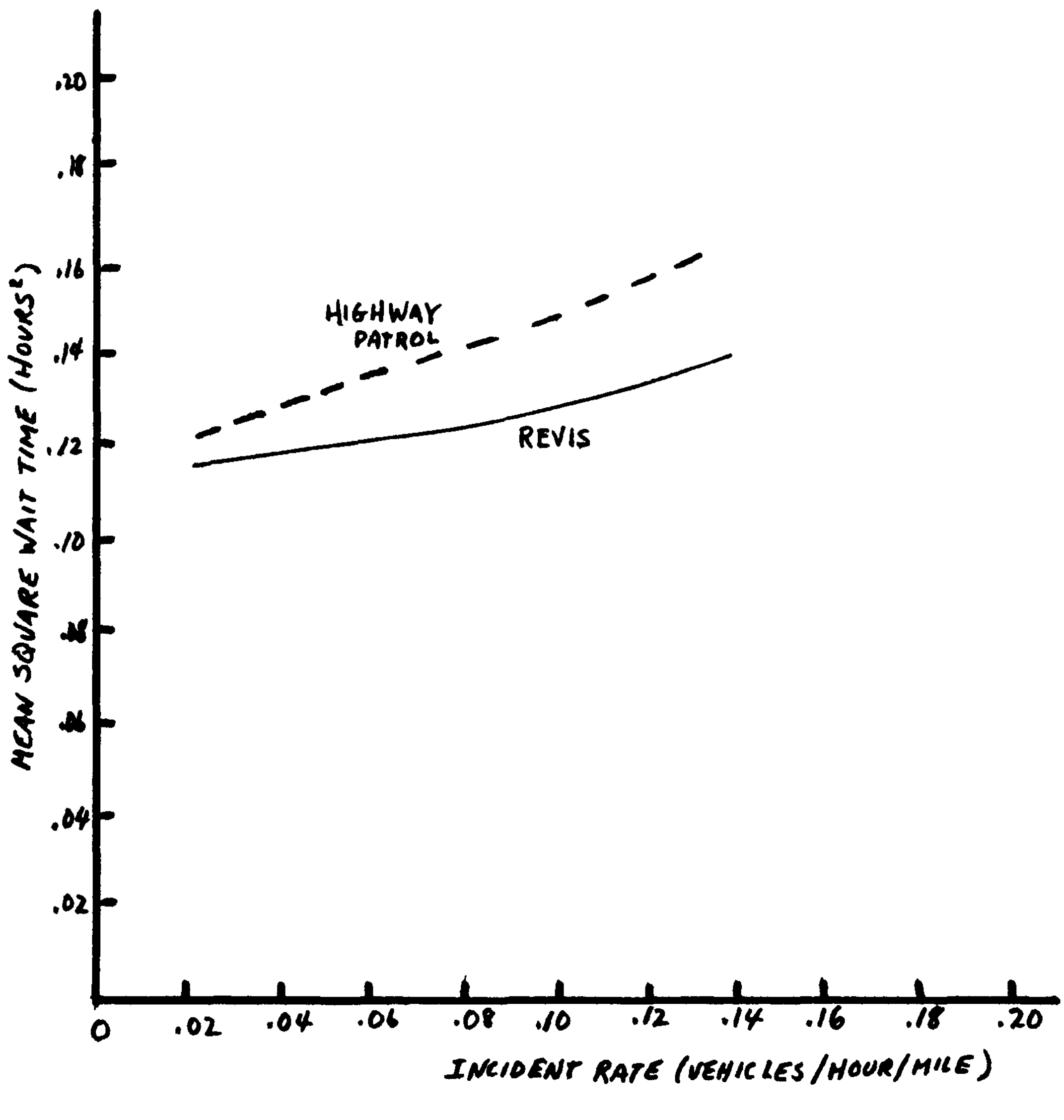


Fig. 5-17 The Estimates of the Mean Square Wait Time of a 10 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-12 The Estimated Mean, Variance and 95% Confidence Interval for the Cost of an Aid Vehicle on a 10 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{C}_{REVIS}$ (dollars)	$Var(\bar{C}_{REVIS})$ (dollars^2)	95% C.I. (dollars)	$\bar{C}_{HP}$ (dollars)	$Var(\bar{C}_{HP})$ (dollars^2)	95% C.I. (dollars)
.015	18646.	9052	(18528., 18764.5)	115785	358	(115761.5, 115808.5)
.045	25989.	77975.9	(126542.5, 26335.8)	114728.8	1216.2	(114685.5, 114772.1)
.075	33246.	232207.4	(32647.6, 33844.)	113712	865	(113675.5, 113748.5)
.105	40527.	451949.8	(39692.4, 91361.6)	112709	2472	(112647.3, 112770.7)
.135	47954.	1159325	(46617.4, 49290.8)	111673.2	5519.7	(111640., 111706.4)

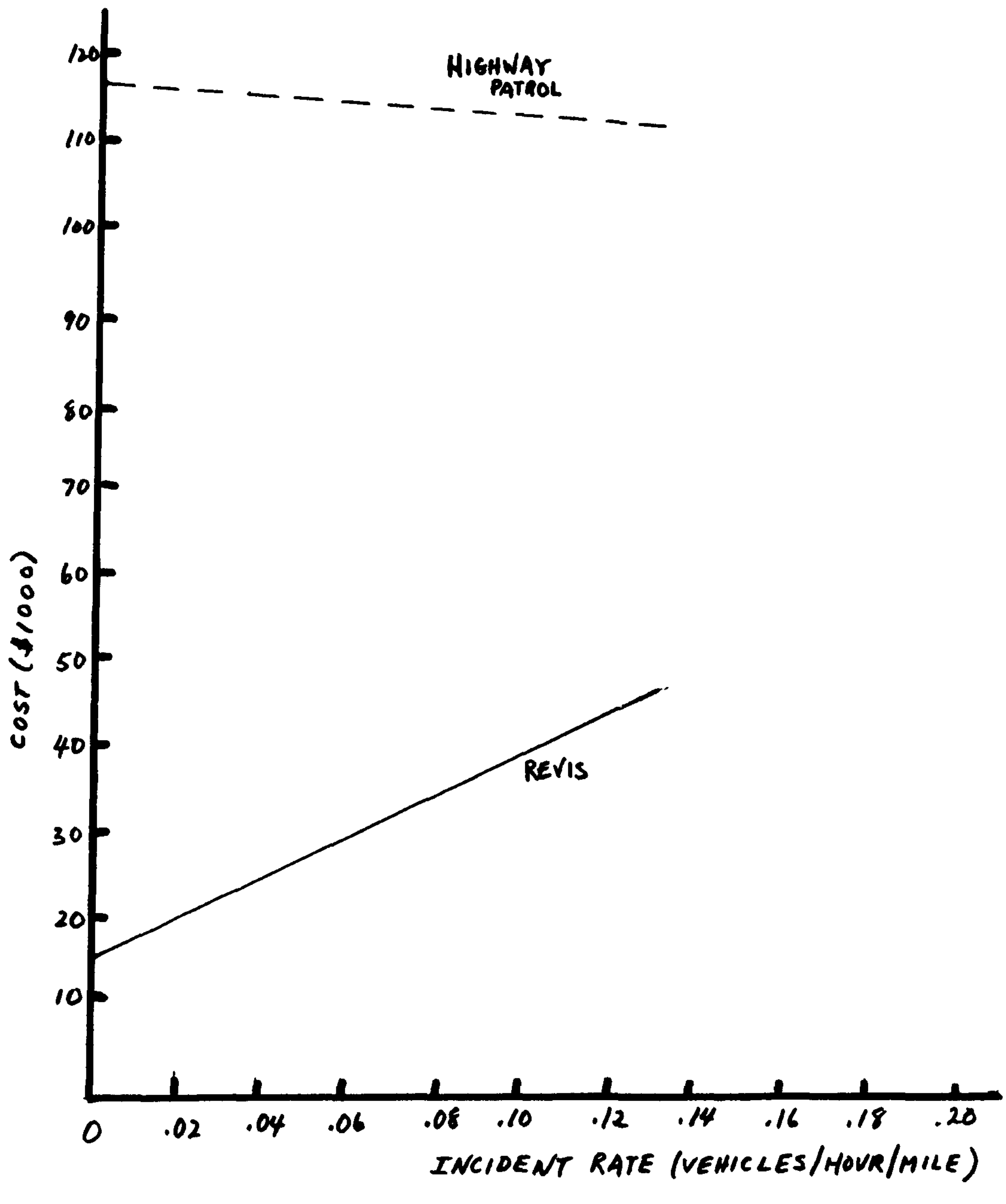


Fig. 5-18 The Estimates of the Mean Cost of an Aid Vehicle on a 10 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-13 The Estimated Mean, Variance and 95% Confidence Interval for the Number of Trips of an Aid Vehicle for a 10 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{\bar{T}}$	Var $(\bar{T})$	95% C.I.	$\bar{\bar{T}}$	Var $(\bar{T})$	95% C.I.
.015	667	293.5	(645.7, 6883.)	51569.4	1460.3	(51522, 51616.8)
.045	2016	2094.5	(1959.2, 2072.8)	49457	4874.5	(49370.3, 49543.7)
.075	3338.6	5011.3	(3256.7, 3426.5)	47423.4	3434.3	(47350.6, 47496.2)
.105	4673	17068.5	(4510.8, 4835.2)	45417.8	9843.2	(45294.6, 45541.)
.135	5991.6	49677.8	(5714.7, 6268.3)	43345.	21969.8	(43161., 43529.)

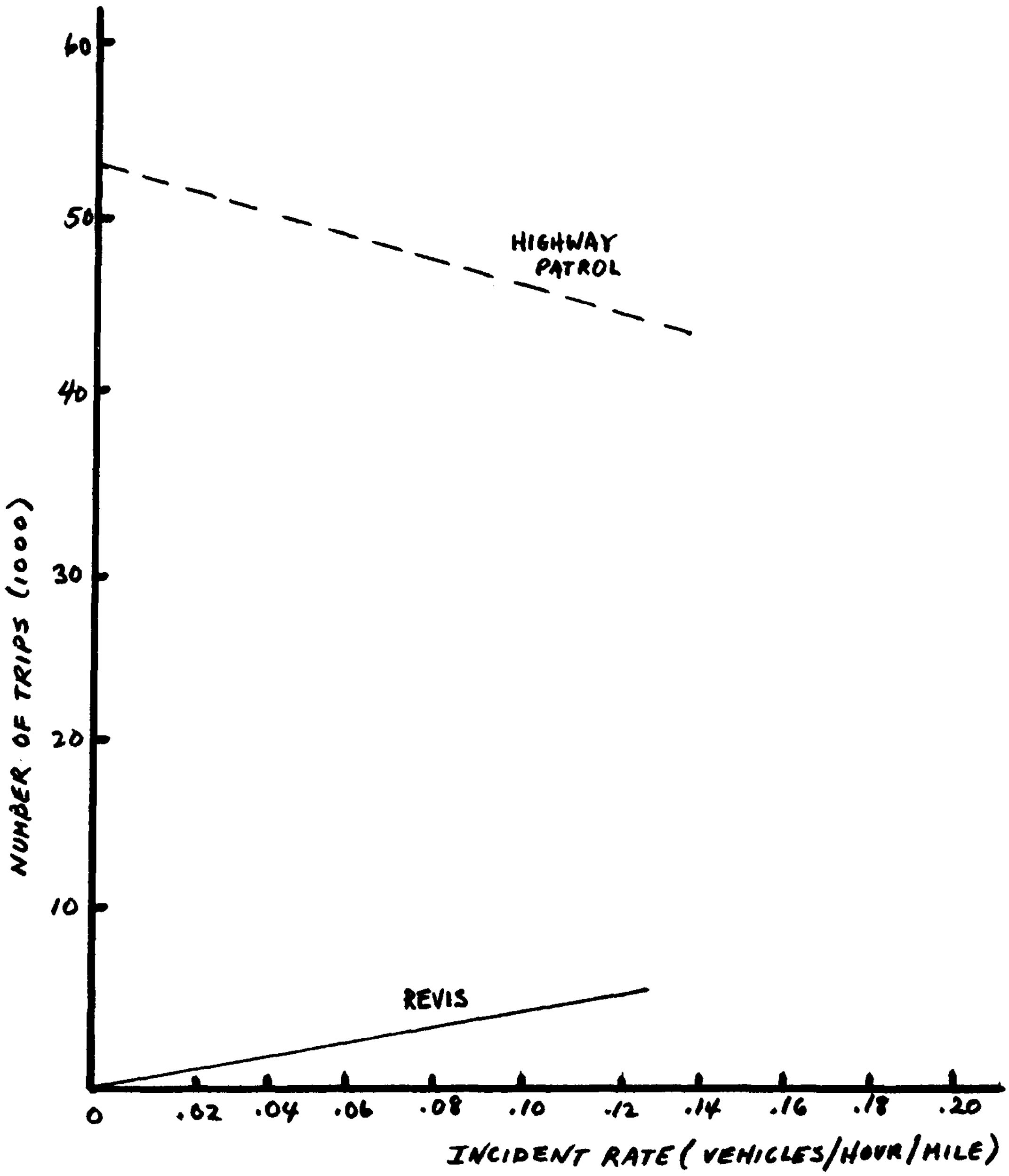


Fig. 5-19 The Estimates of the Mean Number of Trips of an Aid Vehicle for a 10 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-14 The Estimated Mean, Variance and 95% Confidence Interval for the Squared Wait Time of a 20 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)
.015	.1571	.000005147	(.1543, .1599)	.2012	.000009341	(.1974, .2050)
.045	.1850	.00001538	(.1801, .1899)	.2361	.00001477	(.2313, .2409)
.075	.2196	.00006306	(.2097, .2295)	.2814	.00003140	(.2744, .2884)
.105	.2664	.0001689	(.2503, .2825)	.3373	.000008163	(.3338, .3408)
.135	.3455	.0008576	(.3091, .3819)	.4176	.003632	(.3939, .4413)

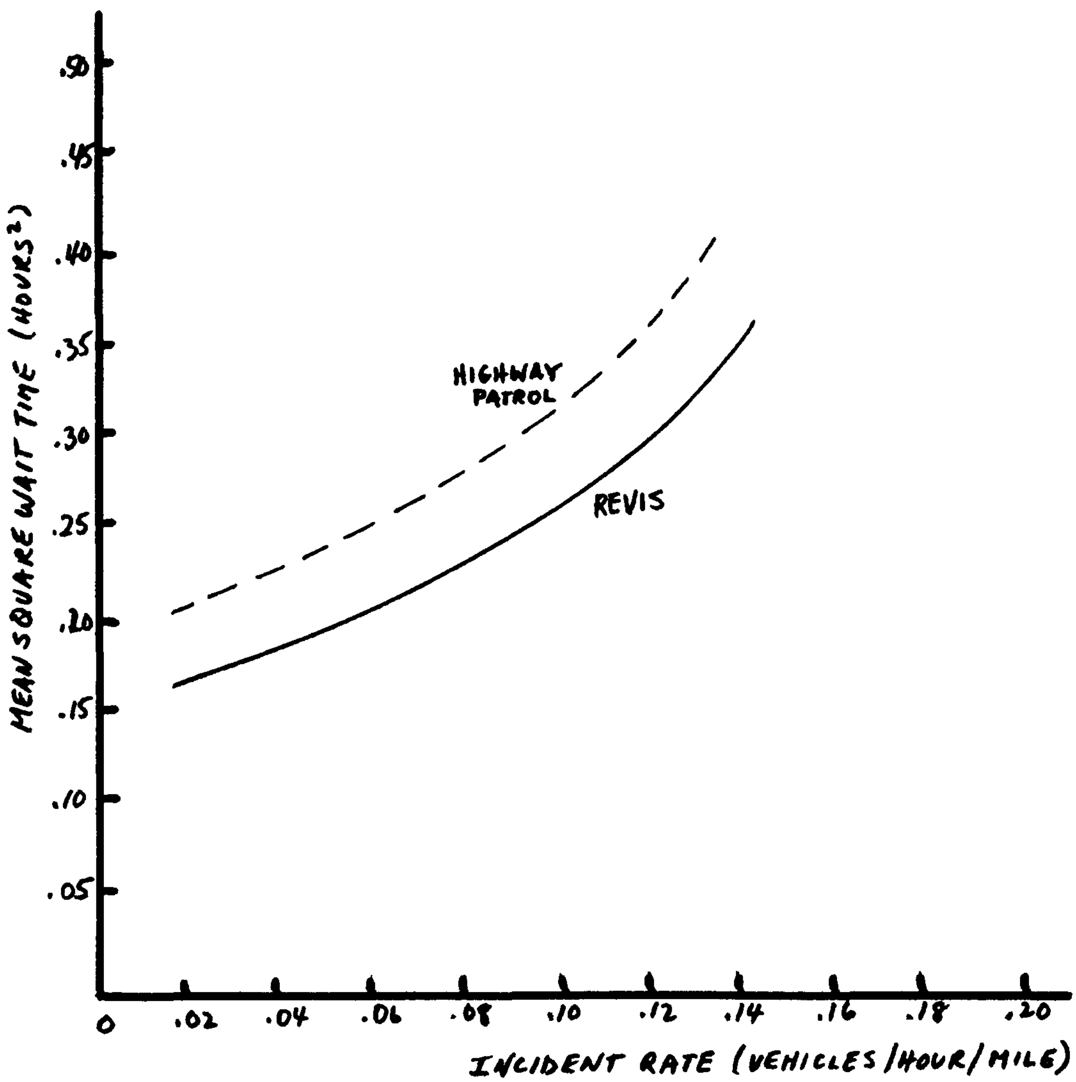


Fig. 5-20 The Estimates of the Mean Square Wait Time of a 20 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-15 The Estimated Mean, Variance and 95% Confidence Intervals for the Cost of an Aid Vehicle on a 20 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{C}_{REVIS}$ (dollars)	$Var(\bar{C}_{REVIS})$ (dollars^2)	95% C.I. (dollars)	$\bar{C}_{HP}$ (dollars)	$Var(\bar{C}_{HP})$ (dollars^2)	95% C.I. (dollars)
.015	2567.34	83577.75	(25328.9, 26045.2)	115279.2	757.7	(115245, 115313)
.045	47331.92	687950.8	(46302.2, 48361.6)	113218.6	1591.8	(113169.1, 113268.1)
.075	67437.25	4060140	(64935.7, 69938.8)	111175.2	7314.2	(111069., 111281.4)
.105	85223.75	2186430	(83388.0, 87059.4)	109169.8	8601.2	(109054.7, 109284.0)
.135	100069.9	3296589	(97815.8, 102324.0)	107139.4	10475.8	(107012.3, 107266.5)

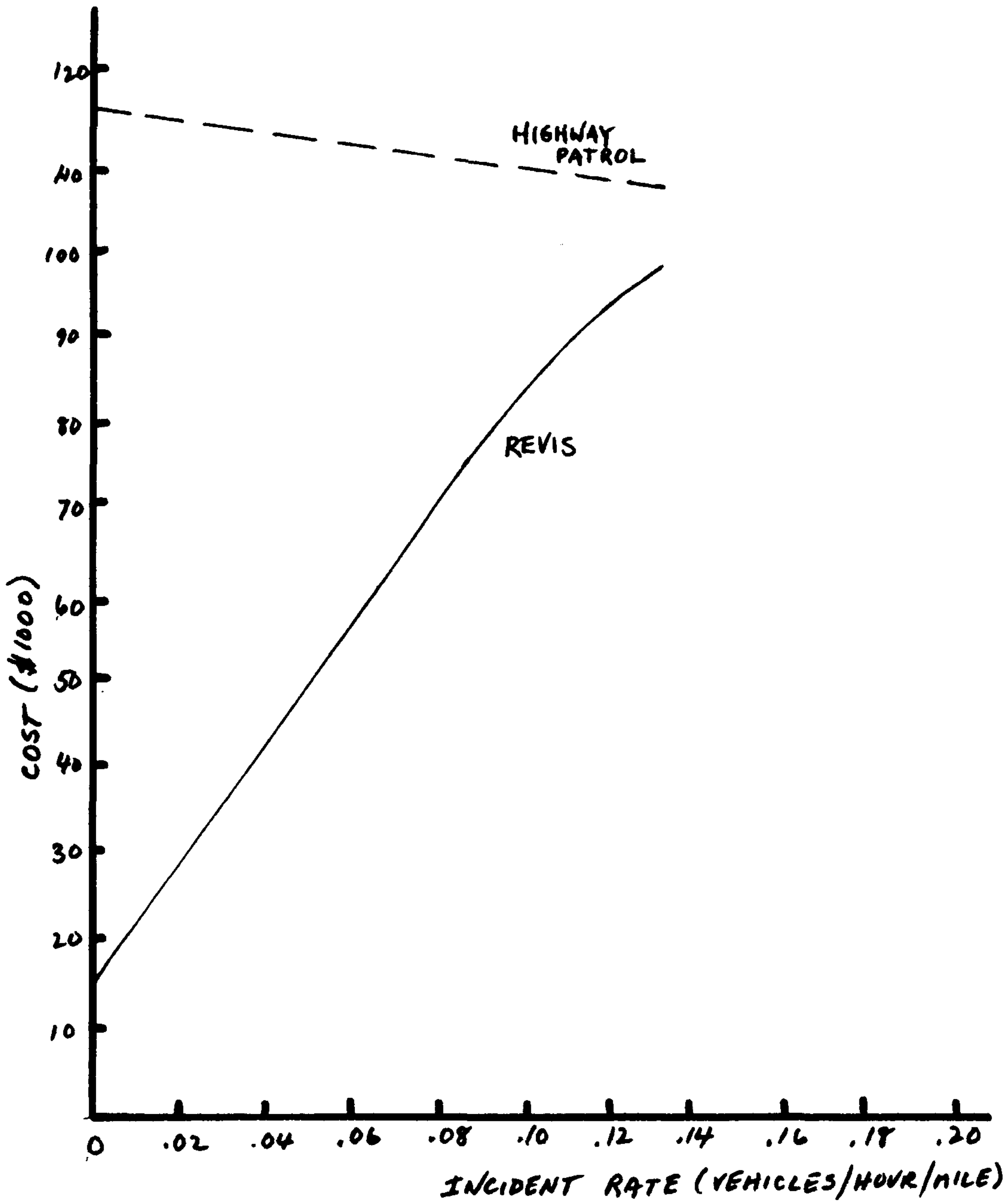


Fig. 5-21 The Estimates of the Mean Cost of an Aid Vehicle on a 20 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-16 The Estimated Mean, Variance and 95% Confidence Intervals for the Number of Trips of an Aid Vehicle for a 20 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{\bar{T}}$	Var($\bar{T}$)	95% C.I.	$\bar{\bar{T}}$	Var($\bar{T}$)	95% C.I.
.015	1368.8	836.2	(1332.9, 1404.7)	25279.2	757.7	(25245, 25313.4)
.045	4039.2	15555.25	(3884.4, 4194.)	23218.6	1591.8	(23169.1, 23268.1)
.075	6506.4	88028.8	(6138.1, 6894.7)	21175.2	7314.2	(21009., 21281.4)
.105	8519.8	16103.2	(8362.3, 8677.3)	19169.8	8601.2	(10954.7, 19284.9)
.135	9794.6	162053	(9294.8, 10294.4)	18139.4	10475.8	(17012.3, 17266.5)

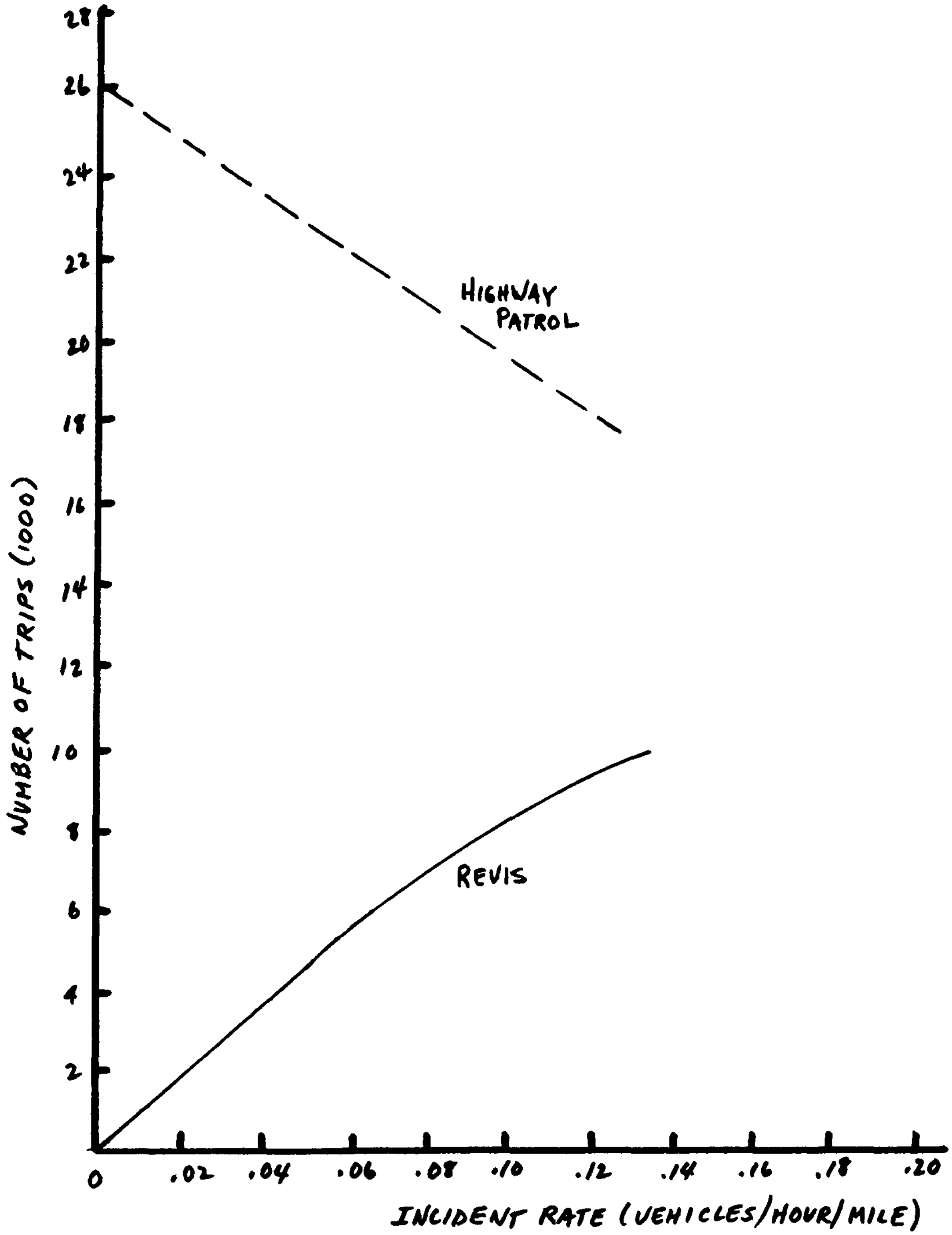


Fig. 5-22 The Estimates of the Mean Number of Trips of an Aid Vehicle on a 20 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-17 The Estimated Mean, Variance and 95% Confidence Intervals for the Squared Wait Time of a 30 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)	$\overline{W^2}$ (hr^2)	Var($\overline{W^2}$) (hr^4)	95% C.I. (hr^2)
.015	.1968	.00001273	(.1924, .2012)	.3133	.000006107	(.3102, .3164)
.045	.2848	.00017	(.2686, .3010)	.3936	.00005854	(.3841, .4031)
.075	.4491	.0009789	(.4103, .4879)	.5273	.0002925	(.5061, .5485)
.105	.6562	.004192	(.5758, .7366)	.7547	.0008653	(.7182, .7912)
.135	1.1758	.0003925	(1.1512, 1.2004)	1.1657	.006909	(1.0625, 1.2689)

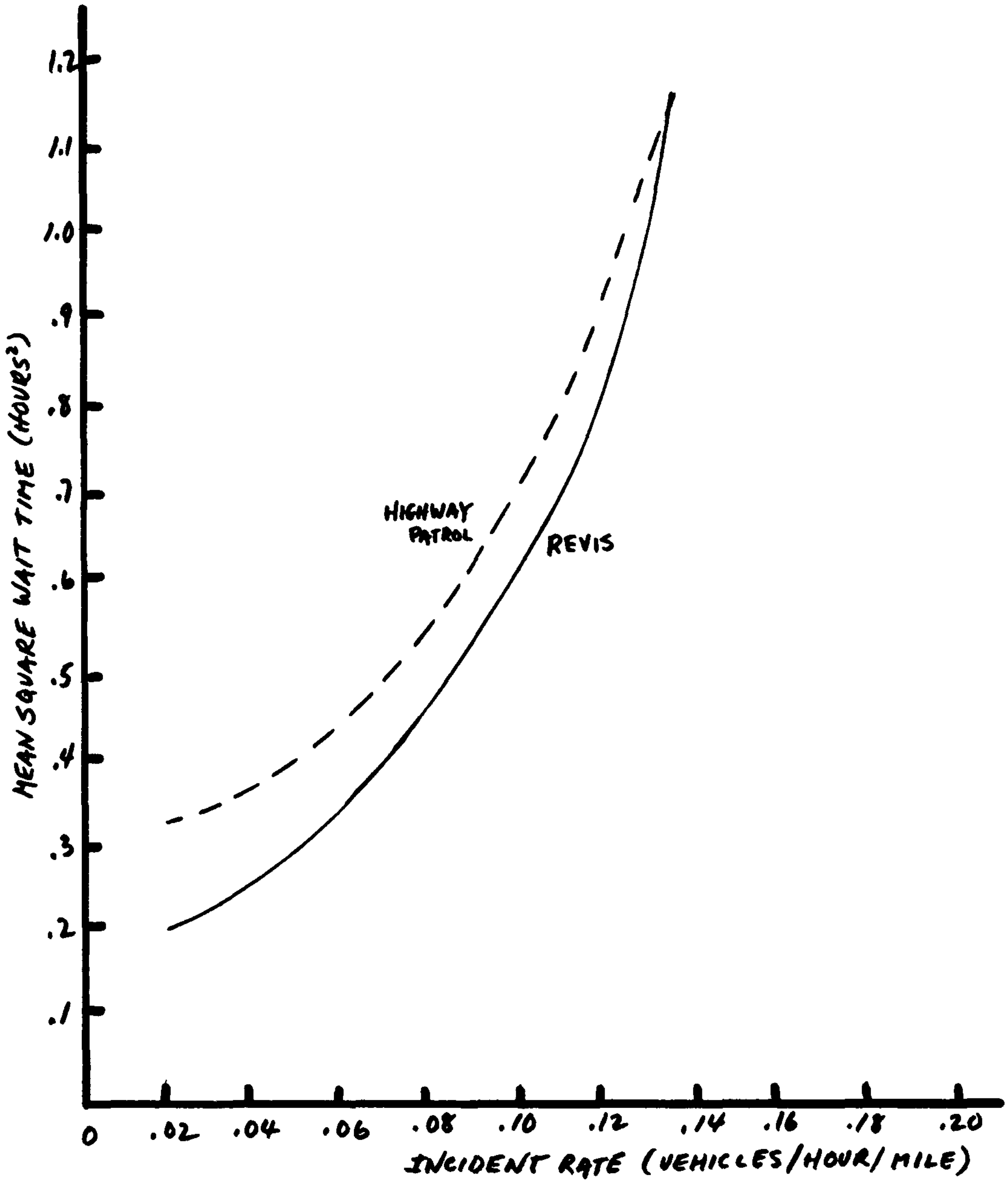


Fig. 5-23 The Estimates of Mean Square Wait Time of a 30 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-18 The Estimated Mean, Variance and 95% Confidence Intervals for the Cost of an Aid Vehicle on a 30 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{C}_{REVIS}$ (dollars)	$Var(\bar{C}_{REVIS})$ (dollars^2)	95% C.I. (dollars)	$\bar{C}_{HP}$ (dollars)	$Var(\bar{C}_{HP})$ (dollars^2)	95% C.I. (dollars)
.015	36264.4	271912.8	(35617., 36911.8)	114731.3	1235.9	(114687.7, 114774.9)
.045	75975	4541676	(73329.3, 78620)	111680.4	5429.9	(111588.9, 111771.9)
.075	104998.1	3625182	(102634.4, 107361.8)	108677.7	7170.1	(108572.6, 108782.8)
.105	119875.3	579501.3	(119780.7, 119968.1)	105576.9	12616.4	(105437.5, 105716.3)
.135	125704.3	1402146	(124234.3, 127174.3)	102514.8	14631.1	(102364.6, 102665)

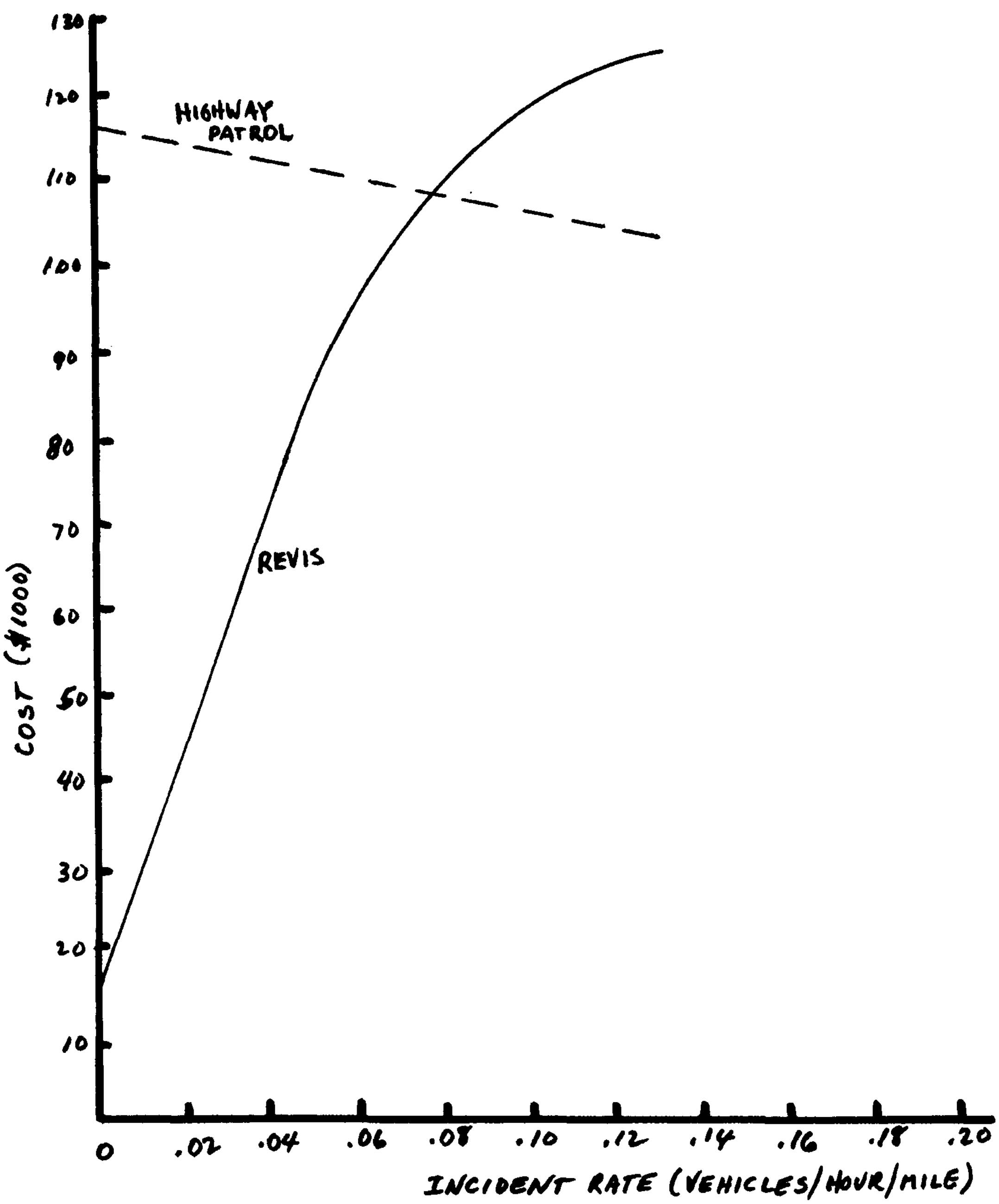


Fig. 5-24 The Estimates of the Mean Cost of an Aid Vehicle on a 30 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

Table 5-19 The Estimated Mean, Variance and 95% Confidence Interval for the Number of Trips of an Aid Vehicle for a 30 Mile REVIS Section and a Highway Patrol Section

Incident Rate (Vehicles/ hr/mile)	REVIS			Highway Patrol		
	$\bar{T}$	Var $(\bar{T})$	95% C.I.	$\bar{T}$	Var $(\bar{T})$	95% C.I.
.015	2042.2	2311.7	(1982.5, 2101.9)	16487.6	545.8	(16458.6, 16516.6)
.045	5755.8	36120.7	(5519.9, 5991.7)	14453.6	2413.3	(14392.6, 14514.6)
.075	8001.6	25826.9	(79816.5, 80215.5)	12451.8	3186.7	(12381.7, 12521.9)
.105	8389.6	39421.3	(8143.1, 8636.1)	10384.6	5607.3	(10291.6, 10477.6)
.135	7641.8	63283.7	(7329.5, 7954.1)	8343.2	6502.7	(8243.1, 8443.3)

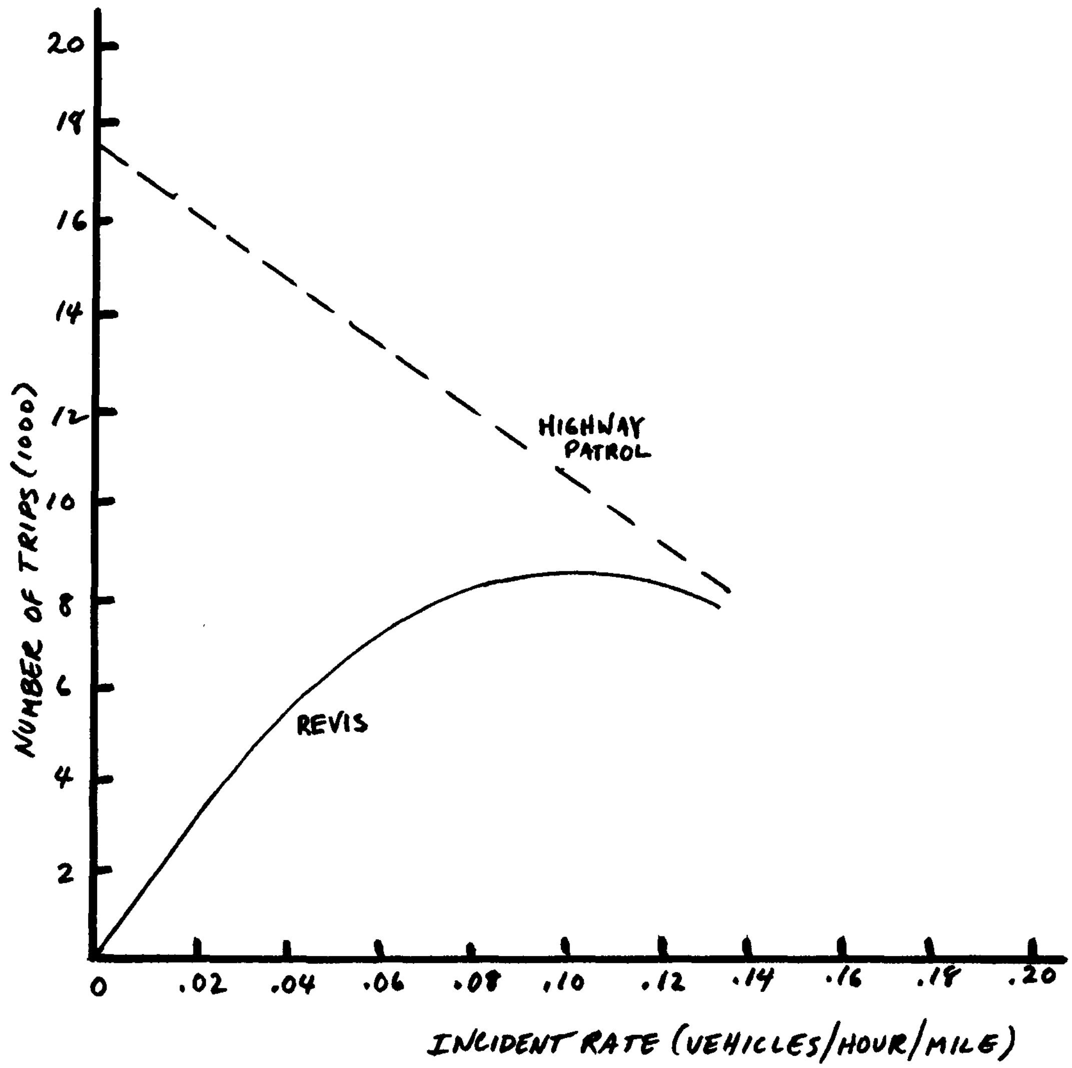


Fig. 5-25 The Estimates of the Mean Number of Trips of an Aid Vehicle on a 30 Mile REVIS Section and a Highway Patrol Section for Various Incident Rates

incident rates greater than .08 incidents per mile per hour correspond to moderate urban to very heavy urban conditions). Therefore, for the traffic conditions tested, it may be concluded that the REVIS system costs less to operate than the equivalent highway patrol systems for highways of 15 sections or more with section lengths between 10 and 20 miles. This conclusion is based on a comparison of the overall highway cost of a sectioned highway operating under the coupled REVIS system to the cost of an identical sectioned highway employing the uncoupled highway patrol system. From Fig. 5-21, for .135 incidents per hour per mile, the total operating cost of a highway of N sections assuming homogeneous sections,* for the highway patrol system is,

$$C_{HP} = 107{,}000N \text{ dollars}, \tag{5-11}$$

and for

$$C_{REVIS} = 100{,}000(N+1) \text{ dollars}. \tag{5-12}$$

After equating Eqs. (5-11) and (5-12) the critical number of sections at which REVIS costs more to operate is 15 sections.

*In the following sections, this assumption is examined.

5.9 Analysis of Multiple Sections - End Effects

In this section the variation of the section performance of a multiple section highway is determined by comparing the estimated mean square wait time of each section to the estimated mean square wait time of the inner most section of the highway. It is assumed that a N-sectioned highway is symmetrical about section N_{SYM}, for N odd and the pair of sections (N_{SYM}, $N_{SYM}+1$) for N even, where

$$N_{SYM} = \begin{cases} N/2, & N \text{ even}, \\ N/2+1, & N \text{ odd}, \end{cases}$$

then only one half of the highway may be observed.

Since any aid vehicle stationed between two inner* sections on the average will divide its workload equally between the two sections while the aid vehicles stationed at the end of the highway, i.e. the 1st and N+1th aid vehicle will spend all their worktime in their respective sections, it is speculated that the section performance profile (i.e. the mean square wait time per section) will exhibit end effects.

In Tables 5-20, 5-21 and 5-22, the estimated mean square wait time for each section of a 20 section 200 mile highway, 20 section 400 mile highway, and 20 section 600 mile highway, respectively, is listed as a function of the section from which the estimate was taken. Also listed is the statistic t' for the test of significance between each section and section N_{SYM}. These three cases correspond to highways of 10 miles per section, 20 miles per section, and 30 miles

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*An inner section is a section adjacent to section N_{SYM}.

Table 5-20 The Estimated Mean Square Wait Time and Statistic t' for the Test of Significance Between the 10th Section and Each Section of a Twenty Section 200 Mile Highway

Incident Rate	1.5 Vehicles/hr		13.5 Vehicles/hr	
Section Number	M.S. Wait Time (hr^2)	t'	M.S. Wait Time (hr^2)	t'
1	.1158	-2.845*	.1287	-17.84*
2	.1171	1.16	.1363	- .673
3	.1172	1.25	.1366	- .672
4	.1166	.2476	.1376	.504
5	.1166	- .0635	.1391	1.643
6	.1172	2.1399	.1369	- .2608
7	.1169	1.1785	.1378	.348
8	.1168	.979	.1402	3.256*
9	.1170	2.338	.1375	.2337
10	.1165		.1372	
11	.1173		.1404	
12	.1162		.1393	
13	.1169		.1389	
14	.1179		.1380	
15	.1160		.1373	
16	.1165		.1387	
17	.1171		.1406	
18	.1171		.1396	
19	.1166		.1358	
20	.1164		.1284	

*Statistical significant at 95% level.

Table 5-21 The Estimated Mean Square Wait Time and Statistic t' for the Test of Significance Between the 10th Section and Each Section of a Twenty Section 400 Mile Highway

Incident Rate	3. Vehicles/hr		27. Vehicles/hr	
Section Number	M.S. Wait Time (hr^2)	t'	M.S. Wait Time (hr^2)	t'
1	.1517	-3.4075*	.2532	-6.784*
2	.1575	.1761	.3053	-2.730
3	.1581	.57649	.3220	-1.344
4	.1582	.077	.3281	-1.226
5	.1573	1.240	.3355	- .8066
6	.1577	.0594	.3226	.2367
7	.1591	.341	.3381	- .8761
8	.1563	1.415	.3437	.1551
9	.1571	-.7038	.3450	- .474
10	.1600		.3465	
11	.1569		.3364	
12	.1582		.3371	
13	.1602		.3451	
14	.1562		.3395	
15	.1572		.3434	
16	.1572		.3298	
17	.1593		.3239	
18	.1579		.3236	
19	.1567		.3045	
20	.1536		.2387	

*Statistically significant at 95% level.

Table 5-22 The Estimated Mean Square Wait Time and Statistic t' for the Test of Significance Between the 10th Section and Each Section of a Twenty Section 600 Mile Highway

Incident Rate	4.5 Vehicles/hr		40.5 Vehicles/hr	
Section Number	M.S. Wait Time (hr^2)	t'	M.S. Wait Time (hr^2)	t'
1	.1791	7.653*	.5918	-21.88*
2	.1946	.6025	.8784	- 7.075*
3	.1956	-.4505	1.01268	- 3.553*
4	.1945	-.7115	1.0704	- 2.43
5	.1998	1.7097	1.0399	- 1.84
6	.1975	.1804	1.0228	- 3.03*
7	.1953	-.064	1.0808	- 3.45*
8	.2007	1.494	1.0325	- 5.84*
9	.1948	1.339	1.1011	- 1.86*
10	.1968		1.1758	
11	.2006		1.1203	
12	.1969		1.0748	
13	.1997		1.0949	
14	.1973		1.1304	
15	.1939		1.1383	
16	.1965		1.0195	
17	.2013		1.0319	
18	.2001		.9842	
19	.1914		.8097	
20	.1832		.5030	

*Statistically significant at 95% level.

per section. From these tables it may be concluded that as the incident rate increases for a given section mileage, the end effect becomes more prominent, i.e. the statistic t' for the first and second section to the 10th section becomes more significant. It also may be seen that the end effect is greater as the number of miles per section is increased. The above inferences are expected since for higher incident rates and section mileage, the workload of the aid vehicles increases. In Section 5.8 the assumption of section homogeneity is made in order to determine the critical number of sections for cost-effective operation of the REVIS system. It may now be seen that since the end effects are significant, the aid vehicles stationed at the end of the highway work on the average less than an aid vehicle stationed at an inner section and therefore, the value of the critical number of sections calculated in Section 5.8 is the upper bound.

Unlike the statistical experiments performed in previous sections of this chapter (i.e. the tests of the effects of the aid vehicle speed model, the tests of the effects of the virtual vehicle speed in the hybrid parameter space, etc.), the estimated values of the mean square wait time per section used for the test of significance of the end effects have been generated from independent sets of input sequences. However, the correlated t-test must still be used since adjacent aid vehicles interact in each section and, therefore, a level of correlation exists amongst the section mean square wait times.

5.10 Summary

The major conclusions obtained in this chapter concerning aid dispatching system performance may be summarized as follows:

The most beneficial dispatching policy, i.e. the policy which yields the minimum mean square waiting time for the disabled vehicles, is the one in which the aid vehicle renders aid to the incidents in the order it encounters them. Of all the policies considered in this study, this policy is the simplest to implement and is most amenable to electronic detection systems.

On a single section of highway, the proposed electronic detection system, REVIS, employing the first encounter, first serve policy, is benefit-cost superior for rural traffic conditions and is comparable to the competing highway patrol system for heavier than usual traffic conditions. The cost structure used for comparing these systems has been developed from existing data.[1]

For a multiple sectioned highway, the REVIS system is compared to the highway patrol system for evaluating overall highway system performance and single section performance. In the former case, it was shown that the REVIS system is benefit-cost superior for all traffic conditions simulated; while for the latter case, cost-superiority is only maintained by REVIS for multiple section highways with at least 15 sections and section mileage less than 20 miles.

Appendix 5.1 Evaluation of the Incident Rate as a Function of the Average Daily Traffic

Nadan and Wiener[1] show that the average number of incidents per hour per mile, λ, may be related to the following highway parameters: the speed, V; the time headway, H_T; the number of lanes, L; the average daily traffic, ADT; and the vehicle-miles between incidents, VMBI. More precisely, it is shown that

$$\lambda = \left(1 + \frac{3600}{VH_T}\right) \frac{V(L)}{VMBI} \text{ incidents per hour per mile.} \quad (A.5\text{-}1)$$

The vehicle-miles between incidents may be determined empirically as a function of the ADT and the number of lanes. These regression curves are given in Table A.5-1. In Table A.5-2, λ is evaluated for traffic conditions ranging from light rural to very heavy urban. If the length of the highway is 40 miles, 20 in each direction, then incident rates of .3 vehicles per hour to 2.7 vehicles per hour correspond to .015 incidents per hour per mile to .135 incidents per hour per mile. From Table A.5-2 the traffic conditions generating these rates vary from heavy rural to moderate urban.

Table A.5-1 The Regression Curves of the Vehicle-Miles-Between-Incidents

Number of Lanes on Highway	Regression Curve
4	$VMBI = \frac{10^6}{5.226 + 21.637\ ADT \times 10^{-5}}$
6	$VMBI = \frac{10^6}{5.949 + 8.488\ ADT \times 10^{-5}}$
8	$VMBI = \frac{10^6}{4.8591 + 7.0623\ ADT \times 10^{-5}}$

Table A.5-2 Incident Rate per Mile vs. Highway Parameters

V (mph)	H_T (sec)	L (lanes)	ADT* (vehicles)	VMBI (vehicles/mile)	λ (vehicles/ hr/mile)	Nature of Traffic
60	1	6	259200	35778.2	.613785	Very Heavy Urban
60	2	6	129600	58998.9	.189156	Heavy Urban
60	4	6	64800	87342.1	.065948	Moderate Urban
60	8	6	32400	114954.2	.026619	Light Urban
60	15	4	11520	129557.4	.009262	Heavy Rural
60	30	4	5760	154505.	.004660	Moderate Rural
60	60	4	2880	170965.	.002808	Light Rural

$*ADT = \frac{12(3600)L}{H_T}$, where it is assumed that the headway, H_T, is sustained for twelve hours.

Appendix 5.2 The Cost Differential Between REVIS and the Highway Patrol for Heavy Traffic Conditions

From Section 5.3 the cost function for the REVIS and highway patrol system are

$$C_{REVIS} = 15000 + 10 \cdot T + 3 \cdot S, \qquad \text{(A.5-2)}$$

and

$$C_{HP} = 90000 + 2T, \qquad \text{(A.5-3)}$$

respectively. For large breakdown rates, the usage of both systems are equivalent and from Fig. 5-12, the expected annual trips, T, becomes

$$T = 13000 - \frac{10000}{3}\lambda, \qquad \text{(A.5-4)}$$

where λ is the breakdown rate. It may be easily seen that the upper limit of the expected yearly services, S, is

$$S = 8760\,\lambda. \qquad \text{(A.5-5)}$$

From Eqs. (A.5-2) through (A.5-5), the expected difference in cost, C_D, becomes

$$C_D = C_{REVIS} - C_{HP} = 29000 - 333\lambda. \qquad \text{(A.5-6)}$$

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

6.1 Conclusions

A major goal of this research was to gain those insights which enable highway engineers to design more efficient aid dispatching systems. To accomplish this goal, a queuing model and a Monte Carlo computer simulation model were developed to analyze various aid dispatching strategies. From the analysis of these models in Chapters 3 and 5, it was shown that a first encounter, first serve aid dispatching policy is more favorable than a first disabled, first serve dispatching policy. Evidence for this conclusion was based on the observation that the waiting times experienced by the disabled motorist were lowest when the aid dispatching system employed the first encounter, first serve policy.

Secondly, from the analysis of the Monte Carlo simulation model, it was shown that under low traffic volume conditions, an electronic surveillance system which employed automatic vehicle identification was operationally cost-effective when compared to the conventional highway patrolling system. The simulation analysis also illustrated that an electronic surveillance system operating on a multiple sectioned highway is superior to the equivalent highway patrol system for highways of 15 sections or more with section lengths between 10 and 20 miles.

From the above conclusions, it may be recommended that an efficient aid dispatching system should consist of: (1) an electronic detection system which employs microscopic surveillance and dispatches aid according to the first encounter, first serve policy and, (2) be operated on a multi-sectioned limited access highway system where aid vehicles are stationed at each of the section boundaries. Furthermore, the section boundaries of the highway should be defined such that the overall cost for operating the highway does not exceed the benefits derived by the motorists. For example, it may be seen in Section 5.8 that halving the section lengths only decreases the mean square waiting time by 4 minutes, while it increases the operating cost by more than $15,000 per section. The capital costs of purchasing and developing this aid dispatching system[3], depreciated over the life of the system, should not prohibitively increase the total yearly cost of the system.

Finally, it is noted that the aid dispatching models used in this study from which the above recommendations are made are simple models that do not reflect certain practical highway conditions. For example, these models assume that patrolling is regular and not a function of the congestion of the roadway, and that all disabled vehicles may be returned to the traffic flow within 15 minutes. For rural highways, these assumptions are reasonable. For urban highways, they are questionable. An obvious solution to these problems would be to design the highway with exclusive aid vehicle lanes for easy removal of all vehicle incidents from the roadway.

6.2 Suggestions for Further Research

This research has focused on obtaining solutions for aid dispatch problems by applying the theory of queues and Monte Carlo simulation. In this chapter, the following suggestions are proposed for further research in these and other related areas.

In Chapters 2 and 3, the theory of queues was applied to solve the first encounter, first serve highway patrol problem. In particular, the theory of queues with periodic service and constant changeover time[1] was exploited to calculate the average wait time experienced by a disabled motorist serviced by a patrol vehicle employing the first encounter, first serve service policy. There it was shown that the highway patrol problem is isomorphic to an infinite periodic service queue (i.e. the number of queues in the periodic service system is infinite). An algorithm programmable on a digital computer was then formulated for calculating the average wait time for a periodic service system with an arbitrary number of queues, M. The value of the average wait time of the highway patrol problem was, therefore, taken as the value of the average wait time of the periodic service queue with the largest value of M which was capable of being stored by the computer.

A more expeditious and interesting approach for calculating the average wait time of the highway patrol problem is to solve for the wait time probability distribution of the highway problem directly. This may be accomplished by taking the limit of the wait time distribution of the periodic service queue as M approaches infinity. This limit distribution is exactly the wait time distribution of the highway patrol problem. This approach yields the exact solution of the highway patrol problem and, therefore, provides an accurate calculation of the average wait time.

In Chapter 3, it was shown that the probability distribution of the time between detections is no longer exponential when using an imperfect detection system. It is suggested that the results of G/G/1[2] queuing theory be applied to solve the first disabled, first serve highway patrol problem with imperfect detection. Since the probability distribution of the time between detections is a function of the average time to detect an incident (see Section 3.4), the solution for the average waiting time experienced by a disabled motorist for this patrol problem will provide a method for evaluating the effects of an imperfect detection system.

In Chapter 4, the theory of window closing was applied for obtaining a criterion for terminating a Monte Carlo simulation run. In particular, it was determined that the expected value of the smoothed estimator of the sample spectrum $\bar{\bar{\Gamma}}_{xx}(f)$ of a process, $\{X_t\}$, is given by Eq. (4-22).

$$E[\bar{\bar{\Gamma}}_{xx}(f)] \cong \Gamma_{xx}(f) + B_w(f) - \mathrm{Var}\,\bar{X}\; W(f),$$

where $\Gamma_{xx}(f)$ is the spectrum of the process, $B_w(f)$ is the bias term due to the window, $Var\bar{X}$ is the variance of the estimator of the sample mean of the process, and $W(f)$ is the spectral window representation. The term $Var\bar{X}\,W(f)$ in the above equation is the bias due to estimating the mean of the process. It was observed that this term contributed to the degradation of the spectral analysis. When the sample size increases, the bias due to the term $Var\bar{X}\,W(f)$ diminishes (i.e. the $Var\bar{X}$ decreases), and varying the spectral window size alters the bias and variance of $\bar{\bar{\Gamma}}_{xx}(f)$. It is, therefore, suggested that more research be undertaken to determine what are the conditions, if any, for ignoring the bias term, $Var\bar{X}\,W(f)$. A useful refinement to the window closing procedures as applied to determining the stopping conditions for Monte Carlo simulations may be established if the conditions for $|Var\bar{X}\,W(f)| << |B_w(f)|$ are obtained.

In Chapter 5, it was concluded that the most beneficial aid dispatch policy tested was the first encounter, first serve highway policy. It may be conjectured that the assumptions made for the modeling of the physical phenomena of the highway aid dispatch problem (i.e. the vehicle breakdown process, the detection process, the aid vehicle speed model, and the service process) may favorably bias the results to produce the above conclusion. For example, it was assumed that vehicle incidents occur uniformly along the roadway. However, it is questionable whether the first encounter, first serve dispatch policy is still most beneficial when the majority of vehicle incidents occur in a specific segment of the roadway. Similar questions are applicable in the evaluation of the first encounter, first serve policy when the other assumptions of the assumed physical models are changed. Therefore, it is deemed worthwhile to reevaluate the various aid dispatch policies using different assumed models.

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APPENDIX

A.1 Sample Calculation of the Statistic t'

The Effects of Speed Model on the Mean Square Wait Times

Aid Dispatch Policy: Highway Patrol   Breakdown Rate: .3 veh/hr

Speed Model

Constant	Piecewise Linear	Δ_i
.4250	.4395	-.0145
.4336	.4525	-.0189
.4432	.4475	-.0043
.4407	.4411	-.0004
.4294	.4592	-.0298

$$\bar{\Delta} = \frac{1}{5}\sum_{i=1}^{5} \Delta_i = -.01358$$

$$\bar{S}^2 = \frac{1}{4}(\Delta_i - \bar{\Delta})^2 = .011748$$

$$t' = -2.5847$$

A.2 Single Section REVIS - Hybrid Policy

Events

BREAKDOWN	-	The time at which a vehicle breakdown occurs. At this time the time at which the highway detects this incident is calculated and the event DETECTION is scheduled.
DETECTION	-	The time at which an incident is detected by the highway system. At this time an aid vehicle will be dispatched to service this incident. The time at which the event THRESHOLD will occur for this vehicle is scheduled.
T-ACTUAL ARRIVAL	-	The time at which an aid vehicle arrives at the actual position of an incident. At this time the activity service begins and the event DEPARTURE is scheduled. The event THRESHOLD scheduled for this incident is canceled.
T-VIRTUAL ARRIVAL	-	The time at which an aid vehicle arrives at the virtual position of an incident. At this time the event D-ACTUAL ARRIVAL is scheduled for this incident.
F-VIRTUAL ARRIVAL	-	The time at which an incident's virtual position arrives at the position of an aid vehicle which is in the process of servicing another incident.
D-VIRTUAL ARRIVAL	-	The time at which an aid vehicle arrives at the virtual position of an incident while traveling to the actual position of another incident which has effected a T,F or D-VIRTUAL ARRIVAL.
D-ACTUAL ARRIVAL	-	The time at which an aid vehicle arrives at the actual position of an incident. This event will only occur if a T,D, or F-VIRTUAL ARRIVAL has previously occcurred for this aid vehicle-incident pair.
THRESHOLD	-	The time at which an incident has been waiting a preset interval of time. At this time the incident's virtual position will begin to propagate upstream.

A.2 Single Section REVIS - Hybrid Policy

(Continued)

DEPARTURE	-	The time at which an aid vehicle terminates service. At this time the event D-ACTUAL ARRIVAL may be scheduled for every incident which caused a F-VIRTUAL ARRIVAL to occur for this aid vehicle.
RETURN TO GARAGE	-	The time at which an aid vehicle returns to the garage. This event only occurs when the highway is devoid of incident or when there are a sufficient number of aid vehicles to service the remaining incidents.

Entities and Their Attributes

Entity		Attributes
DISABLED VEHICLE	-	Time of breakdown Actual position of breakdown Virtual position of breakdown Time of detection Time of threshold Time required for service Virtual vehicle speed Vehicle mode
AID VEHICLE	-	Highway position Speed Service mode Time of departure Time of D-ACTUAL ARRIVAL Ordered list of incidents which have effected either A, T or F-VIRTUAL ARRIVAL
HIGHWAY	-	Length Number of aid vehicles Number of detectors Lists of the aid vehicles in each service mode category Lists of the disabled vehicles in each vehicle mode category

Vehicle Modes

UNDETECTED	-	The vehicle is broken down but is not detected by the highway system.
DETECTED	-	The disabled vehicle is waiting for service.
BEYOND THRESHOLD	-	The disabled vehicle is waiting for service and is past threshold.
DEMANDING	-	The disabled vehicle is waiting for service and has effected either a T, D or F-VIRTUAL ARRIVAL.
BEING FIXED	-	The disabled vehicle is being serviced by an aid vehicle.

Service Modes

TRAVELING	-	The aid vehicle is traveling either to an incident or back to the garage.
FIXING	-	The aid vehicle is servicing an incident.
DEMANDED	-	The aid vehicle is traveling to an incident which has effected a T, D or F-VIRTUAL ARRIVAL.
GARAGED	-	The aid vehicle is awaiting to be dispatched from the garage.

A.3 Multiple Section - REVIS

Events

BREAKDOWN - The time at which a vehicle breakdown occurs. At this time the time at which the highway detects this incident is calculated and the event DETECTION is scheduled.

DETECTION - The time at which an incident is detected by the highway system. At this time an aid vehicle will be dispatched to service this incident.

ARRIVAL - The time at which an aid vehicle arrives to service an incident. At this time the event DEPARTURE is scheduled.

DEPARTURE - The time at which an aid vehicle terminates service.

SWITCHOVER - The time at which an aid vehicle reaches a crossover point. If the aid vehicle's assigned garage is located at this crossover point, the aid vehicle may return to the garage. This will only occur if the sections the aid vehicle services are devoid of incidents requiring aid.

Entities and Their Attributes

Entity		Attributes
DISABLED VEHICLE	-	Time of breakdown Position of breakdown Time required for service Vehicle mode
AID VEHICLE	-	Highway position Speed Service mode Time of departure
HIGHWAY	-	Length Number of sections Number of detectors Lists of the aid vehicles in each service mode category Lists of the disabled vehicles in each vehicle mode category

Vehicle Modes

UNDETECTED	-	The vehicle is broken down but not detected by the highway system.
DETECTED	-	The disabled vehicle is waiting for service.
BEING FIXED	-	The disabled vehicle is being serviced by an aid vehicle.

Service Modes

TRAVELING	-	The aid vehicle is cruising the highway.
FIXING	-	The aid vehicle is servicing an incident.
GARAGED	-	The aid vehicle is awaiting to be dispatched from the garage.

A.4 Highway Patrol

Events

BREAKDOWN	-	The time at which a vehicle breakdown occurs.
ARRIVAL	-	The time at which a patrol vehicle arrives at the position of an incident. At this time the activity service begins and the event DEPARTURE is scheduled.
DEPARTURE	-	The time at which a patrol vehicle terminates service.

Entities and Their Attributes

Entity		Attributes
DISABLED VEHICLE	-	Time of breakdown Position of breakdown Time required for service Vehicle mode
PATROL VEHICLE	-	Highway position Speed Service mode Time of departure
HIGHWAY	-	Length Number of patrol vehicles Lists of the patrol vehicles in each service mode category Lists of the disabled vehicles in each vehicle mode category

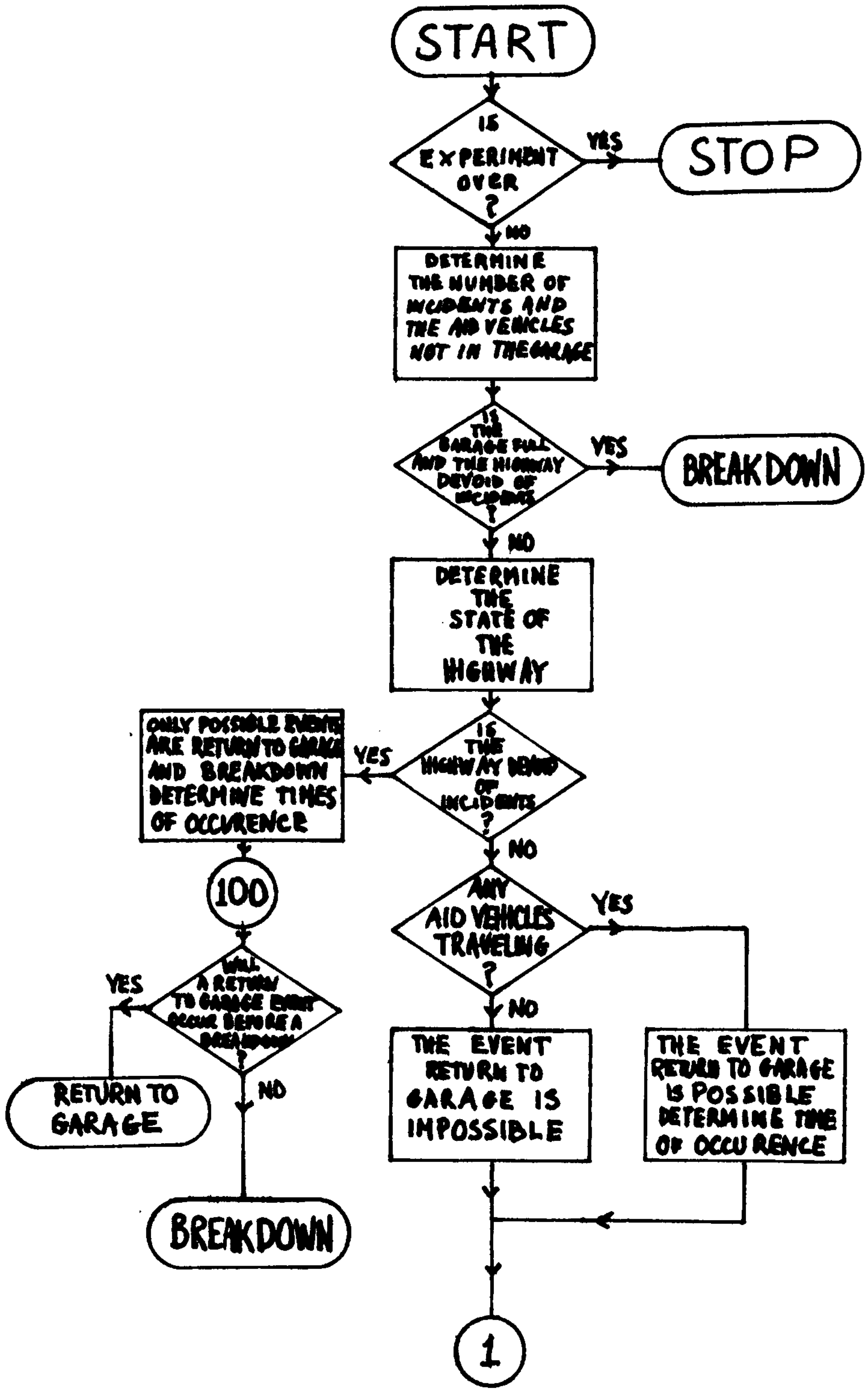
Vehicle Modes

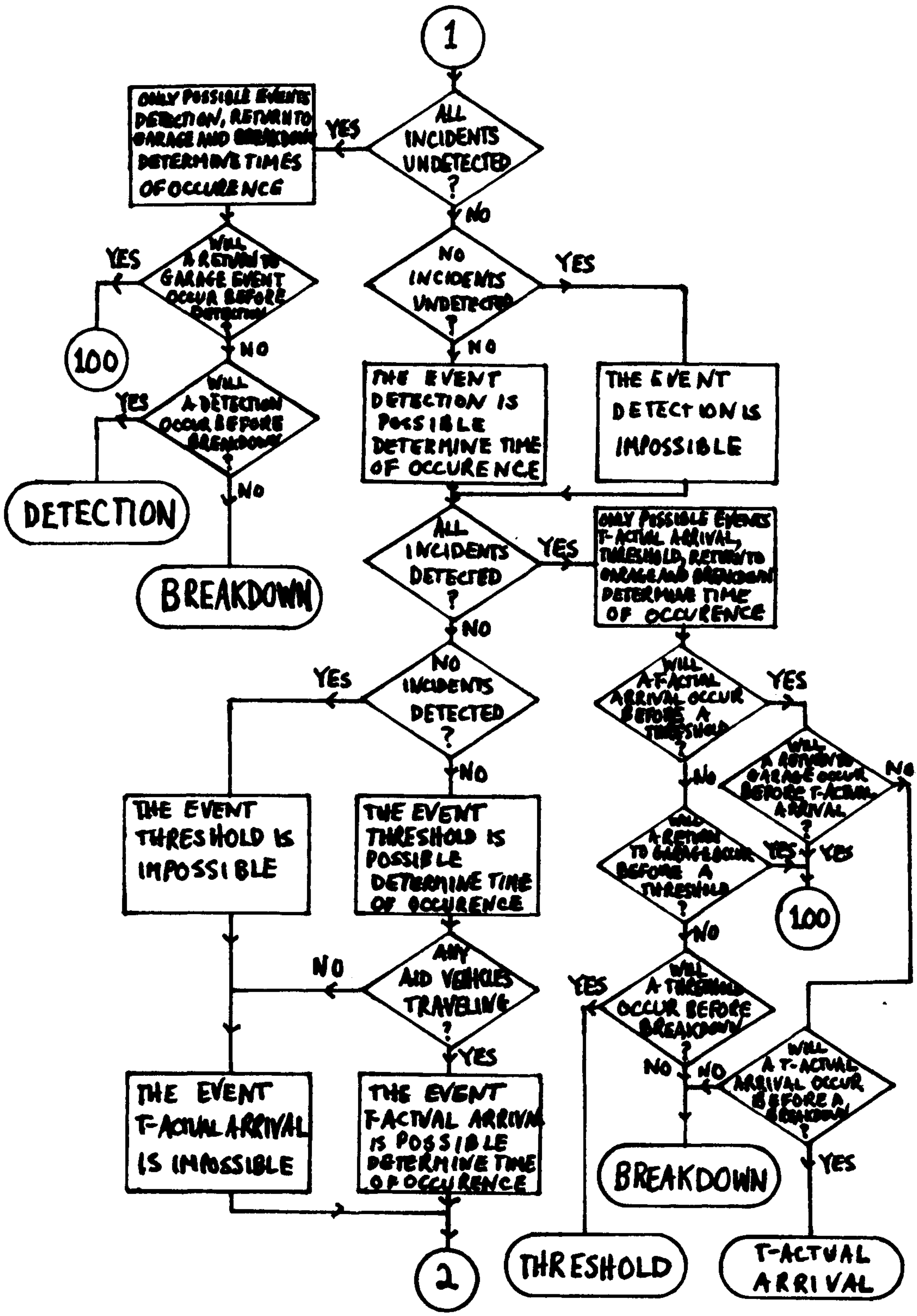
DISABLED	-	The vehicle is disabled and waiting for service.
BEING FIXED	-	The vehicle is being serviced by a patrol vehicle.

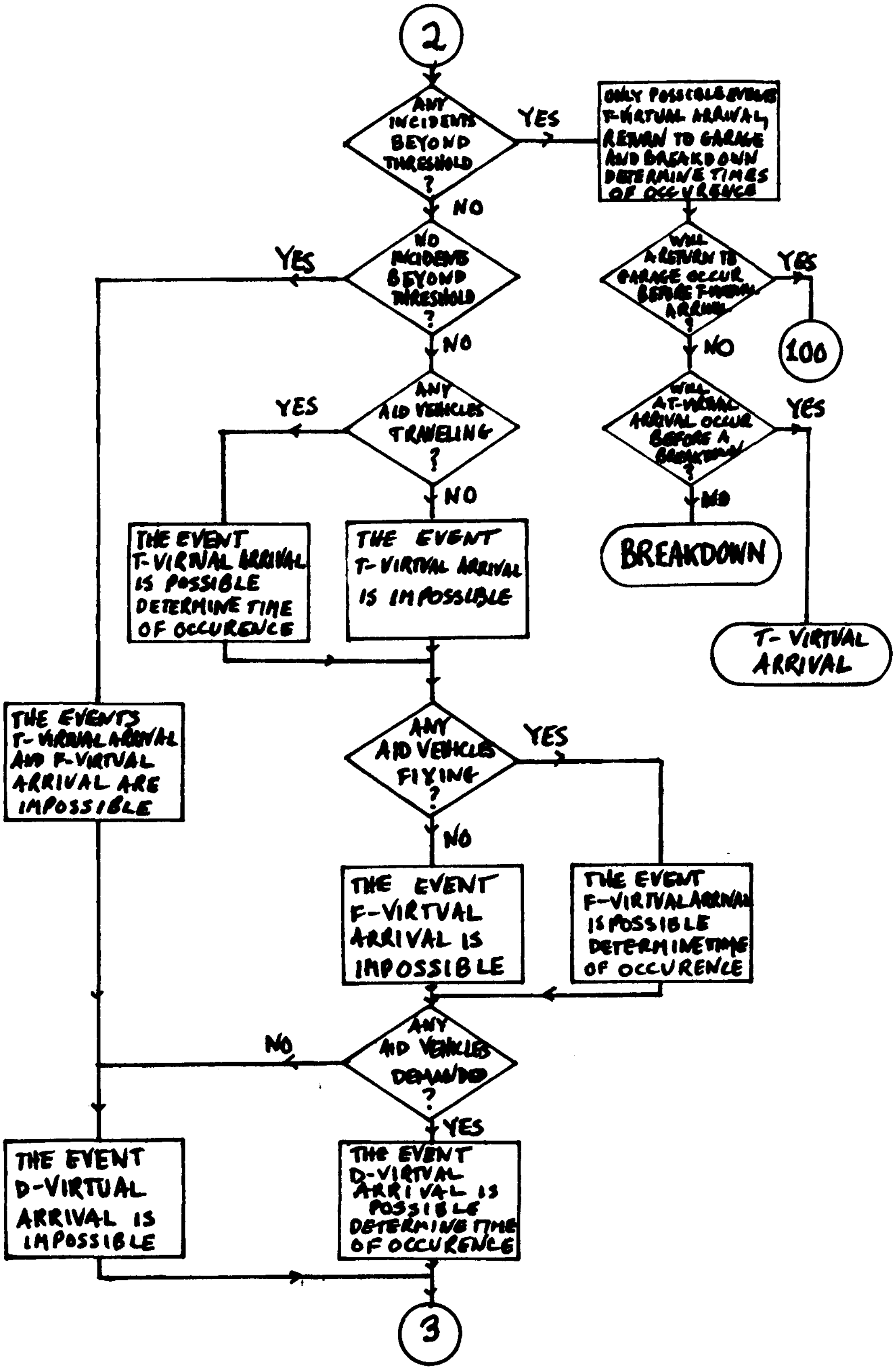
Service Modes

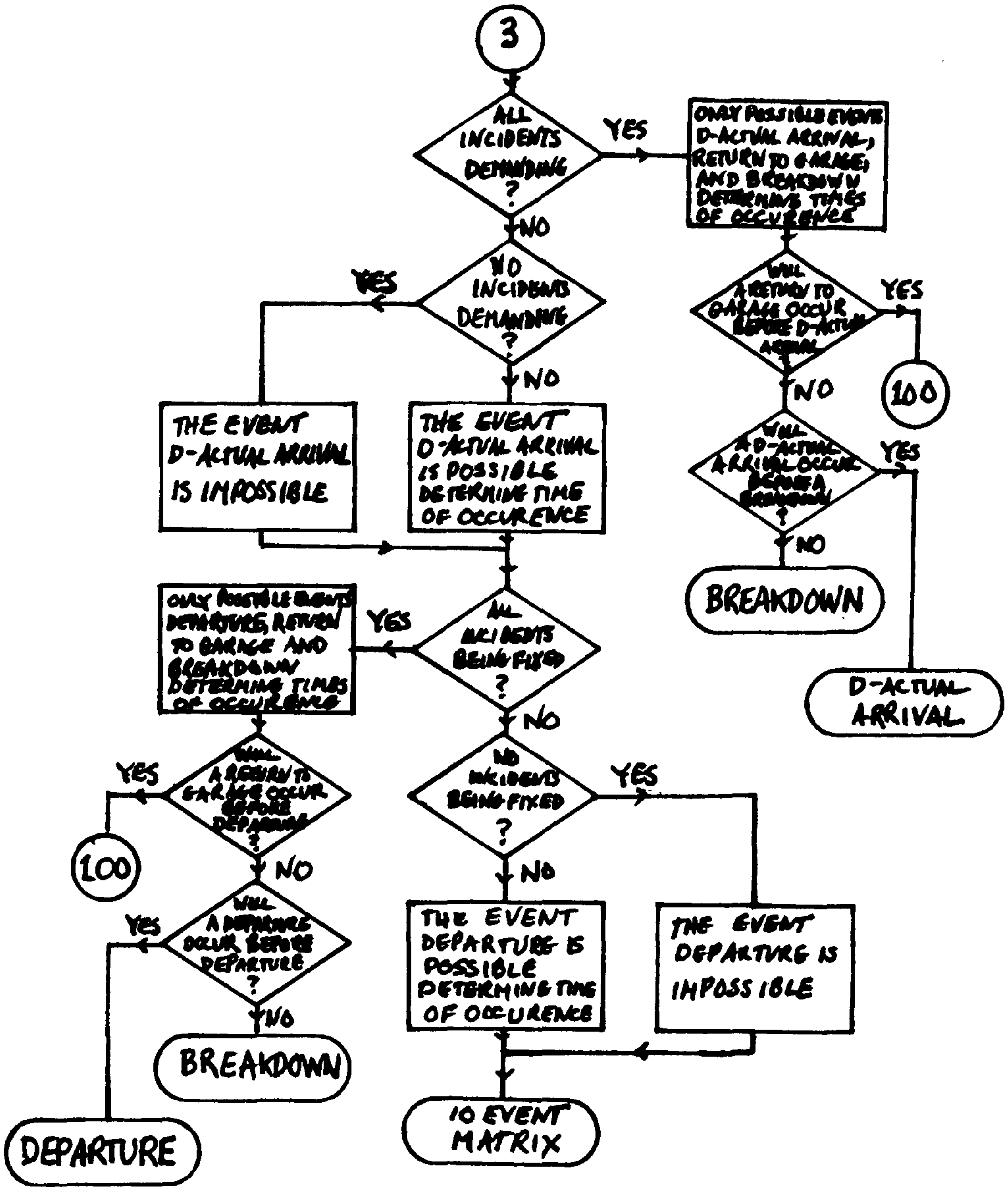
TRAVELING	-	The patrol vehicle is cruising the highway.
FIXING	-	The patrol vehicle is servicing an incident.

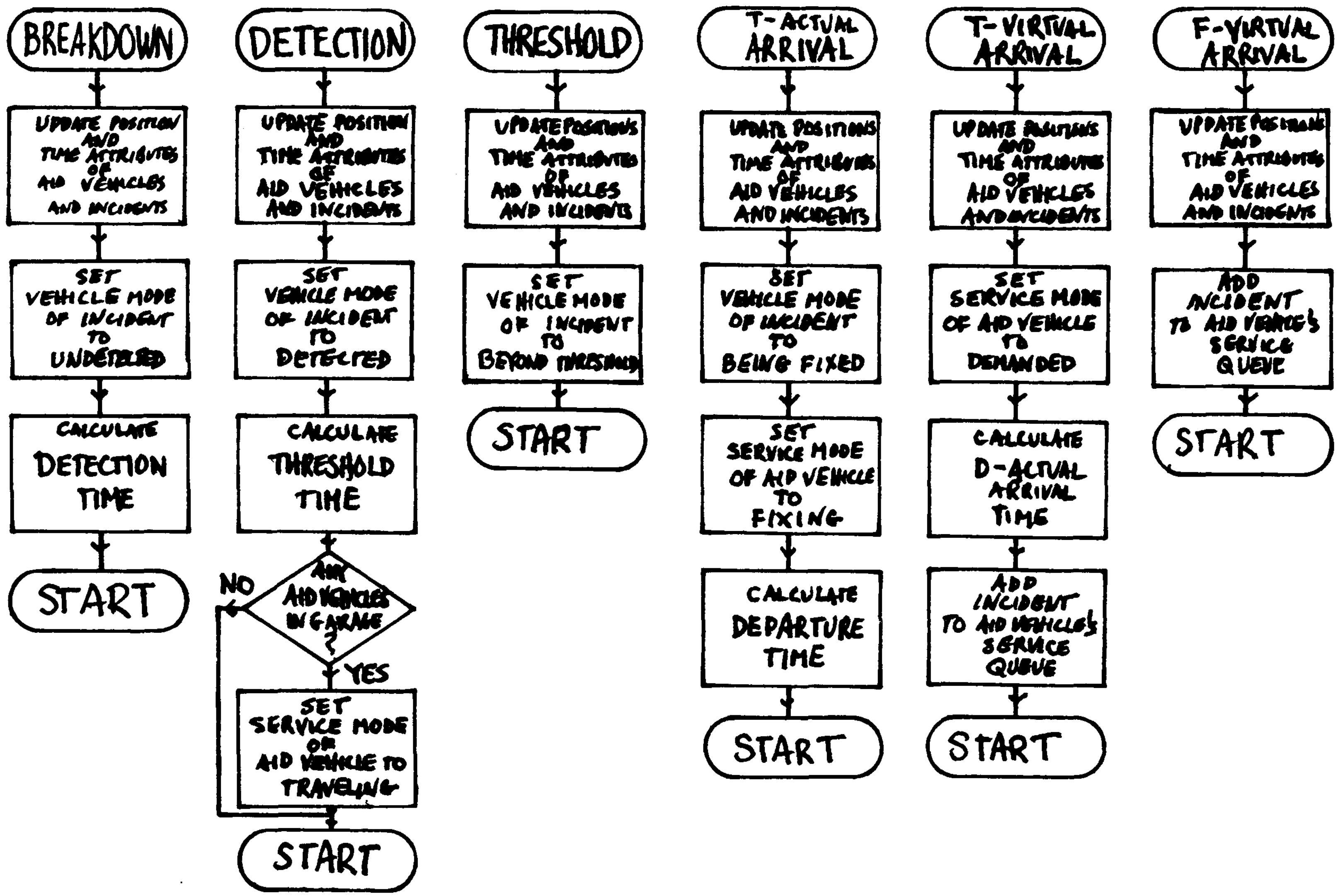
A.5 Flowchart of the Highway Patrol and REVIS Single Section Monte Carlo Simulation Program

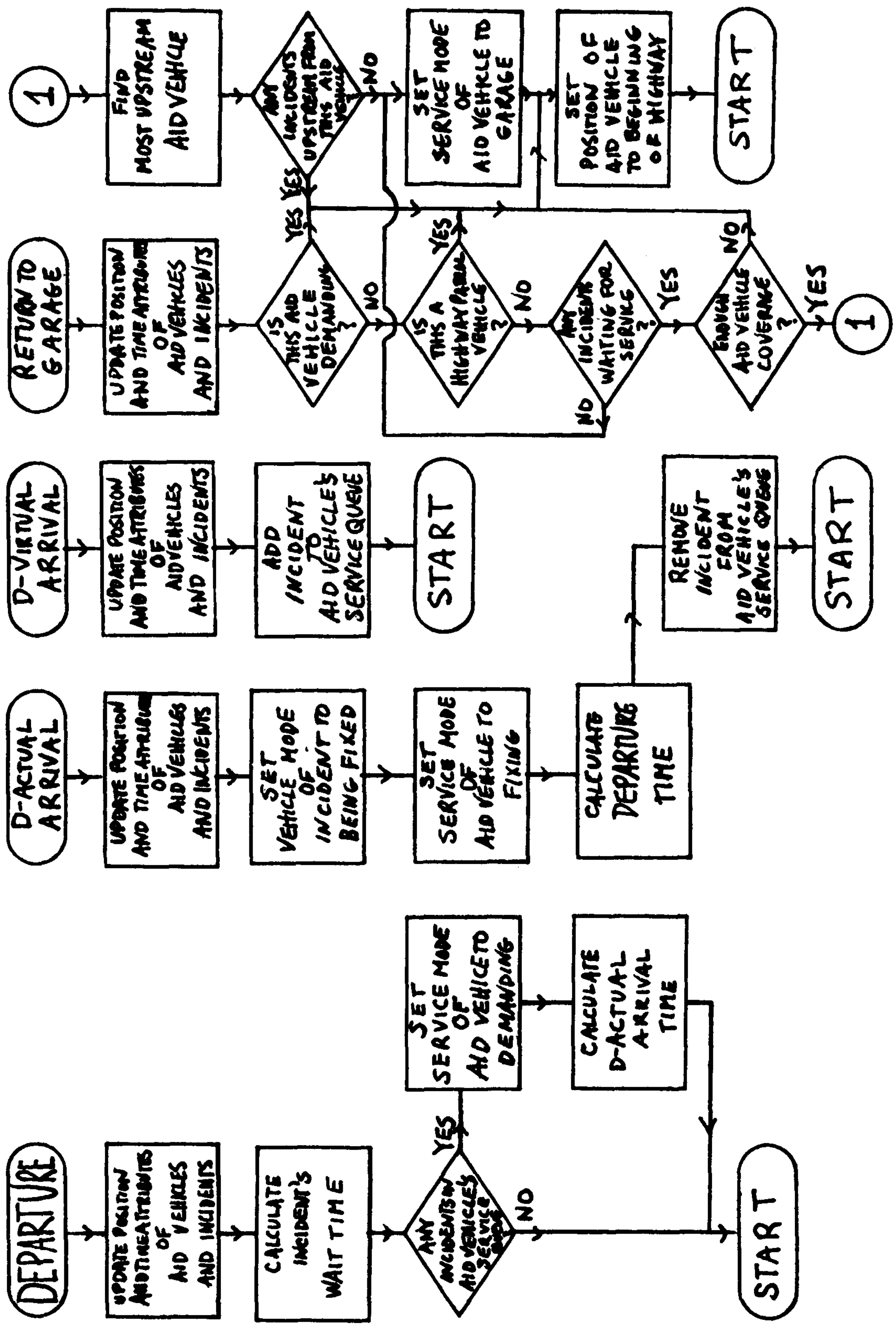

START
IS EXPERIMENT OVER ?
YES
STOP
NO
DETERMINE THE NUMBER OF INCIDENTS AND THE AID VEHICLES NOT IN THE GARAGE
IS THE GARAGE FULL AND THE HIGHWAY DEVOID OF INCIDENTS ?
YES
BREAKDOWN
NO
DETERMINE THE STATE OF THE HIGHWAY
IS THE HIGHWAY DEVOID OF INCIDENTS ?
YES
ONLY POSSIBLE EVENTS ARE RETURN TO GARAGE AND BREAKDOWN DETERMINE TIMES OF OCCURENCE
100
WILL A RETURN TO GARAGE OCCUR BEFORE A ?
YES
RETURN TO GARAGE
NO
BREAKDOWN
NO
ANY AID VEHICLES TRAVELING ?
YES
NO
THE EVENT RETURN TO GARAGE IS IMPOSSIBLE
THE EVENT RETURN TO GARAGE IS POSSIBLE DETERMINE TIME OF OCCURENCE
1


1
ALL INCIDENTS UNDETECTED ?
YES
NO
DETERMINE TIMES OF OCCURENCE
NO INCIDENTS UNDETECTED ?
YES
NO
100
WILL A DETECTION OCCUR BEFORE BREAKDOWN
YES
NO
DETECTION
BREAKDOWN
THE EVENT DETECTION IS POSSIBLE DETERMINE TIME OF OCCURENCE
THE EVENT DETECTION IS IMPOSSIBLE
ALL INCIDENTS DETECTED ?
YES
NO
DETERMINE TIME OF OCCURENCE
NO INCIDENTS DETECTED ?
YES
NO
THE EVENT THRESHOLD IS IMPOSSIBLE
THE EVENT THRESHOLD IS POSSIBLE DETERMINE TIME OF OCCURENCE
ANY AID VEHICLES TRAVELING ?
NO
YES
THE EVENT T-ACTUAL ARRIVAL IS IMPOSSIBLE
THE EVENT T-ACTUAL ARRIVAL IS POSSIBLE DETERMINE TIME OF OCCURENCE
2
WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A BREAKDOWN ?
BREAKDOWN
THRESHOLD
T-ACTUAL ARRIVAL


2
ANY INCIDENTS BEYOND THRESHOLD ?
YES
ONLY POSSIBLE EVENTS F-VIRTUAL ARRIVAL, RETURN TO GARAGE AND BREAKDOWN DETERMINE TIMES OF OCCURENCE
NO
NO INCIDENTS BEYOND THRESHOLD ?
YES
WILL A RETURN TO GARAGE OCCUR BEFORE F-VIRTUAL ARRIVAL ?
YES
100
NO
ANY AID VEHICLES TRAVELING ?
YES
WILL AT-VIRTUAL ARRIVAL OCCUR BEFORE A BREAKDOWN ?
YES
NO
THE EVENT T-VIRTUAL ARRIVAL IS POSSIBLE DETERMINE TIME OF OCCURENCE
THE EVENT T-VIRTUAL ARRIVAL IS IMPOSSIBLE
BREAKDOWN
T-VIRTUAL ARRIVAL
THE EVENTS T-VIRTUAL ARRIVAL AND F-VIRTUAL ARRIVAL ARE IMPOSSIBLE
ANY AID VEHICLES FIXING ?
YES
NO
THE EVENT F-VIRTUAL ARRIVAL IS IMPOSSIBLE
THE EVENT F-VIRTUAL ARRIVAL IS POSSIBLE DETERMINE TIME OF OCCURENCE
ANY AID VEHICLES DEMANDED ?
NO
YES
THE EVENT D-VIRTUAL ARRIVAL IS IMPOSSIBLE
THE EVENT D-VIRTUAL ARRIVAL IS POSSIBLE DETERMINE TIME OF OCCURENCE
3


3
ALL INCIDENTS DEMANDING ?
YES
ONLY POSSIBLE EVENTS D-ACTUAL ARRIVAL, RETURN TO GARAGE, AND BREAKDOWN DETERMINE TIMES OF OCCURENCE
NO
NO INCIDENTS DEMANDING ?
YES
WILL A RETURN TO GARAGE OCCUR BEFORE D-ACTUAL ARRIVAL
YES
100
NO
THE EVENT D-ACTUAL ARRIVAL IS IMPOSSIBLE
THE EVENT D-ACTUAL ARRIVAL IS POSSIBLE DETERMINE TIME OF OCCURENCE
YES
NO
BREAKDOWN
ALL INCIDENTS BEING FIXED ?
YES
ONLY POSSIBLE EVENTS DEPARTURE, RETURN TO GARAGE AND BREAKDOWN DETERMINE TIMES OF OCCURENCE
D-ACTUAL ARRIVAL
NO
NO INCIDENTS BEING FIXED ?
YES
WILL A RETURN TO GARAGE OCCUR BEFORE DEPARTURE ?
YES
100
NO
NO
WILL A DEPARTURE OCCUR BEFORE DEPARTURE ?
YES
THE EVENT DEPARTURE IS POSSIBLE DETERMINE TIME OF OCCURENCE
THE EVENT DEPARTURE IS IMPOSSIBLE
NO
BREAKDOWN
10 EVENT MATRIX
DEPARTURE


BREAKDOWN
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET VEHICLE MODE OF INCIDENT TO UNDETECTED
CALCULATE DETECTION TIME
START
DETECTION
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET VEHICLE MODE OF INCIDENT TO DETECTED
CALCULATE THRESHOLD TIME
ARE AID VEHICLES IN GARAGE ?
NO
YES
SET SERVICE MODE OF AID VEHICLE TO TRAVELING
START
THRESHOLD
UPDATE POSITIONS AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET VEHICLE MODE OF INCIDENT TO BEYOND THRESHOLD
START
T-ACTUAL ARRIVAL
UPDATE POSITIONS AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET VEHICLE MODE OF INCIDENT TO BEING FIXED
SET SERVICE MODE OF AID VEHICLE TO FIXING
CALCULATE DEPARTURE TIME
START
T-VIRTUAL ARRIVAL
UPDATE POSITIONS AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET SERVICE MODE OF AID VEHICLE TO DEMANDED
CALCULATE D-ACTUAL ARRIVAL TIME
ADD INCIDENT TO AID VEHICLE'S SERVICE QUEUE
START
F-VIRTUAL ARRIVAL
UPDATE POSITIONS AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
ADD INCIDENT TO AID VEHICLE'S SERVICE QUEUE
START


DEPARTURE
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
CALCULATE INCIDENT'S WAIT TIME
ANY INCIDENTS ON AID VEHICLE'S SERVICE QUEUE
YES
NO
SET SERVICE MODE OF AID VEHICLE TO DEMANDING
CALCULATE D-ACTUAL ARRIVAL TIME
START
D-ACTUAL ARRIVAL
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
SET VEHICLE MODE OF INCIDENT TO BEING FIXED
SET SERVICE MODE OF AID VEHICLE TO FIXING
CALCULATE DEPARTURE TIME
REMOVE INCIDENT FROM AID VEHICLE'S SERVICE QUEUE
START
D-VIRTUAL ARRIVAL
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
ADD INCIDENT TO AID VEHICLE'S SERVICE QUEUE
START
RETURN TO GARAGE
UPDATE POSITION AND TIME ATTRIBUTES OF AID VEHICLES AND INCIDENTS
IS THIS AID VEHICLE DEMANDING ?
IS THIS A HIGHWAY PATROL VEHICLE ?
ANY INCIDENTS WAITING FOR SERVICE ?
ENOUGH AID VEHICLE COVERAGE ?
YES
NO
1
FIND MOST UPSTREAM AID VEHICLE
ANY INCIDENTS UPSTREAM FROM THIS AID VEHICLE
SET SERVICE MODE OF AID VEHICLE TO GARAGE
SET POSITION OF AID VEHICLE TO BEGINNING OF HIGHWAY
START

A.6 Listing of the Highway Patrol and REVIS Single Section Monte Carlo Simulation Program

Subroutine		Description
SIML	-	The body of the simulation program which includes the Section I and Section II logic.
DITM and DITM3	-	The general purpose routines used by SIML for determining which incident-aid vehicle pair is involved in a particular next possible event.
LAGT	-	The routine used by SIML to determine the time at which an incident will be detected.
UPDATE	-	The routine used by SIML to update the actual positions of the aid vehicles and the virtual positions of the disabled vehicles.
VELT and VELV	-	The routines used by SIML to calculate the speeds of the aid vehicles and the speeds of the disabled vehicles prior to break-down.
QADD and QREMV	-	The routines used by SIML for maintaining the queue of incidents attributed to each aid vehicle.
SCRIBE	-	The routine for printing the output report for each event processed by the simulation program.

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0001          SUBROUTINE SIML(LAMDA,TF,D,DESP,THRT,VVV,ITR,ITRR,ITRS,IVEND,IX,WT
             1M,WTMS,A,WTM1,WTMS1,WMAX,W81,W82,W83,W91,W92,W93,RES,TIME)
0002          DIMENSIONVBT(50),VDTT(50),VABP(50),VVBP(50),JV1(50),JV2(50),JV3(50
             1),JV4(50),JV5(50),JV23(50),TP(10),TADT(10),JTT(10),JTF(10),JTD(10)
             2,JTNG(10),ZERO(2),IONE(2),JTRR(10),JV34(50),JRTT(10),JTDT(10)
0003          COMMON TQ(51,10)
0004          INTEGER VM(50),VID(50),TM(10),TQ,TRUCK(2),VEH(2),VCCUNT(10),GCOUNT
             1(10)
0005          REAL LAGT
0006          REAL LAMDA
0007          DOUBLE PRECISION VBT,VDTT,VABP,TP,TADT,CTL,CT,RTGC,RTGT,DETT,VVBP,
             1THREST,TAAD,TAAT,TVAT,TVAD,DAAD,DAAT,FVAT,FVAD,DEPT,WT,ZERO,D,DUM,
             3UST,DVAT,DVAD,DUMM,WTM,WTMS,DETD,A
0008          TWT=0.0
0009          TWT2=0.0
0010          CT=-1.0
0011          VEQ=VELV(50,D)
0012          IVHO=50
0013          IVHO1=IVHO+1
0014          IVB=50
0015          IVB2=IVB-1
        C 0 NOT SERVICING AND DETECTING
        C 1 SERVICING AND NOT DETECTING
        C 2 SERVICING AND DETECTING
0016          IVS=0
0017          DUM=0.0
0018          IDUM=0
0019          ZERO(1)=0.0
0020          IONE(1)=1
0021          A=0.
0022          DUMS=9999.9999
0023          IREF1=10000100+ITR
0024          IREF2=IREF1+100-ITR+ITRR+1000*ITRS
0025          IF((VVV.GT.DUMS).AND.(THRT.GT.DUMS)) GC TO 9991
0026          IF(VVV.GT.DUMS) GO TO 9111
0027          IF(THRT.GT.DUMS) GO TO 9112
0028          WRITE(6,4401) IREF1,THRT,TF,LAMDA,IREF2,VVV ,D,DESP
0029          GO TO 9113
0030     9991 WRITE(6,4401) IREF1,DUMS,TF,LAMDA,IREF2,DUMS,D,DESF
0031          GO TO 9113
0032     9111 WRITE(6,4401) IREF1,THRT,TF,LAMDA,IREF2,DUMS,D,DESF
0033          GO TO 9113
0034     9112 WRITE(6,4401) IREF1,DUMS,TF,LAMDA,IREF2,VVV ,D,DESF
0035     9113 CONTINUE
0036     4401 FORMAT(' ',2(I9,F10.4,2F8.4,2X))
        CINITIALIZATION OF TRUCK ATTRIBUTES
0037          DO 9100 I=1,ITR
0038          VCOUNT(I)=0
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            GCOUNT(I)=0
            TP(I)=0.0
            TM(I)=0
            IF(I.LE.ITRR)TM(I)=1
            IF(I.LE.ITRR) TP(I)=FLOAT(I-1)/FLOAT(ITRR)*D
            IF((ITRS.NE.1).AND.(I.LE.ITRR)) JTRR(I)=I
            DO 9100 J=1,IVHC1
       9100 TQ(J,I)=0
      C INITIALIZATION OF VEHICLE ATTRIBUTES
            DO 9200 I=1,IVB
            CALL RANDU(IX,IY,R)
            IX=IY
            IF(I.EQ.1) GO TO 9201
            VBT(I)=VBT(I-1)-ALOG(R)/LAMDA
            GO TO 9202
       9201 VBT(1)=0.0
       9202 CALL RANDU(IX,IY,R)
            IX=IY
            VABP(I)=R*D
            VVBP(I)=VABP(I)
            VM(I)=0
            VDTT(I)=0.0
       9200 VID(I)=I
      C
      C START OF EXPERIMENT
      C SECTION 1 - DETERMINATION OF NEXT EVENT
      C
      C IS THE EXPERIMENT OVER
       9999 IF(IVS .EQ. IVEND) GO TO 1999
      C
      C DETERMINE HOW MANY VEHICLES ARE ON THE HIGHWAY AND HOW MANY TRUCKS ARE IN THE
      C GARAGE
            ITNG=0
            IRTT=0
            ITT=0
            ITF=0
            ITD=0
            ITDT=0
            IVH=0
            IV1=0
            IV2=0
            IV3=0
            IV4=0
            IV5=0
            IV23=0
            IV34=0
            DO 1001 I=1,IVB
            IF(VBT(I).GT.CT) GO TO 1002
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      1001 IVH=IVH+1
      1002 DO 1003 I=1,ITR
           IF(TM(I).EQ.0) GO TO 1003
           IF((I.LE.ITRR).AND.(ITRS.EQ.0)) GO TO 1003
           ITNG=ITNG+1
           JTNG(ITNG)=I
      1003 CONTINUE
C
C UPDATE VELOCITY
           VT=VELT(IVH,D)
           VV=VELV(IVH,D)
C
C IS THE GARAGE FULL AND THE HYWAY EMPTY
           IF((IVH.EQ.0).AND.(ITNG.EQ.0)) GO TO 10
C
C DETERMINATION OF THE STATE OF THE HIGHWAY
C
C THE STATE OF THE VEHICLES
           IF(IVH.EQ.0) GO TO 1004
           DO 1005 I=1,IVH
           IF(VM(I).EQ.1) GO TO 1006
           IF(VM(I).EQ.2) GO TO 1007
           IF(VM(I).EQ.3) GO TO 1008
           IF(VM(I).EQ.4) GO TO 1009
           IV5=IV5+1
           JV5(IV5)=I
           GO TO 1005
      1006 IV1=IV1+1
           JV1(IV1)=I
           GO TO 1005
      1007 IV2=IV2+1
           IV23=IV23+1
           JV2(IV2)=I
           JV23(IV23)=I
           GO TO 1005
      1008 IV3=IV3+1
           IV23=IV23+1
           IV34=IV34+1
           JV3(IV3)=I
           JV23(IV23)=I
           JV34(IV34)=I
           GO TO 1005
      1009 IV4=IV4+1
           IV34=IV34+1
           JV4(IV4)=I
           JV34(IV34)=I
      1005 CONTINUE
C
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              C THE STATE OF THE TRUCKS
0117           1004 IF(ITNG.EQ.0) GO TO 1010
0118                DO 1014 I=1,ITNG
0119                IF((ITRS.EQ.0).AND.(JTNG(I).LE.ITRR)) GO TC 1014
0120                IF(TM(JTNG(I)).EQ.1) GO TO 1012
0121                IF(TM(JTNG(I)).EQ.2) GO TO 1013
0122                ITD=ITD+1
0123                ITDT=ITDT+1
0124                JTD(ITD)=JTNG(I)
0125                JTDT(ITDT)=JTNG(I)
0126                GO TO 1014
0127           1012 ITT=ITT+1
0128                ITDT=ITDT+1
0129                JTT(ITT)=JTNG(I)
0130                JTDT(ITDT)=JTNG(I)
0131                IF((ITRS.NE.2).OR.(JTNG(I).GT.ITRR)) GO TO 1014
0132                IRTT=IRTT+1
0133                JRTT(IRTT)=JTNG(I)
0134                GO TO 1014
0135           1013 ITF=ITF+1
0136                JTF(ITF)=JTNG(I)
0137           1014 CONTINUE
              C
              C 1010
              C IS THE HIGHWAY EMPTY
0138           1010 IF(IVH.EQ.0) GO TO 1015
              C NO-ANY TRUCKS TRAVELING
0139                IF(ITDT.NE.0) GO TO 1016
              C NO-THE EVENT RETURN TO GARAGE IS IMPOSSIBLE
0140           1018 RTGD=1.0E+75
0141                RTGT=1.0E+75
0142                GO TO 1017
              C 1016
              C     CALL THE ROUTINE WHICH DETERMINES THE MOST DCWNSTREAM TRUCK WHICH RETURNS
              C TO THE  GARAGE
0143           1016 CALL DITM(1,IONE,1,ZERO,ITDT,JTDT,ITR,TP,D,RTGC,JUNK,JTRTG)
0144                RTGT=CT+RTGD/VT
              C
              C 1017
              C ARE ALL VEHICLES ON THE HYWAY TYPE 1
0145           1017 IF(IV1.EQ.IVH) GO TO 1020
              C NO-ARE NO VEHICLES ON THE HYWAY TYPE 1
0146                IF(IV1.EQ.0) GO TO 1021
              C NO-CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT VEHICLE IS DETECTED
0147                CALL DITM(IV1,JV1,IVH,VDTT,1,IONE,1,ZERO,VDTT(JV1(1)),DETT,JVDET,J
                   1UNK)
0148                IF((ITRS.EQ.0).AND.(ITRR.NE.0)) DETT=CETT/VT+CT
0149                IF((ITRS.EQ.2).AND.(ITRR.NE.0)) GO TO 1122
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0150              GO TO 1022
0151         1122 IF(IRTT.EQ.0) GO TO 1021
0152              CALL DITM(IV1,JV1,IVH,VABP,IRTT,JRTT,ITR,TP,C,CETC,JVDET,JTDET)
0153              DETT=DETD/VT+CT
0154              GO TO 1022
            C 1021
            C THE EVENT DETECTION IS IMPOSSIBLE
0155         1021 DETT=1.0E+75
            C
            C 1022
            C ARE ALL VEHICLES ON THE HYWAY TYPE 2
0156         1022 IF(IV2.EQ.IVH) GO TO 1023
            C NO-ARE NO VEHICLES ON THE HYWAY TYPE 2
0157              IF(IV2.EQ.0) GO TO 1024
            C NO-CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT VEHICLE WHICH PASSES
            C THRESHOLD
0158              CALL DITM(IV2,JV2,IVH,VDTT,1,IONE,1,ZERO,VCTT(JV2(1)),THREST,JVTHR
                 1,JUNK)
            C ANY TRUCKS TRAVELING
0159              IF(ITT.NE.0) GO TO 1025
            C NO-THE EVENT T-ACTUAL ARRIVAL IS IMPOSSIBLE
0160         1026 TAAD=1.0E+75
0161              TAAT=1.0E+75
0162              GO TO 1027
            C 1025
            C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT T-ACTUAL ARRIVAL WILL
            C OCCUR
0163         1025 CALL DITM(IV23,JV23,IVH,VABP,ITT,JTT,ITR,TP,C,TAAC,JVTAA,JTTAA)
0164              TAAT=CT+TAAD/VT
0165              GO TO 1027
            C 1024
            C THE EVENT THRESHOLD IS IMPOSIBBLE
0166         1024 THREST=1.0E+75
0167              GO TO 1026
            C 1027
            C ARE ALL VEHICLES ON THE HYWAY TYPE 3
0168         1027 IF(IV3.EQ.IVH) GO TO 1028
            C NO-ARE NO VEHICLES ON THE HYWAY TYPE 3
0169              IF(IV3.EQ.0) GO TO 1029
            C NO-ANY TRUCKS TRAVELING
0170              IF(ITT.NE.0) GO TO 1030
            C NO-THE EVENT T-VIRTUAL ARRIVAL IS IMPOSSIBLE
0171              TVAD=1.0E+75
0172              TVAT=1.0E+75
            C ANY TRUCKS FIXING
0173         1033 IF(ITF.NE.0) GO TO 1031
            C 1131 NO- THE EVENT F-VIRTUAL ARRIVAL IS IMPOSSIBLE
0174         1131 FVAD=1.0E+75
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0175             FVAT=1.0E+75
           C 1132 NO TRUCKS DEMANDED
0176        1132 IF(ITD.EQ.0) GO TO 1232
           C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT D-VIRTUAL ARRIVAL WILL
           C OCCUR
0177             CALL DIT3(IV3,JV3,IVH,VVBP,VID,ITD,JTD,ITR,TP,C,DVAD,JVDVA,JTDVA)
0178             DVAT=CT+DVAD/(VT+VVV)
0179             IF(DVAD.EQ.1.0D+75) DVAT=1.0D+75
0180             GO TO 1032
           C 1030
           C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT T-VIRTUAL ARRIVAL WILL
           C OCCUR
0181        1030 CALL DITM(IV3,JV3,IVH,VVBP,ITT,JTT,ITR,TP,D,TVAD,JVTVA,JTTVA)
0182             TVAT=CT+TVAD/(VT+VVV)
0183             GO TO 1033
           C 1031
           C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT F-VIRTUAL ARRIVAL WILL
           C OCCUR
0184        1031 IF(VVV.EQ.0) GO TO 1131
0185             CALL DIT3(IV3,JV3,IVH,VVBP,VID,ITF,JTF,ITR,TP,C,FVAD,JVFVA,JTFVA)
0186             FVAT=CT+FVAD/VVV
0187             IF(FVAD.EQ.1.0D+75) FVAT=1.0D+75
0188             GO TO 1132
           C 1029
           C THE EVENTS T-VIRTUAL ARRIVAL AND F-VIRTUAL ARRIVAL ARE BOTH IMPOSSIBLE
0189        1029 TVAD=1.E+75
0190             TVAT=1.E+75
0191             FVAT=1.E+75
0192             FVAD=1.E+75
           C 1232 THE EVENT D-VRITUAL ARRIVAL IS IMPOSSIBLE
0193        1232 DVAT=1.E+75
0194             DVAD=1.E+75
           C
           C 1032
           C ARE ALL VEHICLES ON THE HYWAY TYPE 4
0195        1032 IF(IV4.EQ.IVH) GO TO 1034
           C NO-ARE NO VEHICLES ON THE HYWAY TYPE 4
0196             IF(IV4.EQ.0) GO TO 1035
           C NO-CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT D-ACTUAL ARRIVAL WILL
           C OCCUR
0197             CALL DITM(ITD,JTD,ITR,TADT,1,IONE,1,ZERO,TACT(JTD(1)),DAAD,JTDAA,J
                1UNK)
0198             DAAT=CT+DAAD/VT
0199             GO TO 1036
           C 1035
           C THE EVENT D-ACTUAL ARRIVAL IS IMPOSSIBLE
0200        1035 DAAD=1.0E+75
0201             DAAT=1.0E+75
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               C
               C 1036
               C ARE ALL VEHICLES ON THE HYWAY TYPE 5
 0202           1036 IF(IV5.EQ.IVH) GO TO 1037
               C NO- ARE NO VEHICLES ON THE HYWAY TYPE 5
 0203                IF(IV5.EQ.0) GO TO 1038
               C NO-CALL THE ROUTINE WHICH DETERMINES THE NEXT TRUCK DEPARTURE
 0204                CALL DITM(ITF,JTF,ITR,TADT,1,IONE,1,ZERO,TADT(JTF(1)),DEPT,JTDEP,J
                    1UNK)
 0205                GO TO 1039
               C 1038
               C THE EVENT DEPARTURE IS IMPOSSIBLE
 0206           1038 DEPT=1.0E+75
 0207                GO TO 1039
               C
               C 1015
               C THE ONLY POSSIBLE EVENTS ARE RETURN TO GARAGE AND BREAKDOWN
               C CALL THE ROUTINE WHICH DETERMINES THE TIME AT WHICH THE MOST DOWNSTREAM TRUCK
               C RETURNS TO THE GARAGE
 0208           1015 CALL DITM(1,IONE,1,ZERO,ITT,JTT,ITR,TP,D,RTGD,JUNK,JTRTG)
 0209                RTGT=CT+RTGD/VT
               C 100
               C WILL A VEHICLE BREAK DOWN BEFORE A TRUCK RETURNS TO GARAGE
 0210            100 IF(VBT(IVH+1).LE.RTGT) GO TO 10
 0211                GO TO 20
               C
               C 1020
               C THE ONLY POSSIBLE EVENTS ARE DETECTION, RETURN TO GARAGE, AND BREAKDOWN
               C CALL THE ROUTINE DETERMINES THE TIME THE NEXT VEHICLE IS DETECTED
 0212           1020 CALL DITM(IV1,JV1,IVH,VDTT,1,IONE,1,ZERO,VDTT(JV1(1)),DETT,JVDET,J
                    1UNK)
 0213                IF((ITRS.EQ.0).AND.(ITRR.NE.0)) DETT=DETT/VT+CT
 0214                IF((ITRS.EQ.2).AND.(ITRR.NE.0)) GO TO 1120
               C 200
               C WILL A TRUCK RETUN TO THE GARAGE BEFORE THE VEHICLE IS DETECTED
 0215            200 IF(RTGT.LE.DETT) GO TO 100
               C NO-WILL A VEHICLE BREAKDOWN BEFORE A TRUCK RETURNS TO GARAGE
 0216                IF(VBT(IVH+1).LE.DETT) GO TO 10
 0217                GO TO 30
 0218           1120 CALL DITM(IV1,JV1,IVH,VABP,IRTT,JRTT,ITR,TP,D,DETD,JVDET,JTDET)
 0219                DETT=DETD/VT+CT
 0220                GO TO 200
               C
               C 1023
               C THE ONLY POSSIBLE EVENTS ARE T-ACTUAL ARRIVAL,THRESHOLD,RETURN TO GARAGE,AND
               C BREAKDOWN
               C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT T-ACTUAL ARRIVAL WILL
               C OCCUR
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0221          1023 CALL DITM(IV23,JV23,IVH,VABP,ITT,JTT,ITR,TP,C,TAAC,JVTAA,JTTAA)
0222               TAAT=CT+TAAD/VT
                C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT VEHICLE PASSES THRESHOLD
0223               CALL DITM(IV2,JV2,IVH,VDTT,1,IONE,1,ZERO,VDTT(JV2(1)),THREST,JVTHR
                  1,JUNK)
                C WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A VEHICLE PASSES THRESHOLD
0224               IF(TAAT.LE.THREST) GO TO 400
                C 300
                C NO-WILL A TRUCK RETURN TO THE GARAGE BEFORE THE VEHICLE PASSES THRESHOLD
0225            300 IF(RTGT.LE.THREST) GO TO 100
                C NO-WILL A VEHICLE BREAKDOWN BEFORE THE VEHICLE PASSES THRESHOLD
0226               IF(VBT(IVH+1).LE.THREST) GO TO 10
0227               GO TO 40
                C 400
                C WILL A TRUCK RETURN TO GARAGE BEFORE A T-ACTUAL ARRIVAL
0228            400 IF(RTGD.LE.TAAD) GO TO 100
                C NO-WILL A VEHICLE BREAK DOWN BEFORE THE T-ACTUAL ARRIVAL
0229               IF(VBT(IVH+1).LE.TAAT) GO TO 10
0230               GO TO 50
                C
                C 1028
                C THE ONLY POSSIBLE EVENTS ARE T-VIRTUAL ARRIVAL,RETURN TO GARAGE, AND
                C BREAKDOWN
                C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT T-VIRTUAL ARRIVAL WILL
                C OCCUR
0231          1028 CALL DITM(IV3,JV3,IVH,VVBP,ITT,JTT,ITR,TP,D,TVAC,JVTVA,JTTVA)
0232               TVAT=CT+TVAD/(VT+VVV)
                C 500
                C WILL A TRUCK RETURN TO GARAGE BEFORE THE NEXT T-VIRTUAL ARRIVAL
0233            500 IF(RTGT.LE.TVAT) GO TO 100
                C NO-WILL A VEHICLE BREAKDCWN BEFORE THE T-VIRTUAL ARRIVAL CCCURS
0234               IF(VBT(IVH+1).LE.TVAT) GO TO 10
0235               GO TO 60
                C
                C 1034
                C THE ONLY POSSIBLE EVENTS ARE D-ACTUAL ARRIVAL, RETURN TO GARAGE, AND BREAKDOWN
                C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT D-ACTUAL ARRIVAL WILL
                C OCCUR
0236          1034 CALL DITM(ITD,JTD,ITR,TADT,1,IONE,1,ZERO,TADT(JTD(1)),DAAD,JTDAA,J
                  1UNK)
0237               DAAT=CT+DAAD/VT
                C 600
                C WILL A TRUCK RETURN TO GARAGE BEFORE THE NEXT D-ACTUAL ARRIVAL
0238            600 IF(RTGD.LE.DAAD) GO TO 100
                C NO-WILL A VEHICLE BREAKDOWN BEFORE THE D-ACTUAL ARRIVAL CCCURS
0239               IF(VBT(IVH+1).LE.DAAT) GO TO 10
0240               GO TO 70
                C
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               C 1037
               C THE CNLY POSSIBLE EVENTS ARE DEPARTURE, RETURN TC GARAGE, AND BREAKDOWN
               C CALL THE ROUTINE WHICH DETERMINES THE TIME THE NEXT TRUCK DEPARTURE WILL
               C OCCUR
0241            1037 CALL DITM(ITF,JTF,ITR,TADT,1,IONE,1,ZERO,TADT(JTF(1)),DEPT,JTDEP,J
                    1UNK)
               C 700
               C WILL A TRUCK RETURN TO GARAGE BEFORE A DEPARTURE
0242             700 IF(RTGT.LE.DEPT) GO TO 100
               C NO- WILL A VEHICLE BREAKDOWN BEFORE THE DEPARTUE CCCURS
0243                 IF(VBT(IVH+1).LE.DEPT) GO TO 10
0244                 GO TO 80
               C
               C 1039
               C ALL EVENTS ARE POSSIBLE-DETERMINATION OF THE NEXT EVENT
               C WILL A D-ACTUAL ARRIVAL OCCUR BEFORE A DEPARTURE
0245            1039 IF(DAAT.LE.DEPT) GO TO 1040
               C WILL A T-VIRTUAL ARRIVAL OCCUR A DEPARTURE
0246                 IF(TVAT.LE.DEPT) GO TO 1041
               C WILL A F-VIRTUAL ARRIVAL OCCUR BEFORE A DEPARTURE
0247                 IF(FVAT.LE.DEPT) GO TO 1042
               C WILL A D-VIRTUAL ARRIVAL OCCUR BEFORE A DEPARTURE
0248                 IF(DVAT.LE.DEPT) GO TO 1043
               C WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A DEPARTURE
0249                 IF(TAAT.LE.DEPT) GO TO 1044
               C WILL A THRESHOLD OCCUR BEFORE A DEPARTURE
0250                 IF(THREST.LE.DEPT) GO TO 1045
               C WILL A DETECTION OCCUR BEFORE A DEPARTURE
0251                 IF(DETT-DEPT)200,200,700
               C 1040 WILL A T-VIRTUAL ARRIVAL CCCUR BEFORE A D-ACTUAL ARRIVAL
0252            1040 IF(TVAT.LE.DAAT) GO TO 1041
               C WILL A F-VIRTUAL ARRIVAL OCCUR BEFORE A D-ACTUAL ARRIVAL
0253                 IF(FVAT.LE.DAAT)GO TO 1042
               C WILL A D-VIRTUAL ARRIVAL OCCUR BEFORE A D-ACTUAL ARRIVAL
0254                 IF(DVAT.LE.DAAT) GO TO 1043
               C WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A D-ACTUAL ARRIVAL
0255                 IF(TAAT.LE.DAAT) GO TO 1044
               C WILL A THRESHOLD OCCUR BEFORE A D-ACTUAL ARRIVAL
0256                 IF(THREST.LE.DAAT) GO TO 1045
               C WILL A DETECTION OCCUR BEFORE A D-ACTUAL ARRIVAL
0257                 IF(DETT-DAAT)200,200,600
               C 1041 WILL A F-VIRTUAL ARRIVAL CCCUR BEFORE A T-VIRTUAL ARRIVAL
0258            1041 IF(FVAD.LE.TVAD*(VVV/(VT+VVV))) GO TO 1042
               C WILL A D-VIRTUAL ARRIVAL OCCUR BEFORE A T-VIRTUAL ARRIVAL
0259                 IF(DVAD.LE.TVAD) GO TO 1043
               C WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A T-VIRTUAL ARRIVAL
0260                 IF(TAAT.LE.TVAT) GO TO 1044
               C WILL A THRESHOLD OCCUR BEFORE A T-VIRTUAL ARRIVAL
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0261            IF(THREST.LE.TVAT) GO TO 1045
          C WILL A DETECTION OCCUR BEFORE A T-VIRTUAL ARRIVAL
0262            IF(DETT-TVAT)200,200,500
          C 1042 WILL A D-VIRTUAL ARRIVAL OCCUR BEFORE A F-VIRTUAL ARRIVAL
0263       1042 IF(DVAD*(VVV/(VT+VVV)).LE.FVAD) GO TO 1043
          C WILL A T-ACTUAL ARRIVAL OCCUR BEFORE A F-VIRTUAL ARRIVAL
0264            IF(TAAT.LE.FVAT) GO TO 1044
          C WILL A THRESHOLD OCCUR BEFORE A F-VIRTUAL ARRIVAL
0265            IF(THREST.LE.FVAT)GO TO 1045
          C WILL A DETECTION OCCUR BEFORE A F-VIRTUAL ARRIVAL
0266            IF(DETT.LE.FVAT) GO TO 200
          C WILL A RETURN TO GARAGE OCCUR BEFORE A F-VIRTUAL ARRIVAL
0267            IF(RTGT.LE.FVAT) GO TO 100
          C WILL A VEHICLE BREAKDOWN BEFORE A F-VIRTUAL ARRIVAL
0268            IF(VBT(IVH+1)-FVAT)10,10,90
          C 1043 WILL A T-ACTUAL ARRIVAL OCCUR BEFCRE A D-VIRTUAL ARRIVAL
0269       1043 IF(TAAT.LE.DVAT) GO TO 1044
          C WILL A THRESHOLD OCCUR BEFORE A D-VIRTUAL ARRIVAL
0270            IF(THREST.LE.DVAT) GO TO 1045
          C WILL A DETECTION OCCUR BEFORE A D-VIRTUAL ARRIVAL
0271            IF(DETT.LE.DVAT) GO TO 200
          C WILL A RETURN TO GARAGE OCCUR BEFORE A D-VIRTUAL ARRIVAL
0272            IF(RTGT.LE.DVAT) GO TO 100
          C WILL A VEHICLE BREAKDOWN BEFORE A D-VIRTUAL ARRIVAL
0273            IF(VBT(IVH+1)-DVAT) 10,10,99
          C 1044 WILL A THRESHOLD OCCUR BEFORE A T-ACTUAL ARRIVAL
0274       1044 IF(THREST.LE.TAAT) GO TO 1045
          C WILL A DETECTION OCCUR BEFORE A T-ACTUAL ARRIVAL
0275            IF(DETT-TAAT)200,200,400
          C 1045 WILL A DETECTION OCCUR BEFORE A THRESHCLD
0276       1045 IF(DETT-THREST) 200,200,300
          C
          C SECTION 2 THE EVENTS
          C
          C 10
          C BREAKDOWN
          C UPDATE CLOCK
0277         10 CTL=CT
0278            CT=VBT(IVH+1)
          C ANY TRUCKS TRAVELING
0279            IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,C)
0280            IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
               1L,VT,D)
          C ANY TRUCKS DEMANDED
0281            IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,C)
0282            IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
          C ANY TYPE 3 VEHICLES ON THE HYWAY
0283            IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
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            C ANY VEHICLES TYPE 1
0284              IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                 1V1,IVH,VDTT,CTL,CT,VT,D)
            C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,VEHICLE ID
0285              IREF=11000000+100*VID(IVH+1)
0286              CALL SCRIBE(IREF,CT,VABP(IVH+1),DUM,IDUM)
            C IS HIGHWAY OVERLOADED
0287              IF(IVH.EQ.IVHO-1) GO TO 1999
            C DETERMINE TIME OF DETECTION
0288              IF((ITRS.EQ.0).AND.(ITRR.NE.0)) GO TO 14
0289              IF((ITRS.EQ.2).AND.(ITRR.NE.0)) GO TO 15
0290              VDTT(IVH+1)=CT+LAGT(D,DESP,VABP(IVH+1),VV,VEC)
0291              GO TO 15
0292           14 VEH(1)=IVH+1
0293              IHH=IVH+1
0294              CALL DITM(1,VEH(1),IHH,VABP,ITRR,JTRR,ITR,TP,D,VDTT(IVH+1),JUNK,JT
                 1RT)
            C 15 SET MODE TO TYPE 1
0295           15 VM(IVH+1)=1
0296              GO TO 9999
            C
            C 20
            C RETURN TO GARAGE
            C UPDATE CLOCK AND TRAVELING TRUCKS POSITIONS
0297           20 CTL=CT
0298              CT=RTGT
0299              GCOUNT(JTRTG)=GCOUNT(JTRTG)+1
0300              A=A+1
0301              IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
0302              IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                 1L,VT,D)
            C ANY TRUCKS DEMANDED
0303              IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
0304              IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
            C ANY TYPE 3 VEHICLES ON THE HYWAY
0305              IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
            C ANY VEHICLES TYPE 1
0306              IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                 1V1,IVH,VDTT,CTL,CT,VT,D)
            C IS THIS TRUCK A DEMANDING TRUCK
0307              IF(ITD.EQ.0) GO TO 26
0308              DO 25 I=1,ITD
0309              IF(JTRTG.EQ.JTD(ITD)) GO TO 23
0310           25 CONTINUE
            C IS THIS A REVOLVING TRUCK
0311           26 IF(JTRTG.LE.ITRR) GO TO 23
            C ANY TYPE2 OR TYPE 3 VEHICLES ON THE HYWAY
0312              IF(IV23.NE.0) GO TO 21
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                C 22 SET TRUCK TO GARAGE
0313              22 TM(JTRTG)=0
                C PRINT EVENT REF.NO., CLOCK TIME, TRUCK ID.
0314                 IREF=12000000+JTRTG
0315                 CALL SCRIBE(IREF,CT,TP(JTRTG),DUM,IDUM)
                C SET TRUCK POSITION TO BEGINNING OF HYWAY
0316              23 TP(JTRTG)=0.0
0317                 GO TO 9999
                C 21
                C ARE THERE MORE TYPE 2 AND TYPE 3 VEHICLES THAN TRUCKS TRAVELING
0318              21 IF(IV23.GE.ITT) GO TO 23
                C CALL THE ROUTINE WHICH DETERMINES THE MOST UPSTREAM TRUCK
0319                 CALL DITM(ITT,JTT,ITR,TP,1,IONE,1,ZERO,D,UST,JUST,JUNK)
                C ANY TYPE 2 OR 3 VEHICLE UPSTREAM OF IT
0320                 DO 24 I=1,IV23
0321                 IF(VABP(JV23(I)).LT.UST) GO TO 23
0322              24 CONTINUE
0323                 GO TO 22
                C
                C 30
                C DETECTION
                C UPDATE CLOCK
0324              30 CTL=CT
0325                 CT=DETT
                C SET VEHICLE MODE TO TYPE 2
0326                 VM(JVDET)=2
                C ANY TRUCKS TRAVELING
0327                 IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
0328                 IF((ITRS.EQ.2).AND.(ITRR.NE.0)) TP(JTDET)=VABP(JVDET)-.00001/VELT(
                    10,D)
0329                 IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                    1L,VT,D)
                C ANY TRUCKS DEMANDED
0330                 IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
0331                 IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
                C ANY TYPE 3 VEHICLES ON THE HYWAY
0332                 IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
                C ANY VEHICLES TYPE 1
0333                 IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                    1V1,IVH,VDTT,CTL,CT,VT,D)
                C DETERMINE TIME OF THRESHOLD
0334                 VDTT(JVDET)=CT+THRT
                C ANY TRUCKS IN THE GARAGE
0335                 IF(((ITNG.NE.ITR-ITRR).AND.(ITRS.EQ.0)).OR.((ITNG.NE.ITR).AND.(ITR
                    1S.NE.0))) GO TO 31
                C PRINT EVENT REF.NO., CLOCK TIME, HYWAY POSITION, VEHICLE ID
0336                 IREF=13000000+100*VID(JVDET)
0337                 CALL SCRIBE(IREF,CT,VABP(JVDET),DUM,IDUM)
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 0338              GO TO 9999
             C SET TRUCK MODE TO TRAVEL
 0339           31 DO 32 I=1,ITR
 0340              IF(TM(I).EQ.0) GO TO 33
 0341           32 CONTINUE
 0342           33 TM(I)=1
             C PRINT EVENT REF. NO., CLOCK TIME, HYWAY POSITICN, VENICLE ID, TRUCK ID
 0343              IREF=14000000+100*VID(JVDET)+I
 0344              CALL SCRIBE(IREF,CT,VABP(JVDET),TP(I),IDUM)
 0345              GO TO 9999
             C
             C 40
             C THRESHOLD
             C UPDATE CLOCK
 0346           40 CTL=CT
 0347              CT=THREST
             C ANY TRUCKS TRAVELING
 0348              IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
 0349              IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                 1L,VT,D)
             C ANY TRUCKS DEMANDED
 0350              IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
 0351              IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
             C ANY TYPE 3 VEHICLES ON THE HYWAY
 0352              IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
             C ANY VEHICLES TYPE 1
 0353              IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                 1V1,IVH,VDTT,CTL,CT,VT,D)
             C SET VEHICLE MODE TO TYPE 3
 0354              VM(JVTHR)=3
             C PRINT EVENT REF. NO.,CLOCK TIME HYWAY POSITICN,VEHICLE ID
 0355              IREF=15000000+100*VID(JVTHR)
 0356              CALL SCRIBE(IREF,CT,VABP(JVTHR),DUM,IDUM)
 0357              GO TO 9999
             C
             C 50
             C T-ACTUAL ARRIVAL
             C UPDATE CLOCK AND POSITION OF TRAVELING TRUCKS
 0358           50 CTL=CT
 0359              CT=TAAT
 0360              CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
 0361              IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                 1L,VT,D)
             C ANY VEHICLES TYPE 1
 0362              IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                 1V1,IVH,VDTT,CTL,CT,VT,D)
             C SET VEHICLE MODE TO TYPE5 AND TRUCK MODE TC FIX
 0363              VM(JVTAA)=-JTTAA
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0364            TM(JTTAA)=2
          C DETERMINE DEPARTURE TIME
0365            TADT(JTTAA)=CT+TF
          C ANY TRUCKS DEMANDED
0366            IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
0367            IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
          C ANY TYPE 3 VEHICLES ON THE HYWAY
0368            IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
          C PRINT EVENT REF.NO., CLOCK TIME,HYWAY POSITION,VEHICLE ID,TRUCK ID
0369            IREF=16000000+100*VID(JVTAA)+JTTAA
0370            CALL SCRIBE(IREF,CT,VABP(JVTAA),TP(JTTAA),IDUM)
0371            GO TO 9999
          C
          C 60
          C T-VIRTUAL ARRIVAL
          C UPDATE CLOCK AND TRAVELING TRUCK AND TYPE 3 VEHICLES VIRTUAL POSITIONS
0372         60 CTL=CT
0373            CT=TVAT
0374            CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
0375            IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
               1L,VT,D)
0376            CALL UPDATE(IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
0377            VVBP(JVTVA)=TP(JTTVA)
          C SET VEHICLE MODE TO TYPE 4
0378            VM(JVTVA)=4
          C ANY TRUCKS DEMANDED
0379            IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
0380            IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
          C ANY VEHICLES TYPE 1
0381            IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
               1V1,IVH,VDTT,CTL,CT,VT,D)
          C SET TRUCK TO DEMANDED
0382            TM(JTTVA)=-VID(JVTVA)
          C DETERMINE D-ACTUAL ARRIVAL TIME
0383            VEH(1)=JVTVA
0384            TRUCK(1)=JTTVA
0385            CALL DITM(1,VEH(1),IVH,VABP,1,TRUCK(1),ITR,TP,D,TACT(JTTVA),JUNK,J
               1UNK)
          C ADD TO TRUCK'S QUEUE
0386            CALL QADD(VID(JVTVA),JTTVA)
          C PRINT EVENT REF.NO., CLOCK TIME, HYWAY POSITION, VEHICLE ID, TRUCK ID, VEHICLE
          C ACTUAL HYWAY POSITION
0387            IREF=17000000+100*VID(JVTVA)+JTTVA
0388            CALL SCRIBE(IREF,CT,VVBP(JVTVA),VABP(JVTVA),IDUM)
0389            GO TO 9999
          C
          C 70
          C D-ACTUAL ARRIVAL
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             C UPDATE CLOCK AND DEMANDING TRUCKS POSITIONS
 0390            70 CTL=CT
 0391               CT=DAAT
 0392               CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
 0393               CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
             C SET VEHICLE MODE TO TYPE  5 AND TRUCK MODE TO FIX
 0394               DO 71 I=1,IV4
 0395               IF(VID(JV4(I)).EQ.IABS(TM(JTDAA))) GO TO 72
 0396            71 CONTINUE
 0397            72 VM(JV4(I))=-JTDAA
 0398               JVDAA=JV4(I)
 0399               TM(JTDAA)=2
             C DETERMINE DEPARTURE TIME
 0400               TADT(JTDAA)=CT+TF
             C ANY TRUCKS TRAVELING
 0401               IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
 0402               IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                   1L,VT,D)
             C ANY TYPE 3 VEHICLES ON THE HYWAY
 0403               IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
             C ANY VEHICLES TYPE 1
 0404               IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                   1V1,IVH,VDTT,CTL,CT,VT,D)
             C REMOVE VEHICLE FROM ALL DEMANDING FIXING TRUCKS QUEUES
 0405               CALL QREMV(VID(JVDAA),ITD,JTD)
 0406               IF(ITF.NE.0) CALL QREMV(VID(JVDAA),ITF,JTF)
             C PRINT EVENT REF.NO., CLOCK TIME, HYWAY POSITION, VEHICLE ID,TRUCK ID
 0407               IREF=18000000+100*VID(JVDAA)+JTDAA
 0408               CALL SCRIBE(IREF,CT,VABP(JVDAA),TP(JTDAA),IDUM)
 0409               GO TO 9999
             C
             C 80
             C DEPARTURE
             C UPDATE CLOCK
 0410            80 CTL=CT
 0411               CT=DEPT
 0412               VCOUNT(JTDEP)=VCOUNT(JTDEP)+1
             C CALCULATE THE WAIT TIME
 0413               DO 81 IWTT=1,IV5
 0414               IF(IABS(VM(JV5(IWTT))).EQ.JTDEP) GO TO 82
 0415            81 CONTINUE
 0416            82 WT=CT-VBT(JV5(IWTT))
 0417               TWT=TWT+WT
 0418               TWT2=TWT2+WT**2
             C ANY TRUCKS TRAVELING
 0419               IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
 0420               IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
                   1L,VT,D)
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              C ANY TRUCKS DEMANDED
 0421               IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,C)
 0422               IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
              C ANY TYPE 3 VEHICLES ON THE HYWAY
 0423               IF(IV3.NE.0) CALL UPDATE( IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
              C ANY VEHICLES TYPE 1
 0424               IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
                   1V1,IVH,VDTT,CTL,CT,VT,D)
              C PRINT EVENT REF.NO.,CLOCK TIME, HYWAY POSITICN,VEHICLE ID.,TRUCK IC.,WAIT TIME
 0425               IREF=19000000+100*VID(JV5(IWTT))+JTDEP
 0426               CALL SCRIBE(IREF,CT,VABP(JV5(IWTT)),WT,IDUM)
              C DETERMINATION OF THE TRUCK'S NEW STATUS - DUB THIS TRUCK TRUCK1
 0427               TRUCK(1)=JTDEP
              C 892 ANY VEHICLE IN TRUCK1'S QUEUE
 0428           892 IF(TQ(1,TRUCK(1)).NE.0) GO TO 84
              C SET TRUCK1 TO TRAVEL
 0429               TM(TRUCK(1))=1
              C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,TRUCK IC
 0430               IREF=20000000+TRUCK(1)
 0431               CALL SCRIBE(IREF,CT,TP(TRUCK(1)),DUM,IDUM)
 0432               GO TO 999
              C 84 DETERMINE VEHICLE IN TRUCK1'S QUEUE WITH THE HIGHEST PRIORITY
 0433            84 DO 841 I=1,IV34
 0434               IF(TQ(2,TRUCK(1)).EQ.VID(JV34(I))) GO TO 842
 0435           841 CONTINUE
 0436           842 VEH(1)=JV34(I)
              C ANY TRUCKS DEMANDED
 0437               IF(ITD.NE.0) GO TO 85
              C 86 SET TRUCK1 MODE TO DEMAND AND VEHICLE1 TO TYPE 4
 0438            86 TRUCK(1)=JTDEP
 0439               TM(TRUCK(1))=-VID(VEH(1))
 0440               VM(VEH(1))=4
              C DETERMINE D-ACTUAL ARRIVAL TIME
 0441               CALL DITM(1,VEH(1),IVH,VABP,1,TRUCK(1),ITR,TP,C,TACT(TRUCK(1)),JUN
                   1K,JUNK)
              C PRINT EVENT REF.NO.,CLOCKTIME,HYWAY POSITION,VEHICLE IC,TRUCK ID
 0442               IREF=21000000+100*VID(VEH(1))+TRUCK(1)
 0443               CALL SCRIBE(IREF,CT,TP(TRUCK(1)),VABP(VEH(1)),IDUM)
 0444               GO TO 999
              C 85 ANY TRUCKS DEMANDED BY VEHICLE1
 0445            85 DO 87 I=1,ITD
 0446               IF(TQ(2,JTD(I)).EQ.VID(VEH(1))) GO TO 88
 0447            87 CONTINUE
 0448               GO TO 86
              C 88 THIS IS TRUCK2
 0449            88 TRUCK(2)=JTD(I)
              C IS TRUCK1 CLOSEST TO VEHICLE1
 0450               CALL DITM(1,VEH(1),IVH,VABP,2,TRUCK,ITR,TP,D,DUMM,JV,JT)
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0451              IF(JT.EQ.TRUCK(1)) GO TO 89
            C 891 REMOVE VEHICLE FROM TRUCK1'S QUEUE
0452          891 CALL QREMV(VID(VEH(1)),1,TRUCK(1))
0453              GO TO 892
            C 89 REMOVE VEHICLE1 FROM TRUCK2'S QUEUE
0454           89 CALL QREMV(VID(VEH(1)),1,TRUCK(2))
            C 893 ANY VEHICLES IN TRUCK2'S QUEUE
0455          893 IF(TQ(1,TRUCK(2)).NE.0) GO TO 894
            C SET TRUCK2'S MODE TO TRAVEL
0456              TM(TRUCK(2))=1
            C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,TRUCK ID
0457              IREF=20000000+TRUCK(2)
0458              CALL SCRIBE(IREF,CT,TP(TRUCK(2)),DUM,IDUM)
0459              GO TO 86
            C 894 DETERMINE THE VEHICLE IN TRUCK2'S QUEUE WITH THE HIGHEST PRIORITY
0460          894 DO 8941 I=1,IV34
0461              IF(TQ(2,TRUCK(2)).EQ.VID(JV34(I))) GO TO 8942
0462         8941 CONTINUE
0463         8942 VEH(2)=JV34(I)
0464              TRUCK(1)=TRUCK(2)
            C ANY TRUCKS DEMANDED BY VEHICLE2
0465              DO 895 I=1,ITD
0466              IF(JTD(I).EQ.TRUCK(1)) GO TO 895
0467              IF(TQ(2,JTD(I)).EQ.VID(VEH(2))) GO TO 896
0468          895 CONTINUE
            C SET TRUCK1 MODE TO DEMANDED AND VEHICLE2 TO TYPE 4
0469              TM(TRUCK(1))=-VID(VEH(2))
0470              VM(VEH(2))=4
            C DETERMINE D=ACTUAL ARRIVAL TIME
0471              CALL DITM(1,VEH(2),IVH,VABP,1,TRUCK(1),ITR,TP,D,TACT(TRUCK(1)),JUN
                 1K,JUNK)
            C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,VEHICLE ID,TRUCK ID
0472              IREF=21000000+100*VID(VEH(2))+TRUCK(1)
0473              CALL SCRIBE(IREF,CT,TP(TRUCK(1)),VABP(VEH(2)),IDUM)
0474              GO TO 86
            C 896 THIS IS TRUCK2
0475          896 TRUCK(2)=JTD(I)
            C IS TRUCK1 CLOSEST TO VEHICLE2
0476              CALL DITM(1,VEH(2),IVH,VABP,2,TRUCK,ITR,TP,D,DUMM,JV,JT)
0477              IF(JT.EQ.TRUCK(1)) GO TO 897
            C REMOVE VEHICLE2 FROM TRUCK1'S QUEUE
0478              CALL QREMV(VID(VEH(2)),1,TRUCK(2))
0479              GO TO 893
            C 897 SET TRUCK1'S MODE TO DEMANDED AND VEHICLE2 TO TYPE 4
0480          897 TM(TRUCK(1))=-VID(VEH(2))
0481              VM(VEH(2))=4
            C DETERMINE D=ACTUAL ARRIVAL TIME
0482              CALL DITM(1,VEH(2),IVH,VABP,1,TRUCK(1),ITR,TP,D,TACT(TRUCK(1)),JUN
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              1K,JUNK)
           C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY PCSITICN,VEHICLE ID,TRUCK ID
0483             IREF=21000000+100*VID(VEH(2))+TRUCK(1)
0484             CALL SCRIBE(IREF,CT,TP(TRUCK(1)),VABP(VEH(2)),IDUM)
           C REMOVE VEHICLE2 FROM TRUCK2'S QUEUE
0485             CALL QREMV(VID(VEH(2)),1,TRUCK(2))
           C REDUB TRUCK2 TRUCK1
0486             TRUCK(1)=TRUCK(2)
0487             GO TO 893
           C 999 GENERATE NEW DISABLEMENT
0488         999 IVS=IVS+1
0489             IVB1=JV5(IWTT)
0490             DO 83 J=IVB1,IVB2
0491             VBT(J)=VBT(J+1)
0492             VABP(J)=VABP(J+1)
0493             VVBP(J)=VVBP(J+1)
0494             VM(J)=VM(J+1)
0495             VID(J)=VID(J+1)
0496          83 VDTT(J)=VDTT(J+1)
0497             CALL RANDU(IX,IY,R)
0498             IX=IY
0499             VBT(IVB)=VBT(IVB2)-ALOG(R)/LAMDA
0500             CALL RANDU(IX,IY,R)
0501             IX=IY
0502             VABP(IVB)=R*D
0503             VVBP(IVB)=VABP(IVB)
0504             VID(IVB)=IVB+IVS
0505             GO TO 9999
           C
           C 90
           C F-VIRTUAL ARRIVAL
           C UPDATE CLOCK AND TYPE 3 VIRTUAL POSITICNS
0506          90 CTL=CT
0507             CT=FVAT
0508             CALL UPDATE(IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
0509             VVBP(JVFVA)=TP(JTFVA)
           C ANY TRUCKS TRAVELING
0510             IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,D)
0511             IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
              1L,VT,D)
           C ANY TRUCKS DEMANDED
0512             IF(ITD.NE.0)CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
0513             IF(ITD.NE.0) CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
           C ANY VEHICLES TYPE 1
0514             IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
              1V1,IVH,VDTT,CTL,CT,VT,D)
           C ADD VEHICLE TO QUEUE
0515             ITQ=2+TQ(1,JTFVA)
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      DO 91 I=2,ITQ
      IF(TQ(I,JTFVA).EQ.VID(JVFVA)) GO TC 9999
   91 CONTINUE
      CALL QADD(VID(JVFVA),JTFVA)
C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,VEHICLE ID,TRUCK ID
      IREF=22000000+100*VID(JVFVA)+JTFVA
      CALL SCRIBE(IREF,CT,VVBP(JVFVA),TP(JTFVA),IDUM)
      GO TO 9999
C
C 99
C D-VIRTUAL ARRIVAL
C UPDATE CLOCK, TYPE 3 VIRTUAL POSITIONS, AND DEMANCED TRUCKS
   99 CTL=CT
      CT=DVAT
      CALL UPDATE(IV3,JV3,IVH,VVBP,CTL,CT,VVV,D)
      CALL UPDATE(ITD,JTD,ITR,TP,CT,CTL,VT,D)
      CALL UPDATE(ITD,JTD,ITR,TADT,CTL,CT,VT,D)
      VVBP(JVDVA)=TP(JTDVA)
C ANY TRUCKS TRAVELING
      IF(ITT.NE.0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT,C)
      IF((ITRR.NE.0).AND.(ITRS.EQ.0)) CALL UPDATE(ITRR,JTRR,ITR,TP,CT,CT
     1L,VT,D)
C ANY VEHICLES TYPE 1
      IF(((IV1.NE.0).AND.(ITRS.EQ.0)).AND.(ITRR.NE.0)) CALL UPDATE(IV1,J
     1V1,IVH,VDTT,CTL,CT,VT,D)
C ADD VEHICLE TO QUEUE
      ITQ=2+TQ(1,JTDVA)
      DO991 I=2,ITQ
      IF(TQ(I,JTDVA).EQ.VID(JVDVA)) GO TC 9999
  991 CONTINUE
      CALL QADD(VID(JVDVA),JTDVA)
C PRINT EVENT REF.NO.,CLOCK TIME,HYWAY POSITION,VEHICLE ID,TRUCK ID
      IREF=23000000+100*VID(JVDVA)+JTDVA
      CALL SCRIBE(IREF,CT,VVBP(JVDVA),TP(JTDVA),ICUM)
      GO TO 9999
 1999 CONTINUE
      WTM=TWT/IVS
      WTMS=TWT2/IVS
      IREF=99000000+IVS
      CALL SCRIBE(IREF,WTM,WTMS,A,IDUM)
      RES=(CT+1.)/A
      WRITE(6,3997) RES
 3997 FORMAT(' ',E16.7)
      WRITE(6,3998) CT
 3998 FORMAT(' ',D16.7)
 2999 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DITM(IVEH,JVEH,IVH,VP,ITRUCK,JTRUCK,ITR,TP,D,DT,JV,JT)
      DIMENSION JVEH(IVEH),VP(IVH),JTRUCK(ITRUCK),TP(ITR)
      DOUBLE PRECISION VP,TP,DT,A,D
      DT=D
      DO 1 J=1,ITRUCK
      DO 1 I=1,IVEH
      A=VP(JVEH(I))-TP(JTRUCK(J))
      IF(A.LE.0) A=A+D
      IF(A.GT.DT) GO TO 1
      DT=A
      JV=JVEH(I)
      JT=JTRUCK(J)
    1 CONTINUE
      RETURN
      END
```

```
 0001                 SUBROUTINE DIT3(IVEH,JVEH,IVH,VP,VID,ITRUCK,JTRUCK,ITR,TP,D,DT,JV,
                     1JT)
 0002                 DIMENSION JVEH(IVEH),VP(IVH),JTRUCK(ITRUCK),TP(ITR),VIC(IVH)
 0003                 COMMON TQ(51,10)
 0004                 INTEGER TQ,VID
 0005                 DOUBLE PRECISION VP,TP,DT,A,D
 0006                 DT=1.0D+75
 0007                 DO 1 J=1,ITRUCK
 0008                 DO 1 I=1,IVEH
 0009                 IT=2+TQ(1,JTRUCK(J))
 0010                 DO 2 L=2,IT
 0011                 IF(TQ(L,JTRUCK(J)).EQ.VID(JVEH(I))) GO TC 1
 0012               2 CONTINUE
 0013                 A=VP(JVEH(I))-TP(JTRUCK(J))
 0014                 IF(A.LE.0) A=A+D
 0015                 IF(A.GT.DT) GO TO 1
 0016                 DT=A
 0017                 JV=JVEH(I)
 0018                 JT=JTRUCK(J)
 0019               1 CONTINUE
 0020                 RETURN
 0021                 END
```

```
FORTRAN IV G LEVEL  21                LAGT                 DATE = 75223          11/42/08

              FUNCTION LAGT(D,DESP,VAP,VV,VEQ)
              REAL LAGT
              DOUBLE PRECISION VAP,D
              IF(DESP.EQ.0.0) GO TO 2
              L=D/DESP+0.5
              DO 1 J=1,L
              IF(VAP.LT.J*DESP) GO TO 3
            1 CONTINUE
            2 LAGT=0.0
              GO TO 4
            3 LAGT=DESP/VEQ-(VAP-(J-1)*DESP)/VV
            4 RETURN
              END
```

```
FORTRAN IV G LEVEL  21                  UPDATE              DATE = 75223          11/42/08

            SUBROUTINE UPDATE(IS,JS,ITR,TP,A,B,C,D)
            DIMENSION JS(IS),TP(ITR)
            DOUBLE PRECISION A,B,TP,D
            IF(A.EQ.B) GO TO 2
            IF(C.GE.D*1.0D+20) GO TO 2
            DO 1 I=1,IS
            TP(JS(I))=TP(JS(I))+(A-B)*C
            IF(TP(JS(I)).GT.D) TP(JS(I))=D*(TP(JS(I))/D-IDINT(TP(JS(I))/D))-D
          1 IF(TP(JS(I)).LE.0) TP(JS(I))=D*(TP(JS(I))/D-IDINT(TP(JS(I))/D))+D
          2 RETURN
            END
```

```
      FUNCTION VELT(IVH,D)
      DOUBLE PRECISION D
      VELT=60.
      VELT=60.0-IVH*50.0/D
      IF(VELT.LT.10.0) VELT=10.0
      RETURN
      END
```

```
      FUNCTION VELV(IVH,D)
      DOUBLE PRECISION D
      VELV=60.
      VELV=70.0-IVH*60.0/D
      IF(VELV.LT.10.0) VELV=10.0
      RETURN
      END
```

```
      SUBROUTINE QADD(JV,JT)
      COMMON TQ(51,10)
      INTEGER TQ
      TQ(1,JT)=TQ(1,JT)+1
      I=TQ(1,JT)+1
      TQ(I,JT)=JV
      RETURN
      END
```

```
      SUBROUTINE QREMV(JV,ITRUCK,JTRUCK)
      DIMENSION JTRUCK(ITRUCK)
      COMMON TQ(51,10)
      INTEGER TQ
      DO 1 I=1,ITRUCK
      IF(TQ(1,JTRUCK(I)).EQ.0) GO TO 1
      IT=1+TQ(1,JTRUCK(I))
      DO 2 J=2,IT
      IF(TQ(J,JTRUCK(I)).NE.JV) GO TO 2
      DO 4 K=J,IT
    4 TQ(K,JTRUCK(I))=TQ(K+1,JTRUCK(I))
      TQ(1,JTRUCK(I))=TQ(1,JTRUCK(I))-1
    2 CONTINUE
    1 CONTINUE
      RETURN
      END
```

FORTRAN IV G LEVEL 21 SCRIBE DATE = 75223 11/42/08

```
      SUBROUTINE SCRIBE(I,CT,VP,TP,J)
      DOUBLE PRECISION CT,VP,TP
      IF(I.GE.99000000) WRITE(6,4000) I,CT,VP,TP
      IF(I.GT.0)GO TO 3
      J=J+1
      GO TO(1,2),J
    1 I1=I
      A1=CT
      B1=VP
      C1=TP
      IF(I.GE.99000000) WRITE(6,4000)I,A1,B1,C1
      GO TO 3
    2 I2=I
      A2=CT
      B2=VP
      C2=TP
      J=0
      WRITE(6,4000) I1,A1,B1,C1,I2,A2,B2,C2
 4000 FORMAT(' ',2(I9,F10.4,F8.4,F12.4,2X))
    3 RETURN
      END
```

A.7 Listing of the REVIS Multiple Section Monte Carlo Simulation Program

Subroutine		Description
SIML	-	The body of the simulation program which includes the Section I and Section II logic.
SWIT	-	The routine used by SIML to determine which aid vehicle is involved in the next possible event SWITCHOVER.
DDS	-	The routine used by SIML to determine which incident is involved in the next possible event DETECTION or used by SIML to determine which aid vehicle is involved in the next possible event DEPARTURE.
ARRS	-	The routine used by SIML to determine which incident aid vehicle pair is involved in the next possible event ARRIVAL.
LAGT	-	The routine used by SIML to determine the time at which an incident will be detected.
UPDATE	-	The routine used by SIML to update the actual positions of the aid vehicles.
VELT and VELV	-	The routine used by SIML to calculate the speeds of the aid vehicles and the speeds of the disabled vehicles prior to breakdown.
SCRIBE	-	The routine for printing the output report for each event processed by the simulation program.
POINT	-	The routine for debugging and tracing simulation flow.

Subroutine		Description
BENFT1, COST, and PERCNT	-	The routines for keeping statistics on the wait time of the incidents, the maintenance costs of the aid vehicles, and the percentiles of the wait time distribution, respectively.

```
0001      SUBROUTINE SIML (LAMDA,TF,D,DESP,ISEC,IX,IVENC,TCR,CR,PER,IT,IV,VC
         1OUNT,GCOUNT)
0002      DIMENSION VABP(100),VBT(100),VDT(100),JVC(100),JVF(100),JVU(100),
         1TP(50),JTNG(50),JTT(50),JSWU(100),JSWD(100),DIS(1),TCR(50),
         2PER(25,5),JTF(50)
0003      INTEGER GCOUNT(50),VM(100),TM(50),VID(100),CNE(1),VCOUNT(50)
0004      DOUBLE PRECISION CT,CTL,VBT
0005      COMMON SEC(50,2)
0006      DOUBLE PRECISION VABP,VDT,D,TP,SWT,SWD,DETT,ARRD,ARRT,DEPT,AR1,AR2
0007      DOUBLE PRECISION PDS,DIS,SEC,DSEC
0008      REAL LAMDA,LAGT
0009      DIMENSION DATE(3)
0010      ITEM=0
0011      CT=-1
0012      IVB=100
0013      IVB2=IVB-1
0014      IVS=0
0015      VEQ=VELV(500,D)
0016      ITR=ISEC+1
0017      ONE(1)=1
0018      PDS=0.
0019      JDS=0
0020      AR1=0.
0021      JAR1=0
0022      IAR1=0
0023      AR2=0.
0024      IAR2=0
0025      JAR2=0
0026      JDEPT=0
0027      DEPT=0.
0028      ARRD=0.
0029      ARRT=0.
0030      JARR=0
0031      IARR=0
0032      DETT=0.
0033      JDET=0
0034      SWT=0.
0035      SWD=0.
0036      ISW=0
0037      JSW=0
0038      DO 1238 I=1,50
0039      TP(I)=0.
0040      JTT(I)=0
0041      JTNG(I)=0
0042      JTF(I)=0
0043      GCOUNT(I)=0
0044      TM(I)=0
0045      VCOUNT(I)=0
```

```
0046            SEC(I,1)=0.
0047            SEC(I,2)=0.
0048       1238 CONTINUE
0049            DO 1239  I=1,100
0050            JVD(I)=0
0051            JVF(I)=0
0052            JVU(I)=0
0053            JSWU(I)=0
0054            JSWD(I)=0
0055       1239 CONTINUE
          C
          C  SECTIONS
          C
0056            E=D
0057            DSEC=IFIX(E)/2/ISEC
0058            DO 1 I=1,ITR
0059            SEC(I,1)=(I-1)*DSEC
0060          1 SEC(I,2)=D-(I-1)*DSEC
0061            CALL TODAY(DATE)
0062            IF(ITR.GT.1) GO TO 1111
0063            WRITE (6 ,2) DATE
0064            WRITE(6,2000)       LAMDA,TF,D,DESP ,ISEC
0065          2 FORMAT('1',48X,'**********************************'/
               1' ',48X,'*',32X,'*'/
               2' ',48X,'* REVIS SIMULATION EVENT LISTING *'/
               3' ',48X,'* DATE ',3A4,14X,'*'/
               4' ',48X,'*',32X,'*'/
               6' ',48X,'**********************************'/)
0066       2000 FORMAT('0',55X,'SIMULATION PARAMETERS'/
               1' ',55X,'*********************'/
               2'0',42X,'BREAKDOWN RATE',5X,'=',F8.3,' VEHICLES PER HOUR'/
               3' ',42X,'FIXING TIME',8X,'=',F8.3,' HOURS'/
               4' ',42X,'HIGHWAY LENGTH',5X,'=',F8.3,' MILES'/
               5' ',42X,'DETECTOR SPACING',3X,'=',F8.3,' MILES'/
               6' ',42X,'NUMBER OF SECTIONS =',I8//)
0067            WRITE(6,2020)
0068       2020 FORMAT('0',27X,'CLOCK  HIGHWAY   VEHICLE  TRUCK   WAIT'/
               1' ',27X,'TIME   LOCATION   IDENT   IDENT   TIME'/
               2' ',21X,'ITEM  (HRS)  (MILES)   NUMBER   NUMBER  (HRS)',18X,'DESCR
               4IPTION OF EVENT'/
               5' ',21X,'*****************************************************
               6******************************************'/)
0069       1111  CONTINUE
          C
          C  TRUCKS
          C
0070            DO 3 I=1,ITR
0071            VCOUNT(I)=0
```

```
              GCOUNT(I)=0
              TP(I)=(I-1)*DSEC
            3 TM(I)=0
C
C   VEHICLES
C
              DO 4 I=1,IVB
              CALL RANDU(IX,IY,R)
              IX=IY
              IF (I-1) 5,5,6
            5 VBT(1)=0.0
              GO TO 7
            6 VBT(I)=VBT(I-1)-ALOG(R)/LAMDA
            7 CALL RANDU(IX,IY,R)
              IX=IY
              VABP(I)=R*D
              VM(I)=0.
              VDT(I)=0.
            4 VID(I)=I
C
C
C   SECTION 1 DET. OF NEXT EVENT
C    IS EXPERIMENT OVER
         9999 IF(CT.GT.8760.) GO TO 1999
              IF(IVS.EQ.IVEND) GO TO 1999
C
C   HOW MANY VEHICLES AND TRUCKS ON HIGHWAY
C
              ITNG=0
              IVH=0
              ITT=0
              ITF=0
              IVU=0
              IVD=0
              IVF=0
              DO 8 I=1,IVB
              IF(VBT(I) .GT. CT) GO TO 9
              CALL POINT(CT,1 )
            8 IVH=IVH+1
            9 DO 10 I=1,ITR
              IF (TM (I) .EQ. 0) GO TO 10
              CALL POINT(CT,2 )
              ITNG=ITNG+1
              JTNG(ITNG)=I
           10 CONTINUE
C
C   UPDATE VELOCITIES
              VT=VELT(IVH,D)
```

```
              VV=VELV(IVH,D)
C
C   IS GARAGE FULL AND HIGHWAY EMPTY
C
              IF ((IVH .EQ. 0) .AND. (ITNG .EQ.0)) GO TC 100
C
C   DETERMINE STATE OF HIGHWAY
C   STATE OF VEHICLES
C
              IF (IVH .EQ.0) GO TO 11
              DO 12 I=1,IVH
              IF(VM(I)) 15,13,14
          13  IVU=IVU+1
              CALL POINT(CT,3 )
              JVU(IVU)=I
              GO TO 12
          14  IVD=IVD+1
              CALL POINT(CT,4 )
              JVD(IVD)=I
              GO TO 12
          15  IVF=IVF+1
              CALL POINT(CT,5 )
              JVF(IVF)=I
          12  CONTINUE
C
C   TRUCKS
C
          11  IF(ITNG .EQ.0) GO TO 16
              DO 17 I=1,ITNG
              IF (TM(JTNG(I)))19,18,18
          18  ITT=ITT+1
              CALL POINT(CT,6 )
              JTT(ITT)=JTNG(I)
              GO TO 17
          19  ITF=ITF+1
              CALL POINT(CT,7 )
              JTF(ITF)=JTNG(I)
          17  CONTINUE
C
C   IS HIGHWAY EMPTY
C
          16  IF(IVH .EQ.0) GO TO 20
C
C
              CALL POINT(CT,8 )
              IF(ITT .NE.0) GO TO 21
C
C   NO SWITCH IS POSSIBLE
```

```
                C
 0139                CALL POINT(CT,9 )
 0140                SWT=1.0E+75
 0141                SWD=1.0E+75
 0142                GO TO 22
                C
                C   DET. NEXT SWITCH
                C
 0143             21 CALL SWIT(TP,TM,ITR,JTT,ITT,D,SWD,ISW,JSW)
 0144                CALL POINT(CT,10)
 0145                SWT=CT+SWD/VT
                C
                C   ARE ALL VEHICLES UNDETECTED
                C
 0146             22 IF(IVU .EQ.  IVH) GO TO 23
                C
                C   NO VEHICLES UNDETECTED
                C
 0147                CALL POINT(CT,11)
 0148                IF (IVU .EQ. 0) GO TO 24
                C
                C   DETERMINE NEXT DETECTION
 0149                CALL DDS(IVU,JVU,IVH,VDT,DETT,JDET)
 0150                CALL POINT(CT,12)
 0151                GO TO 25
                C
                C   DETECTION IS IMPOSSIBLE
                C
 0152             24 DETT=1.0E+75
                C
                C   ARE ALL VEHICLES DETECTED
                C
 0153             25 IF(IVD .EQ. IVH) GO TO 26
                C
                C   ARE NO  VEHICLES DETECTED
                C
 0154                CALL POINT(CT,13)
 0155                IF(IVD .EQ. 0) GO TO 27
                C
                C   ANY TRUCKS TRAVELING
                C
 0156                IF(ITT .NE. 0) GO TO 28
                C
                C   ARRIVAL IMPOSSIBLE
                C
 0157             27 ARRT=1.E+75
 0158                CALL POINT(CT,14)
 0159                ARRD=1.E+75
```

```
0160                GO TO 29
              C
              C   DETERMINE NEXT ARRIVAL
              C
0161              28 CALL ARRS(ITT,JTT,ITR,TP,TM,IVD,JVD,IVH,VABP,VM,C,ARRD,IARR,JARR,D
                    1SEC)
0162                 CALL POINT(CT,15)
0163                 ARRT=CT+ARRD/VT
              C
              C   ALL VEHICLES BEING FIXED
              C
0164              29 IF(IVF .EQ. IVH) GO TO 30
0165                 CALL POINT(CT,16)
              C
              C   NO VEHICLES BEING FIXED
              C
0166                 IF (IVF .EQ. 0) GO TO 31
              C
              C   DETERMINE NEXT DEPARTURE
              C
0167                 CALL DDS(IVF,JVF,IVH,VDT,DEPT,JDEPT)
0168                 CALL POINT(CT,17)
0169                 GO TO 32
              C
              C   DEPARTURE IMPOSSIBLE
              C
0170              31 DEPT=1.E+75
0171                 CALL POINT(CT,18)
0172                 GO TO 32
              C
              C   ONLY EVENTS ARE SWITCH AND BREAKDOWN
              C
0173              20 CALL SWIT(TP,TM,ITR,JTT,ITT,D,SWD,ISW,JSW)
0174                 CALL POINT(CT,19)
0175                 SWT=CT+SWD/VT
0176             920 IF (SWT-VBT(IVH+1)) 200,100,100
              C
              C   ONLY EVENTS ARE SWITCH,BREAKDOWN,AND DETECTICN
              C
0177              23 CALL DDS(IVU,JVU,IVH,VDT,DETT,JDET)
0178                 CALL POINT(CT,20)
0179                 IF (SWT-DETT) 920,923,923
0180             923 IF (DETT-VBT(IVH+1)) 300,100,100
              C
              C   ONLY EVENTS ARE SWITCH, BREAKDOWN, AND ARRIVAL
              C
0181              26 CALL ARRS(ITT,JTT,ITR,TP,TM,IVD,JVD,IVH,VABP,VM,C,ARRD,IARR,JARR,D
                    1SEC)
```

```
0182           CALL POINT(CT,21)
0183           ARRT=CT+ARRD/VT
0184           IF (SWD-ARRD) 920,926,926
0185       926 IF (ARRT-VBT(IVH+1)) 400,100,100
         C
         C  ONLY EVENTS ARE SWITCH, BREAKDOWN, AND DEPARTURE
0186        30 CALL DDS(IVF,JVF,IVH,VDT,DEPT,JDEPT)
0187        35 IF (SWT-DEPT) 920,930,930
0188       930 IF (DEPT-VBT(IVH+1)) 500,100,100
         C
         C  MATRIX
         C
0189        32 IF (SWT-DETT) 33,34,34
0190        33 IF (SWD-ARRD) 35,36,36
0191        34 IF (DETT-ARRT) 37,36,36
0192        37 IF (DETT-DEPT) 923,930,930
0193        36  IF (ARRT-DEPT) 926,930,930
         C
         C  SECTION 2--EVENTS
         C
         C
         C  BREAKDOWN
         C
0194       100 CTL=CT
0195           CALL POINT(CT,22)
0196           CT=VBT(IVH+1)
0197           IF (ITT .NE. 0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT)
0198           CALL SCRIBE(CT,VABP(IVH+1),VID(IVH+1),0,0.0,0,1,ITEM)
0199           IF(IVH.EQ.IVB2) GO TO 1999
0200           VDT(IVH+1)=CT+LAGT(D,DESP,VABP(IVH+1),VV,VEQ)
0201           GO TO 9999
         C
         C  SWITCH OVER
         C
0202       200 CTL=CT
0203           CALL POINT(CT,23)
0204           CT=SWT
0205           JSH=TM(ISW)
0206           CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT)
0207           IF (TP(ISW) .LE. D/2) GO TO 201
         C TRUCK=2
0208           TP(ISW)=SEC(JSW,1)
0209           IF( ISW.EQ.JSW) GO TO 202
0210       207 CALL SCRIBE(CT,TP(ISW),ISW,JSW,0.0,JSH,2,ITEM)
0211           GO TO 9999
0212       202 GCOUNT(ISW)= GCOUNT(ISW)+1
0213           IF (IVD .EQ.0) GO TO 208
0214           ISWD=0
```

```
0215              ISWU=0
0216              DO 205 I=1,IVD
0217              IF(VM(JVD(I)).EQ.JSW) GO TO  209
0218              IF(VM(JVD(I)).EQ.JSW-1) GO TO 210
0219              GO TO 205
0220          209 ISWU=ISWU+1
0221              JSWU(ISWU)=JVD(I)
0222              GO TO 205
0223          210 ISWD=ISWD+1
0224              JSWD(ISWD)=JVD(I)
0225          205 CONTINUE
0226              IF((ISWU.NE.0).AND.(ISWD.NE.0)) GO TO 211
0227              IF(ISWU.NE.0) GO TO 212
0228              IF(ISWD.NE.0) GO TO 213
0229          208 TP(ISW)=SEC(JSW,1)
0230              TM(ISW)=0
0231              CALL SCRIBE(CT,TP(ISW),ISW,0,0.0,0,3 ,ITEM)
0232              GO TO 9999
0233          211 IF((TM(ISW+1).EQ.JSW).AND.(TM(ISW-1).EQ.JSW-1)) GO TO 214
0234              IF(TM(ISW+1).EQ.JSW) GO TO 215
0235              IF(TM(ISW-1).EQ.JSW-1) GO TO 216
0236          217 IF(ISWU-ISWD) 215,216,216
0237          214 IF((ISWU.GT.1).AND.(ISWD.GT.1)) GO TO 217
0238              CALL DDS(ISWU,JSWU,IVH,VABP,PDS,JDS)
0239              CALL ARRS(1,ONE,1,TP(ISW+1),TM(ISW+1),1,ONE,1,VABP(JDS),VM(JDS),D,
                 1AR1,IAR1,JAR1,DSEC)
0240              DIS(1)=SEC(JSW,1)
0241              CALL ARRS(1,ONE,1,DIS,VM(JDS),1,ONE,1,VABP(JDS),VM(JDS),D,AR2,IAR2
                 1,JAR2,DSEC)
0242              IF(AR1.GT.AR2) GO TO 218
0243              CALL DDS(ISWD,JSWD,IVH,VABP,PDS,JDS)
0244              CALL ARRS(1,ONE,1,TP(ISW-1),TM(ISW-1),1,ONE,1,VABP(JDS),VM(JDS),D,
                 1AR1,IAR1,JAR1,DSEC)
0245              DIS(1)=SEC(JSW,2)
0246              CALL ARRS(1,ONE,1,DIS,VM(JDS),1,ONE,1,VABP(JDS),VM(JDS),D,AR2,IAR2
                 1,JAR2,DSEC)
0247              IF(AR1.GT.AR2) GO TO 215
0248              GO TO 208
0249          218 CALL DDS(ISWD,JSWD,IVH,VABP,PDS,JDS)
0250              CALL ARRS(1,ONE,1,TP(ISW-1),TM(ISW-1),1,ONE,1,VABP(JDS),VM(JDS),D,
                 1AR1,IAR1,JAR1,DSEC)
0251              DIS(1)=SEC(JSW,2)
0252              CALL ARRS(1,ONE,1,DIS,VM(JDS),1,ONE,1,VABP(JDS),VM(JDS),D,AR2,IAR2
                 1,JAR2,DSEC)
0253              IF(AR1.GT.AR2) GO TO 217
0254          216 TP(ISW)=SEC(JSW,1)
0255              TM(ISW)=JSW
0256              GO TO 207
```

```
  215 TP(ISW)=SEC(JSW,2)
      JSW=JSW-1
      TM(ISW)=JSW
      GO TO 207
  212 IF(TM(ISW+1).EQ.JSW) GO TO 219
      GO TO 216
  219 IF(ISWU.GT.1) GO TO 216
      CALL DDS(ISWU,JSWU,IVH,VABP,PDS,JDS)
      CALL ARRS(1,ONE,1,TP(ISW+1),TM(ISW+1),1,ONE,1,VABP(JDS),VM(JDS),D,
     1AR1,IAR1,JAR1,DSEC)
      DIS(1)=SEC(JSW,1)
      CALL ARRS(1,ONE,1,DIS,VM(JDS),1,ONE,1,VABP(JDS),VM(JDS),D,AR2,IAR2
     1,JAR2,DSEC)
      IF(AR1.GT.AR2) GO TO 216
      GO TO 208
  213 IF(TM(ISW-1).EQ.JSW-1) GO TO 220
      GO TO 215
  220 IF(ISWD.GT.1) GO TO 215
      CALL DDS(ISWD,JSWD,IVH,VABP,PDS,JDS)
      CALL ARRS(1,ONE,1,TP(ISW-1),TM(ISW-1),1,ONE,1,VABP(JDS),VM(JDS),D,
     1AR1,IAR1,JAR1,DSEC)
      DIS(1)=SEC(JSW,2)
      CALL ARRS(1,ONE,1,DIS,VM(JDS),1,ONE,1,VABP(JDS),VM(JDS),D,AR2,IAR2
     1,JAR2,DSEC)
      IF(AR1.GT.AR2) GO TO 215
      GO TO 208
  201 TP(ISW)= SEC(JSW+1,2)
      IF(ISW.NE.JSW+1) GO TO 207
      JSW=JSW+1
      GO TO 202
C
C  DETECTION
C
  300 CTL=CT
      CALL POINT(CT,24)
      CT=DETT
      IF (ITT .NE. 0) CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT)
      K=2
      IF(VABP(JDET) .LE. D/2.) K=1
      DO 301 I=2,ITR
      J=ITR-(I-1)
      IF (VABP(JDET) .LE. D/2.) J=I
      IF (VABP(JDET) .LE. SEC(J,K)) GO TO 302
  301 CONTINUE
  302 IF(K.EQ.1) J=J-1
      VM(JDET)=J
      CALL SCRIBE(CT,VABP(JDET),VID(JDET),J,0.0,0,4,ITEM)
      IF (K .EQ. 2) GO TO 304
```

```
0298            IF (TM(J) .EQ. 0) GO TO 305
0299            IF (TM(J+1) .EQ. 0) GO TO 306
0300            GO TO 9999
0301        304 IF(TM(J+1) .EQ. 0) GO TO 306
0302            IF (TM(J) .EQ. 0) GO TO 305
0303            GO TO 9999
0304        305 TM(J) =J
0305            CALL SCRIBE(CT,TP(J),J,J,0.0,0,5,ITEM)
0306            GO TO 9999
0307        306 TM(J+1)=J
0308            L=J+1
0309            TP(J+1)=SEC(J+1,2)
0310            CALL SCRIBE(CT,TP(J+1),L,J,0.0,0,5,ITEM)
0311            GO TO 9999
          C
          C   ARRIVAL
          C
0312        400 CTL=CT
0313            CALL POINT(CT,25)
0314            CT=ARRT
0315            CALL UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT)
0316            TP(IARR)= VABP(JARR)
0317            TM(IARR)=-VID(JARR)
0318            VM(JARR)=-VM(JARR)
0319            VDT(JARR)=CT+TF
0320            CALL  SCRIBE(CT,VABP(JARR),VID(JARR),IARR,0.0,0,6,ITEM)
0321            GO TO 9999
          C
          C   DEPARTURE
          C
0322        500 CTL=CT
0323            CALL POINT(CT,26)
0324            CT=DEPT
0325            IF(ITT .NE. 0) CALL UPDATE (ITT,JTT,ITR,TP,CT,CTL,VT)
0326            DO 501 I=1,ITF
0327            IF(TM(JTF(I))+VID(JDEPT)) 501,502,501
0328        501 CONTINUE
0329            WRITE(6,1357)    (JTF(II),II=1,ITF),(TM(JTF(II)),II=1,ITF),VID(JDE
               1PT)
0330       1357 FORMAT(' ',      14I7)
0331        502 TM(JTF(I))=-VM(JDEPT)
0332            VCOUNT(JTF(I))=VCOUNT(JTF(I))+1
0333            CALL BENFT1(IVS,CT,VBT(JDEPT),VM(JDEPT),PER,IVEND)
0334            WT=CT-VBT(JDEPT)
0335            CALL SCRIBE(CT,VABP(JDEPT),VID(JDEPT),JTF(I),WT,0,7,ITEM )
0336            IVS=IVS+1
0337            DO 504 J=JDEPT,IVB2
0338            VBT(J)=VBT(J+1)
```

```
      VABP(J)=VABP(J+1)
      VM(J)=VM(J+1)
      VDT(J)=VDT(J+1)
  504 VID(J)=VID(J+1)
      CALL RANDU(IX,IY,R)
      IX=IY
      VBT(IVB)=VBT(IVB2)-ALOG(R)/LAMDA
      CALL RANDU(IX,IY,R)
      IX=IY
      VABP(IVB)=R*D
      VID(IVB)=IVB+IVS
      VDT(IVB)=0.
      GO TO 9999
 1999 WRITE(6 ,2002) DATE
 2002 FORMAT('1',46X,'**************************************'/
     1' ',46X,'*',36X,'*'/
     2' ',46X,'* REVIS SIMULATION OUTPUT STATISTICS *'/
     3' ',46X,'* DATE ',3A4,18X,'*'/
     4' ',46X,'*',36X,'*'/
     5' ',46X,'**************************************' )
      WRITE (6,2000)       LAMDA,TF,D,DESP,ISEC
      IF (IVS.GT.IVEND)IVS=IVEND
      WRITE(6 ,2001) CT,IVS
 2001 FORMAT(' ',57X,'SIMULATION SUMMARY'/
     1' ',57X,'******************'/
     2'0',44X,'TIME DURATION OF SIMULATION',F9.3,' HCURS'/
     3' ',44X,'TOTAL NUMBER OF INCIDENTS',I10//
     4'0',57X,'INCIDENT STATISTICS'/
     5' ',57X,'*******************'/
     6'0',51X,'MEAN'/
     E' ',31X,'HIGHWAY   NUMBER     WAIT   MEAN SQUARE'/
     7' ',31X,'SECTION     OF       TIME    WAIT TIME'/
     8' ',31X,'NUMBER   INCIDENTS  (HRS)    (HCURS)    WAIT TIME (HRS) P
     9ERCENTILES'/
     A' ',31X,'*******************************************************
     B**********'/
     C' ',71X,2X,'100',7X,'90',9X,'80'/
     D ' ',71X,' *****************************'/)
      CALL  BENFT2(IVS,ISEC,PER)
      WRITE(6 ,2021)
 2021 FORMAT('0',56X,'AID VEHICLE STATISTICS'/
     1' ',56X,'**********************'/
     2'0',58X,'NUMBER  NUMBER OF'/
     3' ',45X,'AID VEHICLE    OF     INCIDENTS    CCST'/
     4' ',47X,'NUMBER      TRIPS   SERVICED   (DCLLARS)'/
     5' ',45X,'*****************************************'/)
      CALL COST(VCOUNT,GCOUNT,ITR,TCR,CR,IT,IV,D,CT)
      RETURN
```

```
0363                END
```

```
      SUBROUTINE SWIT(TP,TM,ITR,JTT,ITT,D,SWD,ISW,JSW)
      COMMON SEC(50 ,2)
      DOUBLE PRECISION TP,D,SWD,SWH,SEC
      INTEGER TM
      DIMENSION TP(ITR),TM(ITR),JTT(ITT)
      SWD=D
      DO 1 I=1,ITT
      IF (TP(JTT(I)) .LT. D/2) GO TO 2
      SWH=SEC(TM(JTT(I)),2)-TP(JTT(I))
      GO TO 3
    2 SWH=SEC(1+TM(JTT(I)),1)-TP(JTT(I))
    3 IF(SWH.GT.SWD)GO TO 1
      SWD=SWH
      ISW=JTT(I)
      JSW=TM(JTT(I))
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DDS(K,J,IVH,VDT,DT,JDT)
      DOUBLE PRECISION VDT,DT
      DIMENSION J(K),VDT(IVH)
      DT=1.E+75
      DO 1 I=1,K
      IF (VDT(J(I)) .GT.DT) GO TO 1
      DT=VDT(J(I))
      JDT=J(I)
    1 CONTINUE
      RETURN
      END
```

```
FORTRAN IV G LEVEL  21                ARRS                 DATE = 75223         11/33/57

0001              SUBROUTINE ARRS (ITT,JTT,ITR,TP,TM,IVD,JVD,IVH,VABP,VM,D,ARRD,IARR
                 1,JARR,DSEC)
0002              DOUBLE PRECISION TP,VABP,D,ARRD, DSEC,SEC, ARH
0003              INTEGER TM,VM
0004              DIMENSION JTT(ITT),TP(ITR),TM(ITR),JVD(IVD),VABP(IVH),VM(IVH)
0005              COMMON SEC(50 ,2)
0006              ARRD=D
0007              DO 1 I=1,IVD
0008              DO 2 J=1,ITT
0009              IF(TM(JTT(J)) .NE. VM(JVD(I)))GO TO 2
0010              IF((TP(JTT(J)) .LE. D/2) .AND. (VABP(JVD(I)) .LE. D/2))GO TO 3
0011              IF((TP(JTT(J)) .GT. D/2) .AND. (VABP(JVD(I)) .GT. D/2))GO TO 3
0012              IF (TP(JTT(J)) .LE. D/2)  GO TO 5
            C
            C  TRUCK - 2  VEHICLE - 1
            C
0013              ARH= VABP(JVD(I))-SEC(VM(JVD(I)),1) + SEC(VM(JVD(I)),2)-TP(JTT(J))
0014              GO TO 4
            C
            C  TRUCK - 1  VEHICLE - 2
            C
0015            5 ARH=SEC(VM(JVD(I))+1,1)-TP(JTT(J))+VABP(JVD(I))-SEC(VM(JVD(I))+1,2
                 Y)
0016              GO TO 4
            C
            C  VEH - 2   TRUCK - 2   OR   VEH - 1   TRUCK - 1
            C
0017            3 ARH=VABP(JVD(I))-TP(JTT(J))
0018              IF(ARH.LT.0) ARH=ARH+DSEC*2.
0019            4 IF (ARH .GT. ARRD) GO TO 2
0020              ARRD=ARH
0021              IARR=JTT(J)
0022              JARR=JVD(I)
0023            2 CONTINUE
0024            1 CONTINUE
0025              RETURN
0026              END
```

```
      FUNCTION LAGT(D,DESP,VAP,VV,VEQ)
      DOUBLE PRECISION D,VAP
      REAL LAGT
      IF (DESP .EQ. 0.0) GO TO 2
      L=D/DESP+.5
      DO 1 J=1,L
      IF (VAP .LT. J*DESP) GO TO 3
    1 CONTINUE
    2 LAGT=0.0
      GO TO 4
    3 LAGT=DESP/VEQ-(VAP-(J-1)*DESP)/VV
    4 RETURN
      END
```

```
      SUBROUTINE UPDATE(ITT,JTT,ITR,TP,CT,CTL,VT)
      DOUBLE PRECISION TP
      DOUBLE PRECISION CT,CTL
      DIMENSION JTT(ITT), TP(ITR)
      IF (CT .EQ. CTL) GO TO 2
      DO 1 I=1,ITT
    1 TP(JTT(I))=TP(JTT(I))+(CT-CTL)*VT
    2 RETURN
      END
```

```
      FUNCTION VELT(IVH,D)
      DOUBLE PRECISION D
      VELT=60.-IVH*50./D
      IF(VELT .LT. 10.) VELT=10.0
      RETURN
      END
```

FORTRAN IV G LEVEL 21 VELV DATE = 75223 11/33/57

```
      FUNCTION VELV(IVH,D)
      DOUBLE PRECISION D
      VELV=70.-IVH*60./D
      IF (VELV .LT. 10.) VELV=10.0
      RETURN
      END
```

```
FORTRAN IV G LEVEL  21                 SCRIBE               DATE = 75223              11/33/57

              SUBROUTINE SCRIBE (CT,POS,VTID,TVID,WT,ISEC,I ,ITEM)
              DOUBLE PRECISION POS
              INTEGER VTID,TVID
              DOUBLE PRECISION CT
              IF(I.GT.0) GO TO 8
              ITEM=ITEM+1
            9 GO TO (1,2,3,4,5,6,7),I
            1 WRITE(6,10) CT,POS,VTID
           10 FORMAT(' ',F12.4,4X,F10.4,4X,I7,16X,'BKN')
              GO TO 8
            2 WRITE(6,20) CT,POS,VTID,ISEC,TVID
           20 FORMAT(' ',F12.4,4X,F10.4,15X,I7,I3,'= ',I3,' SWC')
              GO TO 8
            3 WRITE(6,30) CT,POS,VTID
           30 FORMAT(' ',F12.4,4X,F10.4,15X,I7,5X,'GAR')
              GO TO 8
            4 WRITE(6,40) CT,POS,VTID,TVID
           40 FORMAT(' ',F12.4,4X,F10.4,4X,I7,14X,I3,' DET')
              GO TO 8
            5 WRITE(6,50) CT,POS,VTID,TVID
           50 FORMAT(' ',F12.4,4X,F10.4,15X,I7,2X,I3,' DIS')
              GO TO 8
            6 WRITE(6,60) CT,POS,VTID,TVID
           60 FORMAT(' ',F12.4,4X,F10.4,4X,I7,4X,I7,5X,'ARR')
              GO TO 8
            7 WRITE(6,70) CT,POS,VTID,TVID,WT
           70 FORMAT(' ',F12.4,4X,F10.4,4X,I7,4X,I7,5X,'DEP',4X,F10.4 )
            8 RETURN
              END
```

```
      SUBROUTINE POINT(CT,N)
      DOUBLE PRECISION CT
      IF(N.GT.0) GO TO 1
      WRITE(6,2) N
    2 FORMAT(' ',I7)
    1 RETURN
      END
```

FORTRAN IV G LEVEL 21 BENFT1 DATE = 75223 11/33/57

```
      SUBROUTINE BENFT1(I,CT,BT,J,PER,IVEND)
      DIMENSION WT(10000,2),W(10000),A(10000),PER(25,5)
      DOUBLE PRECISION CT,BT
      IF(I.GE.IVEND) GO TO 4
      WT(I+1,1)=CT-BT
      W(I+1)=WT(I+1,1)
      WT(I+1,2)=-J
    4 RETURN
      ENTRY BENFT2(I,ISEC,PER)
      IF(I.GT.IVEND) I=IVEND
      PER(1,4)=0.
      PER(1,5)=0.
      DO 1 J=1,I
      PER(1,4)=PER(1,4)+WT(J,1)
    1 PER(1,5)=PER(1,5)+WT(J,1)**2
      PER(1,4)=PER(1,4)/I
      PER(1,5)=PER(1,5)/I
      CALL PERCNT(W,A,I,PER(1,1),PER(1,2),PER(1,3))
      DO 2 J=1,ISEC
      PER(J+1,4)=0.
      PER(J+1,5)=0.
      K=0
      DO 3 L=1,I
      IF(WT(L,2).NE.J) GO TO 3
      PER(J+1,4)=PER(J+1,4)+WT(L,1)
      PER(J+1,5)=PER(J+1,5)+WT(L,1)**2
      K=K+1
      W(K)=WT(L,1)
    3 CONTINUE
      IF(K.EQ.0) GO TO 2
      PER(J+1,4)=PER(J+1,4)/K
      PER(J+1,5)=PER(J+1,5)/K
      CALL PERCNT(W,A,K,PER(J+1,1),PER(J+1,2),PER(J+1,3))
    2 WRITE(6,30) J,K,PER(J+1,4),PER(J+1,5),PER(J+1,1),PER(J+1,2),PER(J+
     11,3)
   30 FORMAT(' ',31X,I4,6X,I4,4X,F7.4,3X,F7.4,5X,F7.4,3X,F7.4,3X,F7.4)
      WRITE(6,20) I,PER(1,4),PER(1,5),PER(1,1),PER(1,2),PER(1,3)
   20 FORMAT(' ',31X,' TOTAL',1X,I7,4X,F7.4,3X,F7.4,5X,F7.4,3X,F7.4,3X,F
     17.4//)
      RETURN
      END
```

```
      SUBROUTINE COST(VCOUNT,GCOUNT,ITR,TCR,CR,IT,IV,D,CT)
      DOUBLE PRECISION CT
      DIMENSION TCR(ITR)
      INTEGER VCOUNT(ITR),GCOUNT(ITR)
      WRITE(6,30)
   30 FORMAT(' ')
      ADJ=CT/8760.
      IF(ADJ.GT.1.) ADJ=1.
      IT=0
      IV=0
      CR=0.
      DO 1 I=1,ITR
      TCR(I)=(15000.*ADJ+.25*D*GCOUNT(I)/(ITR-1)+3.*VCCUNT(I))/ADJ
      WRITE(6,10) I,GCOUNT(I),VCOUNT(I),TCR(I)
   10 FORMAT(' ' ,44X,I7, 4X,I7, 2X,I7 ,3X,F10.0)
      IT=IT+GCOUNT(I)
      IV=IV+VCOUNT(I)
    1 CR=CR+TCR(I)
      WRITE(6,20) IT,IV,CR
   20 FORMAT(' ',47X,'TOTAL', 3X,I7, 2X,I7,3X,F10.0)
      RETURN
      END
```

```
      SUBROUTINE PERCNT(WT,A,I,WMAX,W9,W8)
      DIMENSION WT(I),A(I)
      DO 1 J=1,I
      A(J)=0.
      DO 2 K=1,I
      IF(WT(K).LT.A(J)) GO TO 2
      A(J)=WT(K)
      KH=K
    2 CONTINUE
    1 WT(KH)=-WT(KH)
      WMAX=A(1)
      I9=.1*I+.5
      I8=.2*I+.5
      IF(I9.EQ.0) I9=1
      IF(I8.EQ.0) I8=1
      W9=A(I9)
      W8=A(I8)
      RETURN
      END
```

A.8 Listing of the Spectral Analysis Program

```
      SUBROUTINE  SPECS(A,N,NN)
      CIMENSION A(2000),COV(2000),W(2000),SPEC(4006)
      DIMENSION IGRAP(101)
      DO 300 I=1,101
  300 IGRAP(I)=BLANK
C FIND MEANS
      SUM=0.
      DO 2 I=1,N
    2 SUM=SUM+A(I)
      AVE=SUM/N
C CALCULATE DIFFERENCES
      DO 3 I=1,N
    3 A(I)=A(I)-AVE
C CALCULATE COVARIANCE AND CORRELATIONS
      N1=N
      IF(NN.EQ.1)N1=1
      DO 4 I=1,N1
      SUM=0.
      K=N-I+1
      DO 5 J=1,K
    5 SUM=SUM+A(J)*A(J+I-1)
      COV(I)=SUM/N
      IF (I.EQ.1) VARHAT=COV(1)
    4 COV(I)=COV(I)/VARHAT
      DO 110 I10=1,N
  110 A(I10)=A(I10)+AVE
      WRITE(6,1001) N
 1001 FORMAT(1H ,' THE ESTIMATED MEAN, VARIANCE, ANC CCRRELATIONS FOR N
     1= ',I4)
      WRITE(6,1000) AVE,VARHAT,(COV(I),I=1,N1)
 1000 FORMAT(1H ,6E16.7)
      IF(NN.EQ.1) GO TO 1007
C FIND BAND M
      DO 6 I=1,N
      J=N-I+1
      IF(ABS(COV(J)).GE.0.1) GOTO 7
    6 CONTINUE
C DOUBLE M
    7 M=J*2
C CALCULATE VHAT,C,NI,AND SPECTRAL DENSITY
      DO 9I2=1,10
      M=M/2
      IF(M.EQ.0) GO TO 100
      SUM=COV(1)
      K=M-1
      IF(K.EQ.0) GO TO 12
      DO 8 I=1,K
      SUM=SUM+2.*COV(I+1)*(1.-FLOAT(I)/FLOAT(M))
```

```
      8 W(I)=0.5*(1.+COS(3.1416* I/M))
     12 VHAT=SUM/N*VARHAT
        C=VHAT*N/(2.*VARHAT)
        NI=VARHAT/VHAT
        L=2*M+1
        DO 10 I=1,L
        SUM=COV(1)
        IF(K.EQ.0) GO TO 10
        DO 11 J=1,K
     11 SUM=SUM+2.*W(J)*COV(J+1)*COS(3.1416*J*(I-1)/(2.*M))
     10 SPEC(I)=2.*SUM
        WRITE(6,1004)
   1004 FORMAT(1H ,' RECORD LENGTH,WINDOW LAG,VHAT,CCR LAG AND IND NO OBS
       1')
        WRITE(6,1003) N,M,VHAT,C,NI
   1003 FORMAT(1H ,2I5,2E16.7,I5)
        FREQ=1./(4.*M)
        WRITE(6,1005) L,FREQ
   1005 FORMAT(1H ,' THE ',I5,' SPECTRAL DENSITY COMPONENTS BETWEEN 0 AND
       11/2 CYCLE AT INTERVALS OF 1/4M = ',E16.7,' CYCLES')
        SPEC(L+1)=0.0
        SPEC(L+2)=0.0
        SPEC(L+3)=0.0
        K=L/3+1
        KK=1
        DO 200 I=1,K
        F1=FREQ*(KK-1)
        F2=FREQ*(KK  )
        F3=FREQ*(KK+1)
        WRITE(6,1010) F1,SPEC(KK),F2,SPEC(KK+1),F3,SPEC(KK+2)
   1010 FORMAT(1H ,3(E16.7,' / ',E16.7,' . '))
        KK=KK+3
    200 CONTINUE
      9 CONTINUE
    100 CONTINUE
        WRITE(6,1006)
   1006 FORMAT(1H0, ' THE END')
   1007 RETURN
        END
```

A.9 Listing of the Program for Calculating the Mean Wait Time of the Periodic Service Queue as a Function of M

Subroutine		Description
DRV	-	The routine to calculate the first and second partial derivatives of $\beta^i(z)$ as a function of M.
MEANS	-	The routine which initializes all constants required by DRV.
WAIT	-	The routine which calculates the first and second central moments of the intervisit time and the first moment of the wait time from the values of the first and second partial derivatives obtained from DRV.
U, DETA, and Fl	-	The routines used by DRV for formulating the linear matrix equations required for the calculation of the first and second partial derivatives of $\beta^i(z)$.
BKSLV, DIAG, ROWSUB, CONS, and ROWINT	-	The routines used by DRV for solving the linear matrix equations.

```
FORTRAN IV G LEVEL  21                DRV                 DATE = 75223          11/40/36

      SUBROUTINE DRV(H,C,B,A,G,H1,C1,D1,F,P,M,M1,M2,ZETA,ETA,THETA,EPS,D
     1UM,W)
      DIMENSION H(M1,M),C(M1,1),B(M1),A(M1,M1),G(M,M1),H1(M1,M1,M),C1(M1
     A,M1),D1(M2),F(M2,M2),P(M2,1),DUM(M2),W(M1,1)
      DO 1 J=1,M1
      DO 1 I=1,M
      H(J,I)=ZETA*DETA(J-M+I-1)
      N=I-1
      IF(N .EQ. 0) GO TO 1
      DO 2 K=1,N
    2 H(J,I)=H(J,I)+ZETA*H(J,K)
    1 CONTINUE
      DO13 I=1,M1
      C(I,1)=(M-I)*ETA
      DO 3 K=1,M
    3 C(I,1)=C(I,1)+K*H(I,M-K+1)*ETA
   13 W(I ,1)=C(I,1)
      DO 5 I=1,M1
      DO 5 J=1,M1
      A(I,J)=-H(I,M-J+1)
    5 IF(I .EQ. J) A(I,I)=1+A(I,I)
      CALL DIAG(A,W,M1,DUM)
      CALL BKSLV(A,W,B,M1)
      DO 6 I=1,M
      DO 6 N=1,M1
      G(I,N)=THETA* DETA(N-I)
      K=M-I
      IF(K .EQ. 0) GO TO 6
      DO 7 L=1,K
    7 G(I,N)=G(I,N)+H(N,L)*THETA
    6 CONTINUE
      DO 8 N=1,M1
      DO 8 J=1,M1
      DO 8 L=1,M
      H1(N,J,L)=G(M-L+1,N)*DETA(J-M+L-1)
      I=L-1
      IF(I .EQ. 0) GO TO 8
      DO 9 K=1,I
    9 H1(N,J,L)=H1(N,J,L)+G(M-L+1,N)*H(J,K)+ZETA*H1(N,J,K)
    8 CONTINUE
      DO 10 N=1,M1
      DO 10 J=1,M1
      C1(N,J)=0.
      DO 12 K=1,M
      DO 12 L=1,M
   12 C1(N,J)=C1(N,J)+EPS*(L*H(N,M-L+1)+(M-L)*U(L-N))*(K*H(J,M-K+1)+(M-K
     A)*U(K-J))
      DO 10 K=1,M
```

```
FORTRAN IV G LEVEL  21                    DRV                    DATE = 75223          11/40/36

     10 C1(N,J)=C1(N,J)+ETA*K*H1(N,J,M-K+1)
        DO 11 L=1,M1
        DO 11 J=L,M1
        DO 11 I=1,M1
        DO 11 K=I,M1
        N1=(L-1)*(2*M-2-L)/2+J
        N2=(I-1)*(2*M-2-I)/2+K
        F(N1,N2)=-(H(L,M-K+1)*H(J,M-I+1)+H(J,M-K+1)*H(L,M-I+1)*F1(I-K))
     11 IF (N1 .EQ. N2)  F(N1,N2)=1+F(N1,N2)
        DO 4 L=1,M1
        DO 4 J=1,M1
        N1=(L-1)*(2*M-2-L)/2+J
        P(N1,1)=C1(L,J)
        DO 4 I=1,M1
      4 P(N1,1)=P(N1,1)+B(I)*H1(L,J,M-I+1)+C(L,1)*B(I)*H(J,M-I+1)+C(J,1)*B
       1(I)*H(L,M-I+1)
        CALL DIAG (F,P,M2,DUM)
        CALL BKSLV (F,P,D1,M2)
        RETURN
        END
```

```
FORTRAN IV G LEVEL  21                 MEANS              DATE = 75223          11/40/36

                SUBROUTINE MEANS(LAMDA,TF,D,V,TF2,ZETA,ETA,THETA,EPS,M)
                REAL LAMDA
                RHO=LAMDA/M*TF
                ZETA=RHO/(1-RHO)
                ETA=LAMDA*D/(M**2*V)
                EPS=ETA**2
                THETA=(LAMDA/M)**2*TF2/(1-RHO)**3
                WRITE(6,1) RHO,ZETA,ETA,EPS,THETA
              1 FORMAT(' ',5E16.7)
                RETURN
                END
```

```
      SUBROUTINE WAIT (LAMDA,TF,D,V,TF2,C,B,M)
      REAL LAMDA
      Z=D/V*(1-LAMDA/M*TF)/(1-LAMDA*TF)
      V2=C*(M/LAMDA)**2+2*B*D/V/LAMDA+(D/V/M)**2
      W=V2/(2*Z)+LAMDA/M*TF2/(2*(1-LAMDA/M*TF))+TF
      WRITE( 6,2) C,B,V2
    2 FORMAT(' ','THE SECOND DERIVATIVE ',E16.7,'THE FIRST',F16.7, 'THE
     1SECOND MOMENT OF THE INTERVISIT TIME ',E16.7)
      WRITE (6,1) W,Z
    1 FORMAT (' ','THE MEAN WAIT',E16.7,'THE MEAN INTERVISIT',E16.7)
      RETURN
      END
```

```
      FUNCTION U(N)
      IF (N) 1,2,1
    2 U=1.
      GO TO 3
    1 U=0.
    3 RETURN
      END
```

```
      FUNCTION DETA(N)
      IF (N) 1,2,2
    1 DETA=1.
      GO TO 3
    2 DETA=0.
    3 RETURN
      END
```

```
      FUNCTION F1(N)
      F1=1-U(N)
      RETURN
      END
```

```
      SUBROUTINE BKSLV(A,B,C,N)
      DIMENSION A(N,N),B(N,1),C(N)
      DO 1 I=1,N
      K=N-I+1
      C(K)=B(K,1)
      IF (I .EQ. 1) GO TO 1
      K1=K+1
      DO 2 J=K1,N
    2 C(K)=C(K)-A(K,J)*C(J)
    1 CONTINUE
      WRITE (6,3) C
    3 FORMAT(' ',6E16.7)
      RETURN
      END
```

FORTRAN IV G LEVEL 21 DIAG DATE = 75223 11/40/36

```
      SUBROUTINE DIAG(A,B,N,DUM)
      DIMENSION A(N,N),B(N,1),DUM(N)
      DO 1 I=1,N
      J=I+1
    3 IF(A(I,I) .EQ. 0.) GO TO 2
      C=A(I,I)
      CALL CONS(A,N,N,I,C)
      CALL CONS (B,N,1,I,C)
      GO TO 4
    2 IF(J .GT. N) GO TO 5
      CALL ROWINT(A,N,N,I,J,DUM)
      CALL ROWINT(B,N,1,I,J,DUM)
      J=J+1
      GO TO 3
    4 K=I+1
      IF(I.EQ.N) GO TO 8
      DO 6 J=K,N
      C=A(J,I)
      CALL ROWSUB (A,N,N,J,I,C)
    6 CALL ROWSUB(B,N,1,J,I,C)
    1 CONTINUE
      GO TO 8
    5 WRITE (6,7)
    7 FORMAT (' ','MATRIX CAN NOT BE INVERTED')
    8 RETURN
      END
```

```
      SUBROUTINE ROWSUB(A,N,M,J,I,C)
      DIMENSION A(N,M)
      DO 1 K=1,M
    1 A(J,K)=A(J,K)-A(I,K)*C
      RETURN
      END
```

```
      SUBROUTINE CONS(A,N,M,I,C)
      DIMENSION A(N,M)
      DO 1 J=1,M
    1 A(I,J)=A(I,J)/C
      RETURN
      END
```

FORTRAN IV G LEVEL 21 ROWINT DATE = 75223 11/40/36

```
      SUBROUTINE ROWINT (A,N,M,I,J,DUM)
      DIMENSION A(N,M),DUM(M)
      DO 1 K=1,M
      DUM (K)=A(I,K)
      A(I,K)=A(J,K)
    1 A(J,K)=DUM(K)
      RETURN
      END
```

A.10 Listing of the Program for Calculating the Mean and Mean Square Wait Time of the First Disabled, First Serve Highway Aid Problem Using M/G/1 Queuing Theory

```
$JOB
      REAL LAMDA
      V=60.
      D=40.
      EXTF=.25
      EXTF2=EXTF**2
      EXTF3=EXTF**3
      EXTT=D/V/2.
      EXTT2=(D/V)**2/3.
      EXTT3=(D/V)**3/4.
      EXTS=EXTF+EXTT
      EXTS2=EXTF2+EXTT2+2.*EXTF*EXTT
      EXTS3=EXTF3+EXTT3+3.*EXTF*EXTT2+3.*EXTF2*EXTT
      LAMDA=0.
      DO 1 I=1,3
      LAMDA=LAMDA+.5
      RHO=LAMDA*EXTS
      EXWT=RHO/LAMDA+LAMDA**2*EXTS2/(2.*LAMDA*(1-RHO))
      EXWT2=EXTS2+RHO*EXTS2/(1-RHO)+LAMDA*EXTS3/(3.*(1-RHO))+LAMDA**2*EX
     1TS2**2/(2.*(1-RHO)**2)
    1 PRINT,LAMDA,RHO,EXWT,EXWT2
      STOP
      END
```

AUTOBIOGRAPHICAL STATEMENT

Mr. Joel Schesser was born in the Bronx, New York in 1945.

He entered City College in 1963 to study Electrical Engineering. During his undergraduate career, he pursued an interest in solid state devices and circuit design.

In 1968 after he received his Bachelor of Electrical Engineering, Mr. Schesser accepted an appointment as Lecturer on the staff of the Department of Electrical Engineering of the City College of the City University of New York and entered the Doctor of Philosophy program at the City University of New York to study electromagnetic wave theory. He received his Master of Science degree in Electrical Engineering in 1971 at the City University.

Mr. Schesser is a member of the Institute of Traffic Engineers, the IEEE Group of Vehicular Technology, Computer Simulation Society, Eta Kappa Nu, and Tau Beta Pi.