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Methodology For Servicing The Geography Of Urban Fire: An Exploration With Special Reference To London, Ontario

Nigel Michael Waters

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METHODOLOGY FOR SERVICING THE GEOGRAPHY OF URBAN FIRE: AN EXPLORATION WITH SPECIAL REFERENCE TO LONDON, ONTARIO

by

Nigel Michael Waters

Department of Geography

Submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
June, 1977

ABSTRACT

This study investigates the problem of providing fire department service in larger North American cities. London, Ontario, is used as an example.

The thesis includes a discussion of methodology which has been previously developed and implemented for the purpose of determining the locations and response districts of fire stations. Prior to this there is an extensive account of the procedures which were used to collect the pertinent data for the case study.

In order to provide a deeper understanding of the nature of the demands for fire department service both the temporal and spatial arrangement of alarms which occurred in London during 1973 are analysed for patterns. Autocorrelation and Fourier methods are used to determine temporal periodicities while trend surface, distance decay models and interpolation techniques are used to analyse the spatial patterns. The relationship between response time and response distance is investigated using regression models. In addition an unsuccessful attempt is made to explain the spatial pattern of residential alarms using a multiple regression model.

Following this there is a review of the location-allocation model literature and a discussion of how these models have been applied to the fire station problem. Various procedures for generating a demand surface using Thiessen polygons are also described.

Having decided upon an appropriate demand surface location-allocation models are applied to a series of fire station problems some of which were being considered by the London Fire Department.

Finally, there is an evaluation of the usefulness of location-allocation models for solving this type of problem and a consideration of how sensitive they are to the assumptions made in the course of the analysis.

In the concluding chapter of the thesis suggestions are made on how a fire department might expedite future studies of this nature and on how they might improve upon the study.

ACKNOWLEDGEMENTS

Researching and writing this thesis has taken a number of years. During that time I have been helped by many people.

First and foremost I would like to thank my supervisor, Michael Goodchild. I could not have wished for better supervision or more steadfast friendship.

I would also like to thank the other members of my supervisory committee, Professors Janelle, Massam and Svrcek. Professor Warntz and numerous other members of the Department of Geography at the University of Western Ontario also provided inspiration and ideas.

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Even a quick perusal of the thesis will show that I have an enormous debt to various members of the fire-fighting profession. In particular I would like to mention the help and encouragement afforded to me by London's Fire Chief, Ray Morley. Without the support and kindness of Chief Morley the thesis would not have been completed. Other members of his department, especially Division Chief Wills, were also very helpful. Roy Philippe, from the Office of the Ontario Fire Marshal, provided me with ideas, a wealth of research material and

hospitality. Fire Chief Jackson and Deputy Chief Beattie of the Calgary Fire Department provided similar help and stimulation.

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CHAPTER 1

Introduction to the Study Area

The research reported in this thesis describes methodology for locating fire-fighting units to service the geography of urban fire. This methodology is applied to a case study for the city of London, Ontario.

The City of London acts as the regional centre for a large portion of south-western Ontario. In 1973 (the year for which the case study was carried out) the city had a population of 232,760 persons and covered an area of 68.64 square miles (see Figure 1.1). There were nine fire stations in 1973 and the equipment located at each of these stations is shown in Table 1.1 which is taken from the City of London Fire Department Annual Report for 1973.

The main change which has occurred in the Department since 1973 has been the closure of the oldest of the Fire Stations, Number 3, which was formerly located on Bruce Street and is shown in Plate 1.1. This Station has now been replaced by a new number 3 Station which was built in 1974 on the south-western corner of the Wonderland and Commissioners Road intersection. The new Station is shown in Plate 1.2 and, as can be seen, it is a two bay station which contains a pumper and a telesquirt fire-fighting unit.

Also worth mentioning are Fire Stations 5 and 6. Fire Station 5 is one of the oldest stations which is still in service in London. It was built in the days when the fire wagons were pulled by horses and it is now suffering from structural problems (Fire Chief Ray Morley, personal communication). If a new station is built in the southeast,

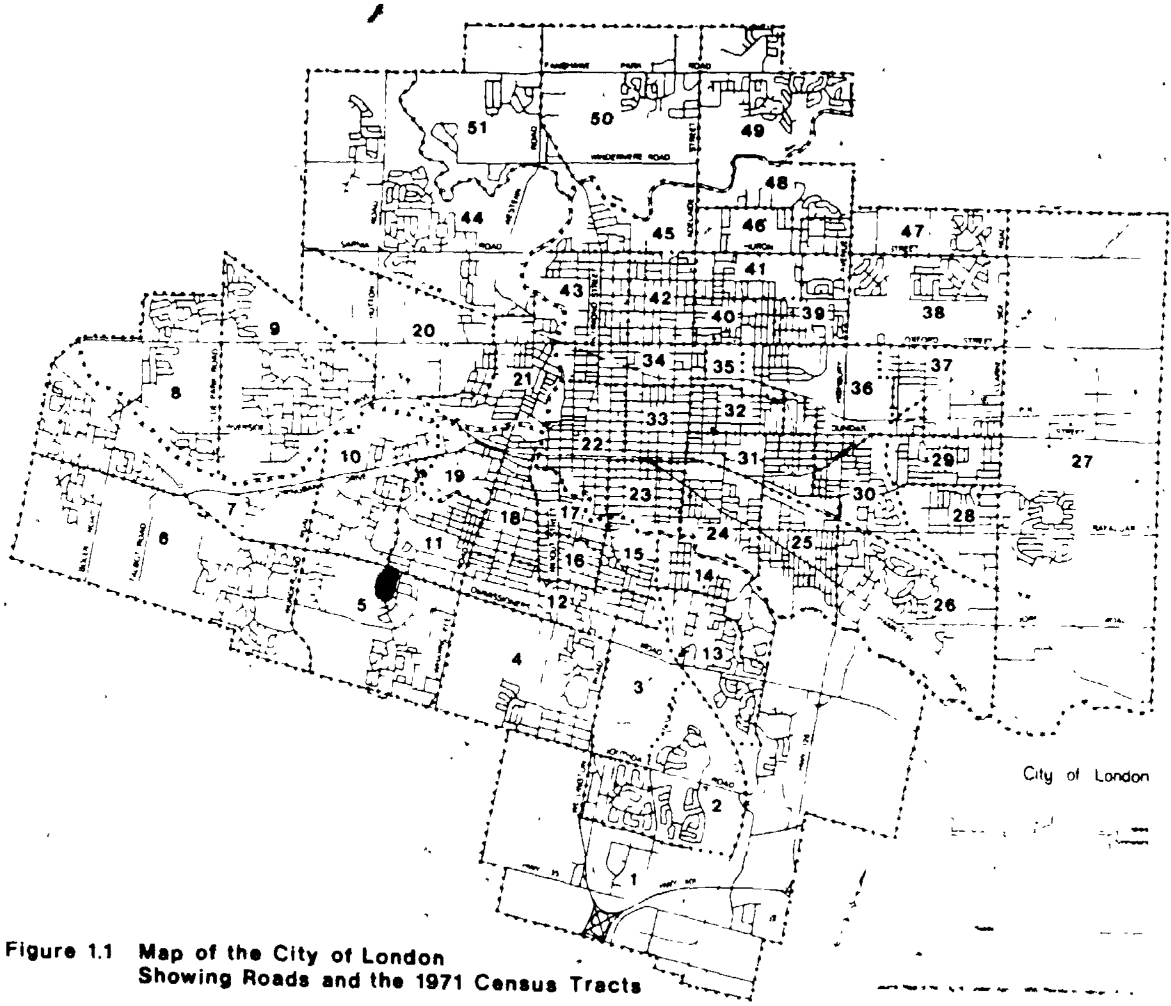


Figure 1.1 Map of the City of London
Showing Roads and the 1971 Census Tracts

TABLE 1.1: Information Relating to London's Nine Fire Stations During 1973 (Source: City of London Fire Department Annual Report for 1973)

Station Number	Fire Hall Address	Date Built	Equipment Available
1	340 Waterloo	1956	Pumper, Aerial Platform, Rescue Unit, 3 cars
2	1101 Florence St.	1953	Pumper, Aerial, 1 car
3	160 Bruce St.	1880	Pumper
4	807 Colborne St.	1909	Pumper
5	155 Adelaide St.	1909	Pumper
6	1293 Commissioners Rd. West	1941/ 1953	Pumper
7	1192 Highbury Ave.	1962	Pumper
8	1565 Western Rd.	1964	Pumper, Aerial
9	746 Wellington Rd. South	1971	Pumper

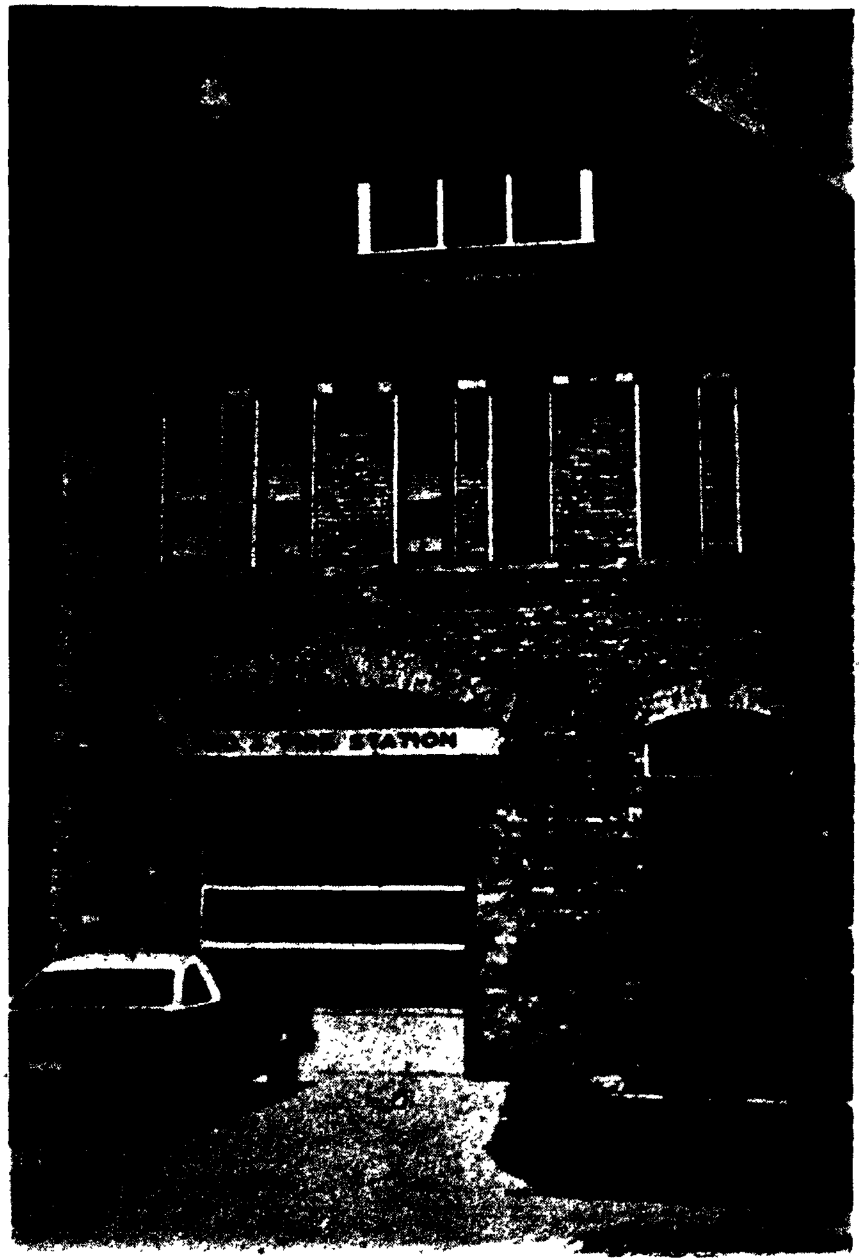


Plate 1.1 The Old Number 3 Fire Station

Plate 1.2 The Present Number 3 Fire Station

where Chief Morley and the analysis described in Chapter 6 suggest it should go, Fire Station 5 might well be closed down. The replacement station would in all likelihood be a two bay station very similar to the new number 3 station. Fire Station 5 is shown in Plate 1.3.

Plate 1.4 shows Fire Station 6. This station is of interest because it is to be relocated in the near future. Again the analysis in Chapter 6 seems to support such a move. At present Fire Station 6 shares its location with the Byron Library and this represents a major impediment to its expansion into a two bay station.

The methodology described in this research is only useful for determining the general location of fire stations. It offers no suggestions as to the most suitable site for a fire station. This, however, is an important aspect of the problem. Ideally, the station should have rapid access to a main through route but if it is actually located on a street with a heavy traffic flow the fire trucks may have problems getting on to the road. Furthermore, it takes a few moments for the truck driver to "settle down" and adjust after the alarm has been turned in (Dr. H. Hosse, personal communication). Thus, it may prove preferable to locate a station on a minor road which has access to a main through route. The problem is illustrated by London's Fire Station 7 (shown in Plate 1.5), which is located on Highbury Avenue. Plate 1.6 shows a view of Highbury Avenue outside Fire Station 7. The photograph shows that not only has the speed limit been reduced from 40 miles per hour to 30 miles per hour but also a special flashing light is required to warn traffic when the fire trucks are exiting. These microscale problems are not examined in the thesis.

Chapter 2 of the thesis discusses the procedures which were

Plate 1.3 Fire Station Number 5

Plate 1.4 Fire Station Number 6

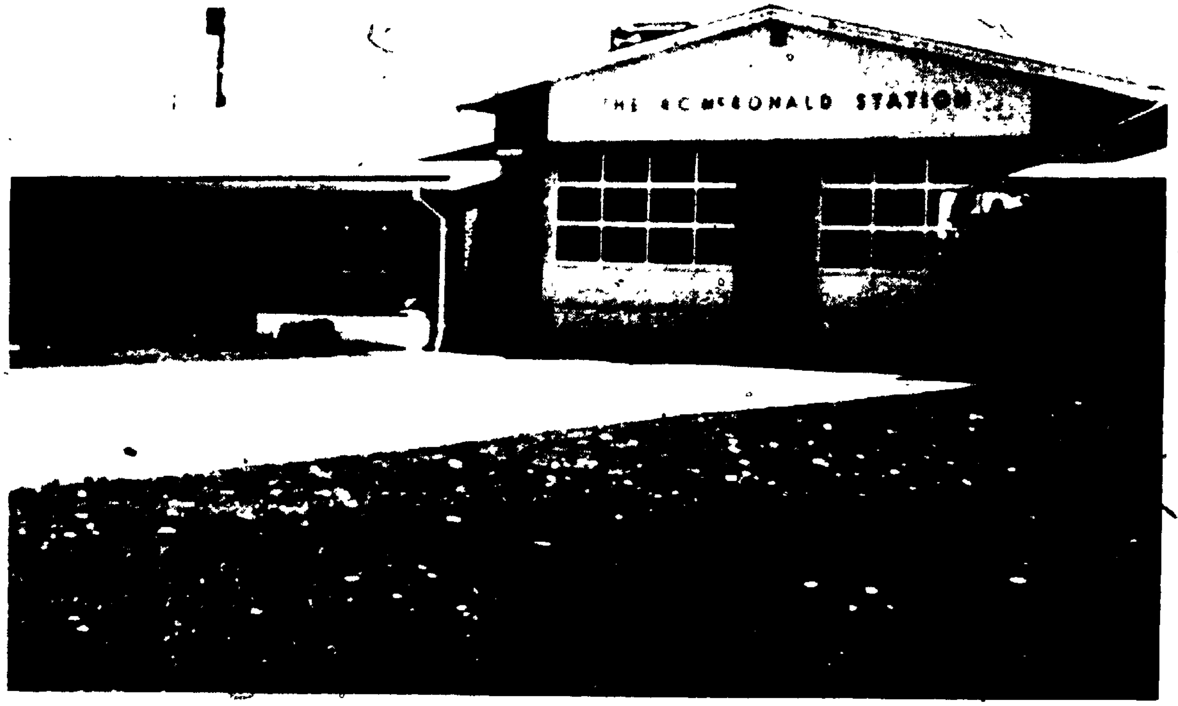


Plate 1.5 Fire Station Number 7

Plate 1.6 Highbury Avenue Close to Fire Station 7.

used to collect the data for the case study. In addition, Chapter 2 includes a review of the literature relating specifically to the fire station location problem. Chapter 3 represents an attempt to describe the spatial and temporal characteristics of both the alarm distribution and the response times in London. An attempt is made to build an explanatory multiple regression in Chapter 4. This model seeks to explain the nature of the alarm distribution in London. A typology of location-allocation models is presented in Chapter 5 along with a review of those mathematical models which have been used to locate fire stations and allocate first due response districts. A series of location-allocation studies are conducted for the London Fire Department in Chapter 6. The assumptions of the models and the efficiency of intuitive solutions are considered in Chapter 7. Finally, in Chapter 8 the main conclusions of the thesis are discussed and suggestions are made for future research in the area of emergency facility location.

CHAPTER 2

Data Collection and Existing Fire Department Planning Procedures

In this chapter the data collection procedures used in the study are described. In addition, the chapter also considers the strengths and weaknesses of the traditional, and some more recent, planning methods which have been used to determine fire station locations and fire department operational procedures.

Data Collection

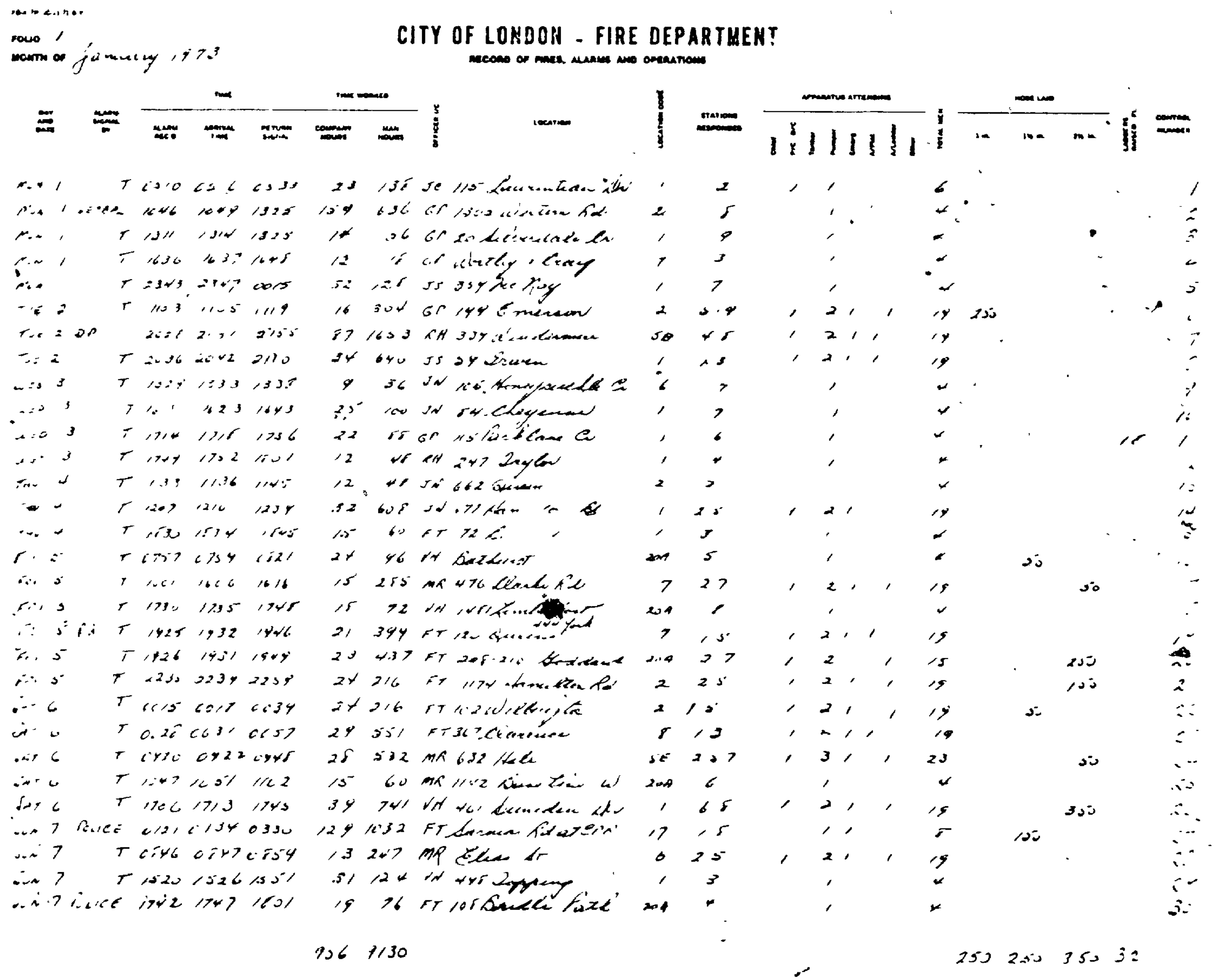
Data for the study were taken from the records of the London Fire Department for 1973. Originally, it had been hoped to collect data for more than one year so that a larger sample would be obtained providing more confidence in the results and so that some analysis of yearly cycles and long term trends could be made. Unfortunately, the process of acquiring the data proved too time consuming and as a result data were collected for only one year. This, however, should not be seen as a severe drawback to the study since during this year there were 2,459 fire alarms and thus the analysis was based on an acceptably large data set. It must be admitted though that since the data for only one year were used no attempt could be made to determine the existenee of yearly cycles or any significant long term trends. These questions will have to be left to subsequent studies, though the answers might possibly be useful in determining the location of future fire stations. The sensitivity of the analysis to such **changes** is discussed in Chapter 7.

The year 1973 was chosen for a number of reasons. At the time the study was started it represented the most recent available data. If long term trends do exist in the data and these trends have a spatial manifestation then it is obviously better to use the most recent data if one of the aims of the thesis is to predict optimum locations for new fire stations. In addition, it was felt that the 1973 fire alarm data were not too remote from the 1971 census variables which it was hoped could be used to help build a predictive and explanatory model of the demand for fire department services in the city (see Chapter 3 and Chapter 4).

The London Fire Department maintains very comprehensive statistics on every fire alarm received. Figures 2.1a and 2.1b show the information available for alarms during 1973. As can be seen from these two figures some of the information, such as the amount of hose laid, was pertinent to some aspects of fire department operations but not to the present analysis and so this information was not recorded. However, any information considered pertinent to the analysis was recorded. Such information was copied onto computer coding sheets and then punched onto computer cards. Each computer card represented the information pertinent to one fire alarm. This information was coded as shown in Table 2.1.

The information on the day, month, year and the time of each alarm was used for a time series analysis to determine whether there were any significant short term cycles in the data which might affect the planning of fire department operations (this is discussed in more detail in Chapter 3). It was also felt that it would be useful to determine whether the fire engines travelled more rapidly to alarms at different times of the day and in different parts of the city due to the different traffic conditions and, as a result, the response times were also required.

It should be noted here that the response time was calculated as

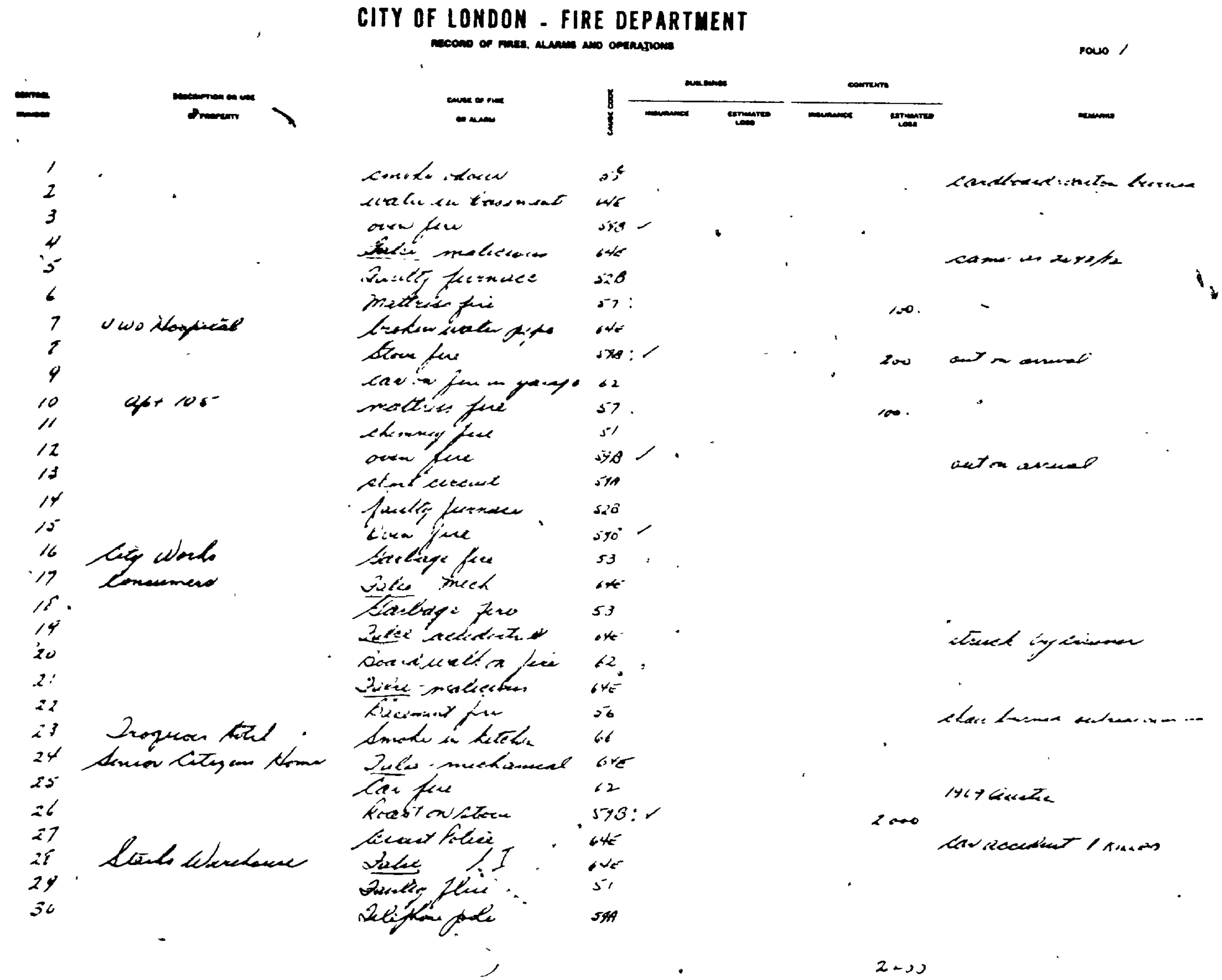


FOLIO 1
MONTH OF January 1973

CITY OF LONDON - FIRE DEPARTMENT
RECORD OF FIRES, ALARMS AND OPERATIONS

DAY AND DATE	ALARM SIGNAL BY	ALARM REC'D	ARRIVAL TIME	RETURN SIGNAL	COMPANY HOURS	MAN HOURS	OFFICER I/C	LOCATION	LOCATION CODE	STATIONS RESPONDED	APPARATUS ATTENDING	TOTAL MEN	HOSE LAID 1 in.	HOSE LAID 1½ in.	HOSE LAID 2½ in.	LADDERS	CONTROL NUMBER
Mon 1	T	0310	[illegible]	0333	23	138	SC	115 Laurentian Ave	1	2	1 1	6					1
Mon 1	[illegible]	1046	1049	1325	159	636	GP	1303 Western Rd.	2	5	1	✓					[illegible]
Mon 1	T	1311	1314	1325	14	56	GP	20 Silverdale Cr.	1	9	1	✓					[illegible]
Mon 1	T	1636	1637	1648	12	48	GP	Wortley & Craig	7	3	1	✓					[illegible]
Mon	T	2343	2347	0015	52	128	SS	354 McRoy	1	7	1	✓					[illegible]
Tue 2	T	1103	1105	1119	16	304	GP	144 Emerson	2	3.4	1 2 1 1	19	250				[illegible]
Tue 2	DP	2021	2031	2155	87	1653	RH	337 [illegible]	5B	4 5	1 2 1 1	19					[illegible]
Tue 2	T	2036	2042	2110	34	640	SS	34 Bruce	1	1 3	1 2 1 1	19					[illegible]
Wed 3	T	1329	1333	1338	9	36	JN	106 Honeysuckle Cr	6	7	1	✓					[illegible]
Wed 3	T	[illegible]	1423	1443	25	100	JN	54 Cheyenne	1	7	1	✓					[illegible]
Wed 3	T	1714	1718	1736	22	88	GP	115 Parkland Cr	1	6	1	✓				18	1
Wed 3	T	1749	1752	1801	12	48	RH	247 Taylor	1	4	1	✓					[illegible]
Thu 4	T	1133	1136	1145	12	48	JN	662 Queen	2	2		✓					[illegible]
Thu 4	T	1207	1210	1234	32	608	JN	171 [illegible]	1	2 5	1 2 1	19					[illegible]
Thu 4	T	1530	1534	1545	15	60	FT	72 [illegible]	1	3	1	✓					[illegible]
Fri 5	T	0757	0759	0821	24	96	FH	Bathurst	204	5	1	✓		50			[illegible]
Fri 5	T	1601	1606	1616	15	255	MR	476 Clarke Rd	7	2 7	1 2 1 1	19			50		[illegible]
Fri 5	T	1730	1735	1748	15	72	VH	1401 [illegible]	204	8	1	✓					[illegible]
Fri 5 FA	T	1925	1932	1946	21	399	FT	120 Queens	7	1 5	1 2 1 1	19					[illegible]
Fri 5	T	1926	1931	1949	23	437	FT	208-210 Goddard	204	2 7	1 2 1	15			250		[illegible]
Fri 5	T	2230	2234	2259	24	216	FT	1174 Hamilton Rd	2	2 5	1 2 1 1	19			100		[illegible]
Sat 6	T	0015	0017	0034	24	216	FT	1020 Wellington	2	1 5	1 2 1 1	19		50			[illegible]
Sat 6	T	0626	0631	0657	24	551	FT	367 Clarence	8	1 3	1 2 1 1	19					[illegible]
Sat 6	T	0910	0922	0948	28	532	MR	632 Hale	5E	2 3 7	1 3 1 1	23			50		[illegible]
Sat 6	T	1047	1051	1102	15	60	MR	1102 [illegible]	20A	6	1	✓					[illegible]
Sat 6	T	1706	1713	1745	39	741	VH	401 [illegible]	1	6 8	1 2 1 1	19			300		[illegible]
Sun 7	Police	0131	0134	0330	129	1032	FT	Sarnia Rd at [illegible]	17	1 5	1 1	5		100			[illegible]
Sun 7	T	0746	0747	0754	13	247	MR	Elias St	6	2 5	1 2 1 1	19					[illegible]
Sun 7	T	1520	1526	1551	51	124	VH	445 [illegible]	1	3	1	✓					[illegible]
Sun 7	Police	1742	1747	1801	19	76	FT	105 [illegible]	204	4	1	✓					[illegible]
					936	9130							250	250	350	32	

Figure 2.1a An Example from the 1973 City of London Fire Department Records - Part 1



CITY OF LONDON - FIRE DEPARTMENT

RECORD OF FIRES, ALARMS AND OPERATIONS

FOLIO 1

CONTROL NUMBER	DESCRIPTION OR USE OF PROPERTY	CAUSE OF FIRE OR ALARM	CAUSE CODE	BUILDINGS		CONTENTS		REMARKS
				INSURANCE	ESTIMATED LOSS	INSURANCE	ESTIMATED LOSS	
1		smoke odour	55					cardboard carton burned
2		water in basement	64E					
3		oven fire	578 ✓					
4		False malicious	64E					came in as [illegible]
5		faulty furnace	52B					
6		Mattress fire	57				150.	
7	UWO Hospital	broken water pipe	64E					
8		Stove fire	578 ✓				200	out on arrival
9		car on fire in garage	62					
10	Apt 105	mattress fire	57				100.	
11		chimney fire	51					
12		oven fire	578 ✓					out on arrival
13		short circuit	57A					
14		faulty furnace	52B					
15		oven fire	578 ✓					
16	City Works	Garbage fire	53					
17	Consumers	False mech	64E					
18		Garbage fire	53					
19		False accidental	64E					struck by [illegible]
20		Boardwalk on fire	62					
21		False - malicious	64E					
22		Basement fire	56					[illegible]
23	Iroquois Hotel	Smoke in kitchen	66					
24	Senior Citizens Home	False - mechanical	64E					
25		Car fire	62					1969 Austin
26		Roast on stove	578 ✓				2000	
27		Assist Police	64E					car accident 1 [illegible]
28	Steels Warehouse	False	64E					
29		Faulty flue	51					
30		Telephone pole	57A					
							2-33	

Figure 2.1b An Example from the 1973 City of London Fire Department Records - Part 2 .

TABLE 2.1: Coding System for the Raw Data

Columns	Data
1 - 2	Day alarm received
3 - 4	Month alarm received
5 - 6	Year alarm received
7 - 10	Time alarm received
11 - 12	Response time in minutes
13 - 16	Company time in minutes
17 - 20	X coordinate of alarm location
22 - 25	Y coordinate of alarm location
29 - 30	Census Tract number for alarm
33 - 35	Enumeration Area number for alarm
36	Fire Stations responding - Station #1
37	" - Station #2
38	" - Station #3
39	" - Station #4
40	" - Station #5
41	" - Station #6
42	" - Station #7
43	" - Station #8
44	" - Station #9
46	Number and type of apparatus responding - Chief's car
47	" - Platoon, District Chief's car
48	" - Tankers

continued . . .

Table 2.1 cont'd.

Columns	Data
49	Number and type of apparatus responding - Pumpers
50	" - Emergency Vehicles
51	" - Aerial platforms
52	" - Aerial ladders
53	" - Other vehicles
55 - 58	Sequence number of alarm
63 - 66	Cause code for alarm
67	Alarm code
68 - 70	Property code
71 - 72	Number of deaths
73 - 80	Assessed damage in dollars

the arrival time minus the time the alarm was received. It does not, therefore, include the burning time between ignition and the time the alarm was turned in and nor does it include the set-up time which is included by Chaiken, Ignall and Walker (1975c, p.11) in their definition of response time as shown in Figure 2.2. Previously, researchers who have studied the relationship between response time and travel distance have included neither set-up time nor dispatching time in their definition of response time (e.g. Hendrick and Plane et al., 1975, p. 20). However, in the present study, dispatching time was included in the definition and this partly explains the high intercepts found when response time was regressed with travel distance (see Chapter 3 for a complete discussion of this topic). The reason for analysing the relationship between response times and distance is that a fundamental axiom necessary for the validity of the location-allocation models discussed in Chapter 6 is that there is a direct relationship between the two variables. The regression analysis described in Chapter 3 provides a series of estimates for this relationship.

The next piece of information coded was the company time in minutes. This is the difference, in minutes, between the time the alarm was received and the time the return signal was given. The original intention was that this should be used as one measure of the "seriousness" of a fire. Thus, it was felt that the length of time a company spent answering a fire call was one measure of the significance of that alarm. Other measures are, of course, important and some of these were recorded and are discussed below. One measure which was not used was the "man-time" spent servicing each alarm. This statistic represents the company time multiplied by the number of men used. In some ways it is a more sophisticated statistic since the

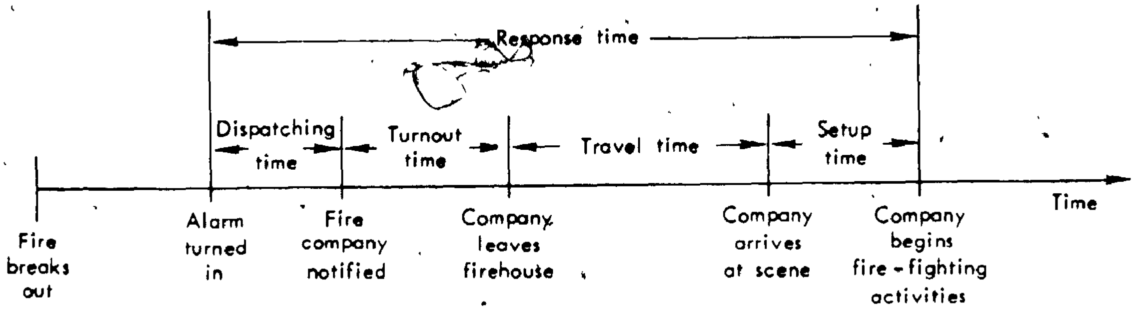


Figure 2.2 The definition of response time used by Chaiken, Ignall and Walker, 1975, p. 11

number of men used in answering an alarm varies from a low of four to over twenty and is thus a significant variable. It is suggested here that future studies should assess the relationship between this and other measures of an alarm's importance. For example, a clustering algorithm could be used to determine which of these measures provide essentially similar information. The company time, which was the measure used in this analysis, does have at least one very important attribute since it represents the span of time over which the equipment is unavailable to answer any other calls and, in this respect, is an important statistic for determining the need for a fire station covering policy or an adaptive response policy (the latter is discussed in Chapter 3).

The X and Y coordinates were recorded for each alarm. This proved to be one of the most tedious, time consuming and uninspiring parts of the analysis. The method used was to take the address location as listed in the fire department records and, where this was not readily identifiable, to use the London Street Directory and Census Tract maps to identify the location accurately. The location was then marked on the City Engineer's Map of London (which is drawn to a scale of 10 centimetres to the mile) and the X and Y coordinates were recorded on a finely defined grid. The spacing between the grid lines was 50 feet. In most cases the accuracy with which the alarm was located was probably excessive. Thus it is suggested here that in future, since great accuracy is not really required with such large samples, and also because the location process is too time consuming, the address matching tapes created by Statistics Canada should be used to provide interpolated block-face coordinates for each alarm. However, if this is to be done the actual street addresses in the fire department records will have to be standardised. An obvious alternative is for the fire department itself to record the geographical coordinates as part of their records.

The Census Tract and Enumeration Area numbers were also recorded. Initially, the main reason for doing this was so that the socio-economic variables provided by the 1971 Census could be used to help build an <u>explanatory</u> multiple regression model. However, the census tracts also proved useful for building a less complex, predictive regression model which is discussed in Chapter 3. One problem in acquiring this data was that on a number of occasions the location of the fire alarm was given as the intersection of a crossroads and where these were major roads they also tended to be at the junction of four enumeration areas or four census tracts. The problem was to decide in which of the enumeration areas or census tracts the alarm should be placed. Frequently, the description of the property allowed one to determine the correct location of the alarm but not always and, in some cases, such as car accidents the alarm could have legitimately fallen into any one of the census tracts. In these latter instances the alarms were assigned to census tracts and enumeration areas on a rotating basis. Thus, under these circumstances, the alarms would be assigned first to the north western census tract and enumeration area. The next time they would be assigned to the south eastern census tract and enumeration area, then to the south western and finally to the north eastern and so on. As shall be seen in Chapter 4 the explanatory model proved unsuccessful (though hardly for this reason since the number of instances in which this problem arose proved to be an acceptably small sample) so this problem does not in any way bring into question the results of the analysis. The demand surface (which is discussed in Chapter 5) was based on 150 demand zones which were centred on the major street intersections of the city and so this problem caused no inaccuracies in the estimation of that surface.

Each fire station responding to a given alarm and the number and type of apparatus attending was also included in the data set. As can be seen in Table 2.1 the apparatus is disaggregated into eight types which include: the chief's car, the platoon and district chief's car, tankers, pumpers, emergency vehicles, aerial platforms, aerial ladders and a "catch-all" category of minor vehicles labelled "other".

A sequence number was also recorded for each alarm to allow a ready cross reference with the original data. The next three variables recorded provide more detailed information on the nature of the alarm. The first is the cause code for the alarm. A list of the possible types of causes is shown in Figure 2.3, which is taken from the City of London Fire Department's Annual Report for 1973. This figure also shows the frequency distribution of the causes. The alarm code was set up solely for this study (that is to say it is not used as such by the London Fire Department) to provide a quick and easy way to distinguish between the various types of false alarms and the alarms listed as emergencies and finally those that fell into none of these categories. The actual coding was as follows:

1 - Emergencies*
2 - False alarms - good intent
3 - False alarms - mechanical and accidental
4 - False alarms - malicious
5 - All others

*as defined in the Fire Department records

ALARMS - CLASSIFICATION OF CAUSES

CODE	CLASSIFICATION	NUMBER OF ALARMS	
		1972	1973
51	Chimneys, flues, cupolas and stacks	22	29
52A	Oil fired space heaters	5	7
52B	Other types of oil burning stoves & furnaces	39	13
52C1	Gas fired stoves, etc, using natural gas	60	65
52C2	Gas fired stoves, etc, using propane gas	5	4
52C3	Gas fired stoves, etc, using other types of gas	5	2
52D	Solid fuel fired appliances (coal wood, etc.)	7	9
52E	Smokepipes, etc., from code '52' sources	6	6
53	Hot ashes, coals, open fires	372	424
54	Sparks on roofs	0	0
55	Exposure fires	1	0
56	Smoking (cigars, pipes, cigarettes, etc.)	129	119
57	Matches	31	37
58	Lights (other than electric)	2	9
59A	Electricity	199	213
59B	Electric stoves and furnaces	106	137
59C	Television sets	13	13
60	Lighting	9	9
61	Spontaneous combustion	9	2
62	Petroleum and its products	268	337
63	Incendiarism	59	54
64A	Gas fired appliances other than cooking-heating	21	15
64B	Defects in gas service lines & inside piping	6	7
64C	Defects in gas distribution systems	2	10 *
64D	Defects in gas transmission lines	3	0
64E	Miscellaneous	621	823
66	Causes unknown	95	117
	TOTALS	2,095	2,459

NOTE: * One alarm caused damage to 49 additional residences.

Figure 2.3 Classification of Alarm Causes from the City of London Fire Department's Annual Report for 1973

The property code breakdown is shown in Figure 2.4, which is also taken from the Fire Department's Annual Report for 1973. The Office of the Ontario Fire Marshal (Roy Philippe, personal communication) has stated that a more detailed property code should be employed in the future and this will no doubt help to increase the sensitivity of subsequent analyses and should also facilitate the building of explanatory regression models.

Finally, the number of deaths at an alarm and the assessed property damage in dollars were recorded. These were both felt to be possible alternatives for measuring the seriousness of an alarm either separately or as a combined measure since a number of studies have tried to assess the worth of a life in monetary terms for the purpose of analysing fire department operations (e.g. see the more recent work by Hogg and also Melinek, 1972).

Existing Fire Department Operations and Planning Procedures

The main objective of the thesis is to suggest new methodology for planning the distribution of fire department resources in urban settings. If this objective is to be achieved the new approaches must be shown to be superior to those which are already in use and thus it becomes necessary to critically evaluate the strengths and weaknesses of present fire department planning procedures.

At the present time the grading schedules, published by the various insurance offices, are the main guides for planning the distribution of fire stations and fire companies. These grading schedules specify, for a given required fire flow, the maximum allowable distances to fire companies of various types. One such set of standards, used in the United States, is shown in Table 2.2. In Canada, the Canadian Underwriters' Association publish the accepted

ALARMS - CLASSIFICATION OF PROPERTY

CODE	CLASSIFICATION	NUMBER OF ALARMS 1972	1973
1	Brick, etc. dwelling	642	832
2	Frame, etc. dwelling	134	137
4	Farm risks	7	18
5A	Churches	5	9
5B	Hospitals, sanitoriums, mental institutions	62	53
5C	Public Halls	14	6
5D	Schools	97	118
5E	Municipal Halls, Fire Halls, Police Stations, Libraries, Museums, Jails, Public Homes, YM & YW CAs, and similar social service organizations, government property, etc.	45	43
6	Warehouses of all kinds (not on mfg. premises)	54	72
7	Retail stores, office buildings, banks	104	164
8	Hotels	35	25
9	Food and food product plants, canning factories, wineries, sugar refineries, packing houses breweries, distilleries, ice factories and bakeries	8	21
10	Flour, cereal mills and grain elevators	1	2
11	Service stations and all oil risks (excluding private and public garages)	17	33
13	Lumber yards, pulpwood in mills, standing timber	7	2
14	Woodworks (excluding saw-mills)	3	3
15	Metal works, public garages, hangars, and foundries	20	16
17	Railway and traction properties, electric light and power plants, gas works, waterworks, sewage works, incinerators, telephone exchanges, radio and TV stations, fireworks	52	39
18	Miscellaneous manufacturing and processing specialists not otherwise classified	47	36
19	Miscellaneous non-manufacturing specialists including theatres, clubs, laundries	12	14
20	Sprinklered risks of whatever nature of occupancy	9	2
20A	Miscellaneous classifications including parks, streets, corners, etc	720	814
	TOTALS	2,095	2,459

Figure 2.4 Property Code Classification from the City of London Fire Department's Annual Report for 1973

TABLE 2.2: Fire Company Distribution Standards

District and Required Fire Flow	Optimum Service Radius in Miles	
	From Engine, Hose, or Engine-Ladder Company	From Ladder Company
High-Value District (commercial, industrial, institutional)		
Where required flow is 9000 gpm or more	3/4	1
Where required fire flow is 4500 to 8999 gpm	1	1.1/4
Where required fire flow is less than 4500 gpm	1.1/2	2
Residential District		
Where required fire flow is more than 2000 gpm or where there are buildings in the district three or more stories in height, including tenement houses, apartments or hotels	1.1/2	2
Same as above, but where the life hazard is above normal	1	1.1/4
For buildings having an average separation of less than 100 feet (and a fire flow requirement of 2000 gpm or less)	2	3
For buildings having an average separation of 100 feet or more (and a fire flow requirement of 2000 gpm or less)	4	4

SOURCE: American Insurance Association (National Board of Fire Underwriters) FIRE DEPARTMENT STANDARDS -DISTRIBUTION OF COMPANIES AND RESPONSE TO ALARMS. Special Interest Bulletin No. 315, January, 1963*.

Note: The above distances shall be reduced if a severe life hazard exists; if streets are narrow or in poor conditions; if traffic, one-way streets, topography, or other unusual locational conditions hinder response; or if other circumstances peculiar to the particular district or municipality indicate that such a reduction is needed.

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*These schedules are now published by the Insurance Services Office, New York.

standards. The following excerpt is taken from their publication "Standard of Municipal Fire Protection" (Canadian Underwriters' Association, 1960, p. 28):

> To accomplish rapid response of the first-due companies, no point in any high value mercantile district shall be more than three-quarters of a mile running distance from either a pumper company, hose company where allowable (Item 11), or a combination of pumper and ladder company. Nor shall such point be more than one mile from a company providing the required ladder service (Item 8).
>
> In other districts where there is congested multi-storey residential or mixed construction, or where there is significant conflagration hazard, these running distances shall be not more than one mile and one-and-one-half miles respectively for pumper and ladder company service. In average closely built residential areas the running distances shall be not more than one-and-one-half miles for the nearest pumper company nor more than two miles for the nearest ladder company.
>
> For outlying areas of scattered buildings, the running distances shall be not more than a maximum of three miles for pumpers and the required ladder service.

Swersey (1974, p. 3) emphasizes the inadequacies and arbitrary nature of the American (and therefore by implication the Canadian) standards in the following statement:

> The number and distribution of companies under the ISO Standards depend upon the city's hazards, where the required fire flow is the basic hazard measure. Although there is a direct relationship between the total number of companies needed and the required fire flow, the maximum allowable distances for first due, first alarm, and maximum multiple alarm are based solely upon subjective judgment. There is, of course, no published quantitative evidence to support these recommended distances. Because of this, it would be difficult, to argue that, for example, at 6,000 gallons per minute, the first engine should be within one mile (the distance specified by the Standard) rather than some similar distance (e.g., 1.2 miles or .83 miles). If the Standard had been developed using the metric system, the distances might have been significantly different from the current distances.

Subsequent work, using the techniques of operations research, has rendered these subjectively determined standards both an obsolete and, in most cases, an unnecessarily expensive approach to the problem. The trend towards a more scientific approach possibly began with Valinsky's study (Valinsky, 1955). However, although Valinsky did carry out some analysis of the distribution of fire incidence and fire company workload this analysis was apparently not used to determine the final distribution of the fire companies.

A major step forward in methodological sophistication occurred in the late 1960s with the work of Hogg (1968a, 1968b, 1970, 1973). In her early work Hogg's initial objective was to minimize total fire company response time to all fires. Subsequently, she sought to determine the number and location of fire companies which would minimize the sum of fire department costs and the expected fire department losses. In this case fire losses were defined as being equal to property losses plus the estimated monetary value of lives lost. Past fire department records were used to determine the relationship between fire department losses and the response times of the fire companies. Hogg's approach may be described as follows. Firstly, the city is divided up into small homogeneous sub-areas. Fire incidence in these areas is assumed to be known or it is estimated from population densities. Secondly, stations are assumed to be located at major intersections near the centre of each region and, finally, travel times are determined by timing fire trucks along the road links or by estimating their travel speeds. Given this information an algorithm is then used to determine a set of fire station locations which will minimize the travel time required to serve the expected frequency distribution of fires.

Generally, Hogg's work has been widely cited and praised

(Massam, 1975, pp. 72-73, provides a useful summary) but Swersey (1974) does point out a number of weaknesses. The relationship between fire loss and response time is developed for the United Kingdom and it is questionable whether this relationship will hold for individual communities. Swersey also notes that other researchers in the United Kingdom have not found significant relationships between the two variables (recent American research on this point is described later in this chapter). Moreover, the objective function of minimizing the average response time may not be the most appropriate one for unless maximum distance constraints are built into the model areas of low fire incidence may have unacceptably long response times. Hogg's use of sub-areas in her study is somewhat similar to the approach used in the present thesis but, as will be seen in Chapter 5, the number of demand zones used in the present analysis is an order of magnitude greater.

A more controversial study was carried out by the Gage-Babcock consulting firm in Milwaukee, Wisconsin (Gage-Babcock and Associates Inc., 1973). This study recommended that the number of engine companies be reduced from 34 to 24 and the ladder companies from 21 to 19. Eight new fire stations were to be built and eight pumper and nine ladder companies were to be permanently relocated. Finally, all companies were to comprise five men (prior to the study some pumper companies had only four men). Nailen (1973) describes the Milwaukee Fire Chief's opposition to the proposed changes and Swersey (1974, p. 6) criticises their study:

> The difficulty is that the authors provide no quantitative measures of the changes in fire protection that would result from the reallocation of companies. For example, what would be the

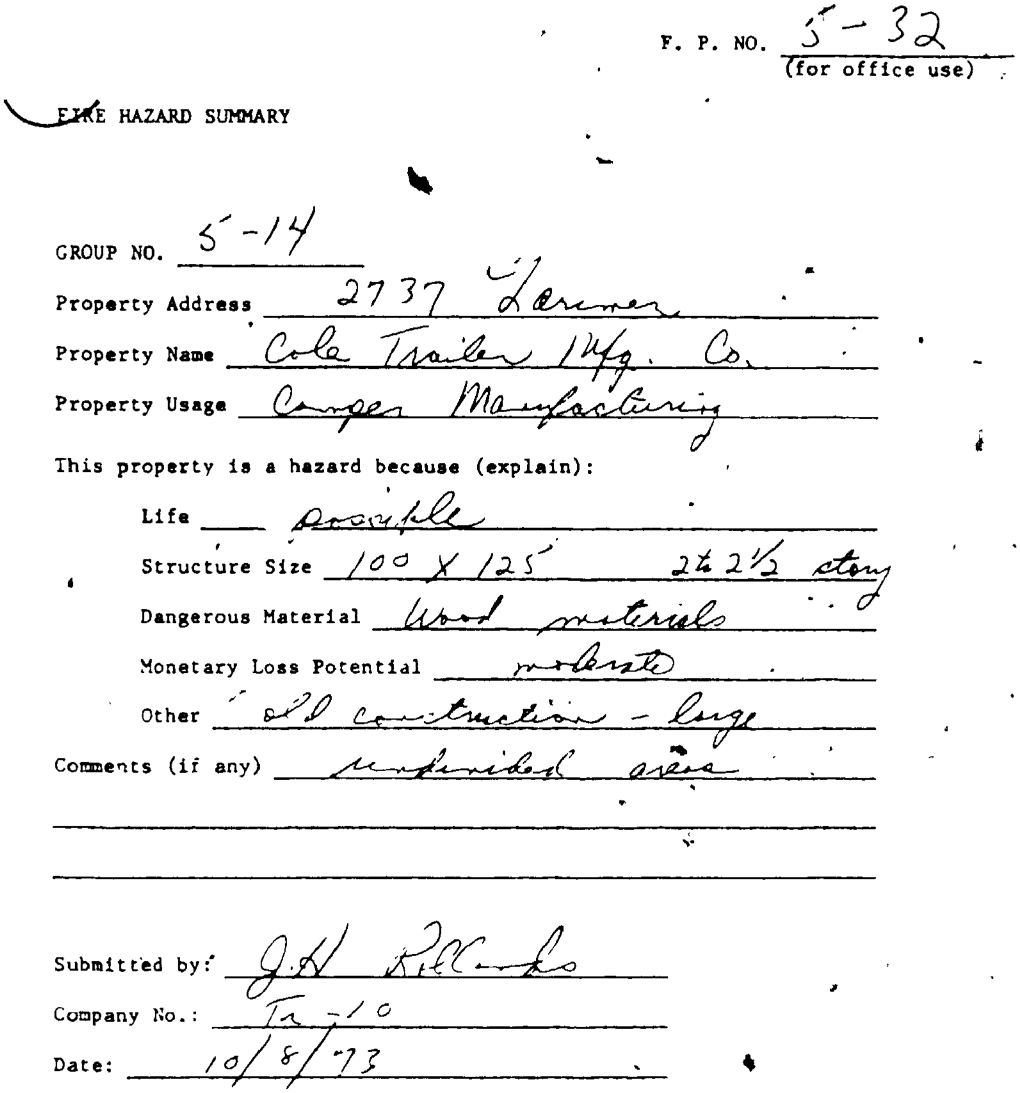
> increase in response times?; over how large an area?; to how many serious fires?;. . . . .

In addition to these studies there is at the present time extensive research being conducted into the development of emergency services by a number of major agencies. Among the more important are Public Technology, Inc. (PTI - for references to their work see Toregas et al., 1971; Public Technology, Inc., 1974), the New York City Rand Institute (NYCRI - reference to the work of the Institute will be made throughout the thesis but useful summaries are provided by Chaiken, Ignall and Walker, 1975a, 1975b; Walker, 1975c) and the Denver Urban Observatory (DUO - see Hendrick, Plane et al., 1975). These three agencies have developed the following computer programs as aids for determining fire station location: the Fire Station Location Package (Public Technology, Inc., 1974); the Firehouse Site Evaluation Model (NYCRI - see Dormont, Hausner and Walker, 1975; Walker, 1975c); and the Station Configuration Information Model which is used in conjunction with programs for solving the set-covering problem (Hendrick, Plane et al., 1975, pp. 44-45). The approaches of the three agencies have a number of features in common. Firstly, in each approach the city has to be divided into a number of small subareas which are reasonably homogeneous in their demand for fire service. Demand for fire service is assumed to occur only at a central point in the subarea and travel time is estimated to this point only. Finally, in each of the approaches the user is allowed to define certain areas as having special hazards such as high risk and/or potentially high loss. One of the important differences between the approaches is that the NYCRI and DUO both use a regression model to estimate fire truck travel time from distances covered. The PTI approach, on the other hand, requires that each link in the road network be assigned a travel time and then a shortest path routine evaluates the travel time between points in the network. The PTI approach tends to be time consuming, expensive and subject to errors. However, if the road network of links with travel times has already been developed (for example, by the city traffic department) then this method can be quite fast. Alternatively, if the road network has not been developed other city departments may find this a useful "spinoff" of the fire department study. This approach also takes into account the idiosyncrasies of the city explicitly. Thus barriers to travel such as railways and rivers and "holes" in the urban structure such as cemeteries, parks and lakes can be modelled directly. A final advantage of the PTI approach to modelling travel time is that fire department officials tend to feel more comfortable with a procedure which models the route followed by the fire trucks directly.

The PTI approach does have a number of drawbacks though. The original objective of the PTI researchers was to determine the minimum number of fire stations which would be required to serve a series of points (the centres of the zones of demand for fire service) within a given travel time. Unfortunately, small changes in the estimated travel times along arcs of the network can lead to significant differences in the minimum number of stations required. As a result, more recent approaches by PTI has simply attempted to specify locations for a predetermined number of fire stations. Even in this less ambitious objective the PTI methodology has its shortcomings. For example, the PTI methodology considers fire hazards but gives no explicit consideration to fire incidence. This is a direct contrast to the approach used in the present thesis in Chapter 6 where fire incidence is incorporated directly into the model. A more serious drawback to the PTI approach is that in their documentation (Public Technology, Inc., 1974) they provide no discussion of how to evaluate different fire station configurations. The PTI computer program provides the travel times of first-, second-, and third-due companies to each focal point. It also provides average first-due travel time for all focal points in a given station's first-due response area. However, this type of output tends to be inadequate because the focal points represent different hazards, are of varying size and have different numbers of fire incidents and thus average travel times to a group of such heterogeneous focal points are really very poor measures which ignore much of the original variation in the data.

The NYCRI approach to the problem of locating fire companies, as noted above, has many similarities to the PTI methodology. Thus the first step in the Institute's approach is to divide the city into relatively homogeneous demand zones whose size varies inversely with their degree of hazard. Data is collected on the past geographical distribution of alarms of varying types. Finally, travel time between potential fire station locations and the centre points of the demand zones are estimated using regression models to relate distance to travel time. These models are discussed in detail in Chapter 3. Given this information the computer program is then used to evaluate various fire station configurations. Each configuration is evaluated according to a number of criteria. Loss in coverage is measured by multiplying the increase in average first-due response time by the size of the region and the increase in average first-due response time to serious fires is measured by multiplying the increase in average first-due response time by the number of serious fires in the region. In addition, the Institute evaluates changes in the maximum response time.

Finally, the approach used by DUO may be considered briefly. The DUO approach is very much a compromise between the PTI and NYCRI methodologies. The first step in DUO's analysis was to define a set of 800 hazards for Denver. These were then reduced to 246 focal points by a procedure which ignored less severe hazards when they were located close to a more severe hazard. The 246 focal points were colour coded. Initially, four colours were used - red, yellow, green and blue (later in the study a new category was added called super-red). The colours represent the seriousness of the hazards in the city. Super-red indicates the most serious hazards while red indicates the slightly less serious hazards. Examples might be run-down hotels or chemical plants. Yellow focal points represent less serious hazards such as public buildings with good internal fire protection systems. Green hazards were even less important and were frequently represented by retail establishments. The least serious hazards were coded blue. Classifying the hazards was a task carried out by senior fire department personnel using Fire Hazard Summary forms of the type shown in Figure 2.5 (from Hendrick, Plane, et al., 1975, p. 35) which were prepared by the fire companies for each response district. The focal point grid for Denver is shown in Figure 2.6 (Hendrick, Plane et al., 1975, p. 39). Response time differentials were then determined between the red, yellow and green focal points by asking fire department personnel where they would locate a station in an equilateral triangle which had a red hazard positioned at one of the apexes, a yellow hazard at another apex and a green hazard at the third apex. There was no differential between the



F. P. NO. 5-32
(for office use)

FIRE HAZARD SUMMARY

GROUP NO. 5-14

Property Address 2737 Larimer

Property Name Cole Trailer Mfg. Co.

Property Usage Camper Manufacturing

This property is a hazard because (explain):

Life possible

Structure Size 100 X 125 2 & 2½ story

Dangerous Material Wood materials

Monetary Loss Potential moderate

Other old construction - large

Comments (if any) undivided area

Submitted by: J.H.

Company No.: Tr-10

Date: 10/8/73

Figure 2.5 Fire Hazard Summary Form used by Hendrick, Plane et al., 1975, p. 35

CHAPTER 3

Spatio-Temporal Analysis of the Data

A preliminary analysis was carried out in order to determine whether there were any patterns in the alarm data. It was hoped that such an analysis would provide insights into the nature of the data and would also help with the rational application of the results of the location-allocation models described in Chapter 6. Two aspects of the data were analysed in this preliminary investigation. The first was the alarm density in time and space and the second was the variation in the length of the response time through time and space.

Analysis of the Temporal Pattern of Alarm Densities

The first analysis was carried out on the temporal distribution of the alarms (part of this analysis was discussed in Waters, 1976). Very little statistical work has been done on such distributions though various writers have observed that there does appear to be some evidence suggesting a daily cycle. One such pattern, that for New York City, is shown in Figure 3.1 (Chaiken and Rolph, 1971, p. 9).

It might be asked why those planning fire department operations should be interested in daily cycles. One reason is that it could be useful in implementing an "adaptive response" policy. Walker (1975a, p. 16) notes that the adaptive response developed by the NYCRI for New York's Fire Department was one of the major accomplishments of the Institute. This type of response is an objective procedure for varying the number of fire companies which are sent out to incoming alarms. The theory is that alarms which are potentially more serious green and blue focal points and the differential between red and super-red was later arbitrarily set at 60 seconds. The maximum response time was initially arbitrarily set to 120 seconds for the red focal points, the super-red were 60 seconds less than the red, the yellow 90 seconds more and the blue and green 120 seconds more. Finally, fire department personnel were asked to provide a list of possible sites for fire stations which included the 27 existing stations. To begin with there were 100 candidate sites but during the course of the study the number was eventually increased to 120. All of the information now existed for solving the set covering problem. Verbally the objective function of this problem is to minimize the number of fire stations subject to the constraint that each focal point is covered by at least one fire station within its specified response time (note, as mentioned above, in the DUO study response times are related to distance by regression equations). Mathematically the problem can be stated as (Hendrick, Plane et al., 1975, p. 31):

$$\text{Minimize} \quad \sum_{j=1}^{n} x_j \qquad 2.1$$

$$\text{Subject to:} \quad \sum_{j=1}^{n} a_{ij} x_j \geq 1 \qquad \text{for } i=1,2,\ldots,m \qquad 2.2$$

$$x_j = 0 \text{ or } 1 \qquad 2.3$$

when n = the number of potential station locations which are numbered 1 to n;

m = the number of specific points for which response time requirements have been set;

x_j = decision variables (in the solution, if $x_j = 1$, a fire station should be placed at location j; if $x_j = 0$, no fire station should be placed at location j);

a_{ij} = indicators for the response time requirements ($a_{ij} = 1$ indicates that point i can be served by location j within the response time requirement for the point; $a_{ij} = 0$

indicates that it cannot be served by location j within the specified response time).

The problem with this traditional set-covering model (which incidentally is also used in PTI's Fire Station Location Package) is that it does not distinguish between those sites which already have a fire station and those which do not. Obviously, the solution which maximizes the number of existing sites used will reduce both capital expenditure costs and the "political costs" of relocating fire stations. Because of this the DUO team modified the original model by substituting a hierarchical objective function which assigned an additional cost for each new fire station incorporated into the solution. The form of this model is given as (Hendrick, Plane et al., 1975, p. 33):

$$\text{Minimize} \quad \sum_{j=1}^{p} x_j + \sum_{j=p+1}^{n} (1+\varepsilon)x_j \qquad 2.4$$

$$\text{Subject to:} \quad \sum_{j=1}^{n} a_{ij}x_j \geq 1 \quad \text{for } i=1,2,\ldots,m \qquad 2.5$$

$$x_j = 0 \text{ or } 1 \qquad 2.6$$

$$0 < \varepsilon < 1/n \qquad 2.7$$

where n, m, x_j and a_{ij} are defined as above;

and the existing station locations are indexed from 1 to p.

The DUO team evaluated the results of the hierarchical set-covering model using another computer program which they designated the Station Configuration Information Model (SCIM). The output from the SCIM program includes a listing of all focal points whose response time requirements are not met by the configuration. The program also provides the average first-due pumper response time for each focal point and each focal point class. These averages are also reported for second-, third-, and fourth-due pumpers and for first-, second-, and third-due ladders. These averages, however, are not weighted by the expected alarm incidence at the focal points. Also included in the output is a frequency distribution of response times by half minute intervals for each focal point class for each of the vehicle types mentioned above. Finally, the program produces a list of focal points for which each company is responsible. This list specifies whether the company is the first-, second-, or third-due pumper or truck.

One of the most attractive features of the DUO study is the extent to which they were able to merge the results of optimization and the informed judgment of the Denver Fire Chief and other fire department personnel. For instance, the "unreasonableness" of the initial solution to the hierarchical set-covering problem led to the creation, at the Fire Chief's suggestion, of the super-red class of focal points which ensured a better covering of the most serious hazards in the city.

Swersey (1974, p. 10) criticises those authors, such as Hogg, PTI and, by implication, DUO, who view fire station location as an optimization problem:

> A number of authors view the question of fire station location as an "optimization problem", i.e. they specify some objective function which is to be optimized (e.g. minimize average response time to fires). Approaches like Hogg's are most useful for planning new fire stations or to suggest possible deployment alternatives. Considering only response time to serious fires may result in poor coverage while considering only coverage and hazards (ISO standards, PTI approach) may result in insufficient companies where fire incidence is great. A potentially useful objective would be one which considers both response times to serious fires and coverage (e.g. minimize average response time subject to specified constraints on maximum response time to each area).

This last objective is being studied by Halpern at the present time (personal communication) and he has already presented a method for combining the graph centre (the point which minimizes average response distance) and the graph median (the point which minimizes the maximum response distance) problems for an undirected tree (Halpern, 1976). The new point is termed a cent-dian.

Swersey also suggests that the ideal fire station location model should consider: (1) response times; (2) hazards; (3) the number of fires and their severity; (4) the size of the demand region; and (5) the fire company workload. It should be added, however, that any program designed to evaluate the success of a suggested station configuration should also look at the <u>sensitivity</u> of these five parameters. For example, by adopting an alternative configuration a relatively insensitive parameter may have its value increased only slightly while a highly sensitive parameter may have its value improved significantly. Alternatively, there may be more than one optimal solution or there may be a series of suboptimal solutions which produce an insignificant increase in the objective function. If there are planning objectives which have not been incorporated into the mathematical model the "best" solution may then be defined as the optimal or marginally suboptimal solution which approaches the non-quantified planning objectives most closely. This point is discussed in detail with respect to the transportation problem by Barr and Smillie (1972). Some analysis of the sensitivity of average response times or total weighted response time is undertaken in Chapter 7.

Before concluding it should be noted that one of the drawbacks to fire station location studies is that the relationship between fire severity and fire company response time has not yet been adequately developed. Indeed it has been suggested by Fire Chief Derek Jackson of Calgary (personal communication) that first-due response time may not be as important as the time it takes to get an effective fire fighting force to the scene of the alarm. He has suggested that in Calgary such a force might, on average, comprise 30 men in the urban core and 7 men outside the core area. His observations appear to be supported by the limited research on the topic. Thus Corman, Ignall, Rider and Stevenson (1975) in their study of the relationship between fire casualties on the one hand and response distance and additional factors on the other hand concluded for New York City that (p. 13):

> ...the effect of fire company response distance (for average distances typical of New York City) on fire casualties is very small compared to other factors.

These "other factors" include significant time of day and time of year influences.

By way of summary, it may be concluded that at the present time there is a rich array of techniques which may be used to assist the planner in locating new fire stations and in rationalizing present configurations. However, these techniques have by no means solved the "fire station location problem". The present study proposes a slightly different methodology from those discussed in this chapter. This methodology also has certain shortcomings (which will be discussed in due course) but it does emphasize those aspects of the problem which other researchers have tended to neglect. Thus part of Chapter 3 analyses the spatial distribution of fire alarms and provides a simple predictive model for the distribution. Chapter 4 discusses the possibility of building explanatory models of such spatial distributions. Chapter 5 discusses methodology for producing the demand zones and Chapter 7 solution sensitivity. All these topics have been partially or completely neglected by previous researchers.

CHAPTER 3

Spatio-Temporal Analysis of the Data

A preliminary analysis was carried out in order to determine whether there were any patterns in the alarm data. It was hoped that such an analysis would provide insights into the nature of the data and would also help with the rational application of the results of the location-allocation models described in Chapter 6. Two aspects of the data were analysed in this preliminary investigation. The first was the alarm density in time and space and the second was the variation in the length of the response time through time and space.

Analysis of the Temporal Pattern of Alarm Densities

The first analysis was carried out on the temporal distribution of the alarms (part of this analysis was discussed in Waters, 1976). Very little statistical work has been done on such distributions though various writers have observed that there does appear to be some evidence suggesting a daily cycle. One such pattern, that for New York City, is shown in Figure 3.1 (Chaiken and Rolph, 1971, p. 9).

It might be asked why those planning fire department operations should be interested in daily cycles. One reason is that it could be useful in implementing an "adaptive response" policy. Walker (1975a, p. 16) notes that the adaptive response developed by the NYCRI for New York's Fire Department was one of the major accomplishments of the Institute. This type of response is an objective procedure for varying the number of fire companies which are sent out to incoming alarms. The theory is that alarms which are potentially more serious

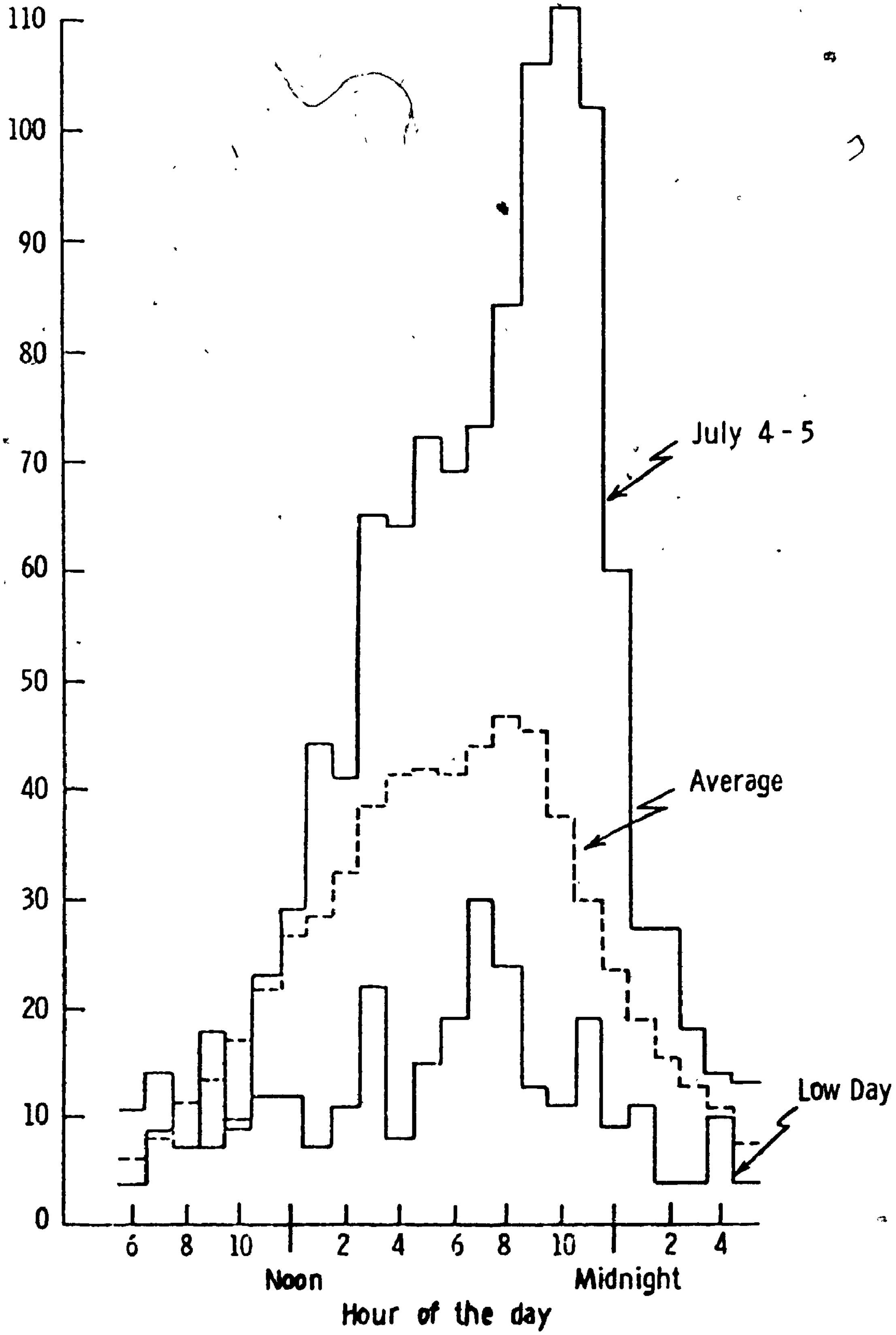


Figure 3.1 Hourly Pattern of Alarms in New York City (From Chaiken and Rolph, 1971, p.9)

should receive more units in the initial response. This policy will only be effective, however, if the demand for fire service, in some parts of the city, during certain periods of the day is so great that there is a high probability that while fire companies are answering one alarm there will be another sent in from the area which they serve. The policy also depends on being able to predict whether the incoming alarm will be serious or not. The NYCRI found that there were predictable variations regarding the likely seriousness of the alarm (for example, whether it was likely to be a false alarm or a structural fire). Others such as Smith (1973, p. 38) have also noted these variations:

> We go to that intersection more often than any other. It is usually a false alarm, but there is no such thing as "crying wolf" in this business.

The Institute's contribution was to incorporate these well known variations into the rigorous adaptive response policy.

In some cities, such as New York, the alarm rate may be high enough to justify continual use of the adaptive response policy, while in smaller centres the alarm rate throughout the day may never be high enough to warrant a reduction in the response level. By extension then, there may be some towns in which there are certain periods of the day when an adaptive response is justified because of the high alarm rate and other periods when the alarm rate is low and a standard response is more appropriate. It would thus be useful to determine whether there were any recurring daily variations in the demand for fire department service. The evidence from New York, shown in Figure 3.1, suggests that there is a daily cycle in which demand is generally higher in the second part of the day than in the first.

In order to analyse for the existence of such a daily cycle, the data was formed into a time series and this was then aggregated into 1,460 six-hour time periods, beginning with the first minute of January 1st, 1973 and finishing at midnight, December 31st, 1973. There were thus four periods each day: the first ending at 6 a.m.; the second at noon; the third at 6 p.m.; and the fourth at midnight. Autocorrelation coefficients were then calculated using lags from 1 to 365 for this time series. This analysis showed a weak, but statistically significant, daily cycle. The autocorrelation coefficients for a lag of one, two, three, and four six hour time periods were +.078, -.144, +.086, and +.228, respectively. This indicated that there was a very weak, negative correlation between periods which are twelve hours out-of-phase and a slightly stronger, positive correlation between periods which are 24 hours, or a complete day, out-of-phase.

This oscillating pattern of autocorrelation coefficients is shown in Figure 3.2. These correlations were, however, extremely weak and this was probably due partly to the paucity of data, for once the year had been divided into 1,460 periods the average number of alarms per period was only about 1.68. In order to determine whether this weak relationship was significant a statistical test was carried out. The 't' test was not used since the data did not meet the assumptions of the test. Instead the time series was randomized and then the autocorrelation coefficient was recalculated for a series of 100 lags. None of these values was as large as the observed autocorrelation coefficient for a lag of 4. Thus the ad hoc,

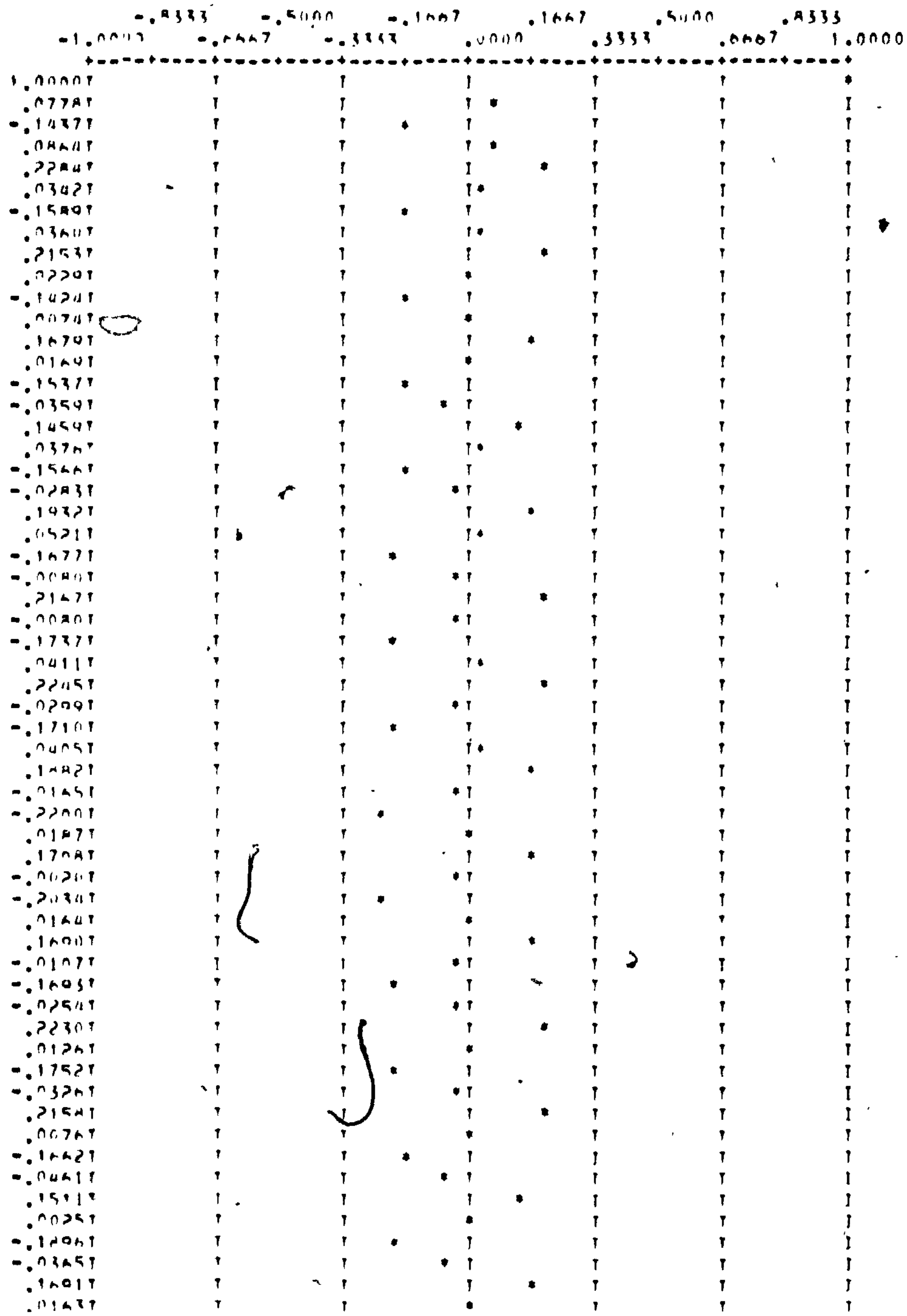


Figure 3.2 The Oscillating Pattern of Autocorrelation Coefficients for the 1973 London Alarms Aggregated by Six Hour Periods

distribution-free test had indicated that there was probably less than 1 chance in 100 of observing an autocorrelation coefficient of the size of the one associated with the lag of 4 periods.

It was also determined that the positive autocorrelation coefficient associated with a lag of 4 declined to values of: +.215, +.168, and +.146 with lags of 8, 12, and 16, respectively. At this point, the trend was reversed and autocorrelation coefficients of: +.193, +.217, and +.225 were observed with lags of 20, 24, and 28, respectively. Since periods which are lagged by 28 are exactly one week out of phase in this series, these values offer some very tentative support for a weekly cycle. This mild, weekly cycle may just be discerned in Figure 3.2. However, it must be concluded that the evidence for the existence of such a cycle is extremely tenuous and this area will require considerable further research.

These results from the autocorrelation analysis were corroborated by a second analysis which involved the use of Fourier methods. Thus the daily pattern was once again shown to exist by a strong 365th harmonic which indicates a cycle of 4 time intervals.

It is appropriate now to discuss whether the autocorrelation coefficients would have been stronger had the starting point for the four time periods been 1 a.m. instead of midnight. In other words, would there have been a stronger, daily cycle if the periods had ended at 7 a.m., 1 p.m., 7 p.m., and 1 a.m., respectively - or indeed if they had started and ended at any other hour of the day. The pattern of alarms for each hour of the day throughout the year is shown in Table 3.1. It is interesting to compare the figures in this table with the graph of the time of day pattern for Tacoma,

TABLE 3.1: Number of Alarms Per Hour in London, Ontario, During 1973.

Time Period	Number of Alarms
00:01 - 01:00	82
01:01 - 02:00	83
02:01 - 03:00	62
03:01 - 04:00	43
04:01 - 05:00	31
05:01 - 06:00	35
06:01 - 07:00	41
07:01 - 08:00	40
08:01 - 09:00	57
09:01 - 10:00	84
10:01 - 11:00	76
11:01 - 12:00	124
12:01 - 13:00	109
13:01 - 14:00	146
14:01 - 15:00	134
15:01 - 16:00	147
16:01 - 17:00	164
17:01 - 18:00	162
18:01 - 19:00	153
19:01 - 20:00	161
20:01 - 21:00	167
21:01 - 22:00	121
22:01 - 23:00	121
23:01 - 24:00	116

Washington shown in Figure 3.3 (Chaiken, Ignall, and Walker, 1975c, p. 61). These two sets of 24 hourly totals have a correlation of +.96 with each other. To determine whether this correlation was merely fortuitous the New York City data from Figure 3.1 was also correlated with the London Data. In this case the correlation coefficient was +.97 which is again an exceptionally high value.

The figures shown in Table 3.1 were grouped 6 times into 4 classes. In the first grouping the members of the first class were the first 6 hourly totals, the members of the second class were the 7th to the 12th hourly totals, the members of the third class were the 13th to the 18th and the fourth class included the 19th to the 24th hourly totals. In the second grouping the members of the first class were the 2nd to the 7th hourly totals, the second class were the 8th to the 13th, the third the 14th to the 19th, and the fourth group contained the 20th to the 24th and also the first hourly total. In the third grouping the classes began with the third total, in the fourth with the fourth total and so on. It was then necessary to determine which of the 6 groupings produced the best classification. The best classification was defined as the grouping which minimized the within-class variation and maximized the between-class variation. In order to determine this a one-way analysis of variance was carried out on each grouping. All of the groupings were found to yield highly significant F ratios. However, the grouping which began with the fourth hourly total did have a higher ratio than the others and so the autocorrelation analysis was repeated using a time series which began at 3:01 a.m. on January 1st, 1973, and which also contained 1,460 six hour periods. The resulting autocorrelation

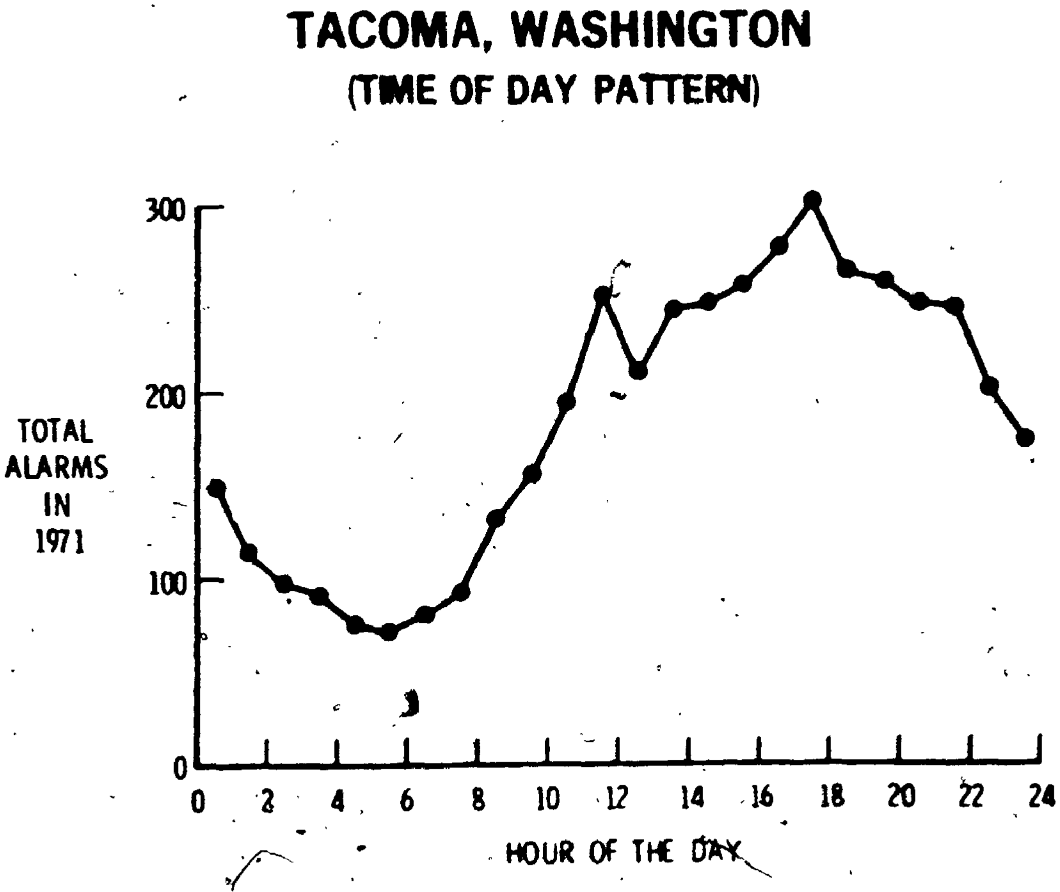


Figure 3.3 Hourly Pattern of Alarms in Tacoma, Washington (from Chaiken, Ignall and Walker, 1975c, p. 61)

coefficients, however, showed practically no difference from those in the original analysis.

The alarms were then split into a number of major types such as residential and non-residential fires and the autocorrelation analysis was repeated. However, the results were now less conclusive because the division of the data into several categories increased the sparseness and thus weakened the autocorrelation coefficients.

Analysis of the Spatial Pattern of Alarm Densities

A further analysis sought to determine whether there were any spatial patterns in the data. Two approaches were used. The first involved employing a local smoothing algorithm while the second involved a global generalization of the spatial pattern.

Local Smoothing. The SURF program (Van Horik and Goodchild, 1975) was used to produce a demand surface map on the line printer, Figure 3.4, and a three-dimensional block diagram, Figure 3.5. This map and diagram were produced using the INTERPOLATE option from the SURF package. This option interpolates a series of grid values from a distance weighted average of nearby data points. This function is given as:

$$z' = \sum_i z_i e^{-ar_i} / \sum_i e^{-ar_i} \qquad 3.1$$

where z' is the interpolated value

z_i is the ith data point

r_i is the distance to the ith data point

a is the fitted constant

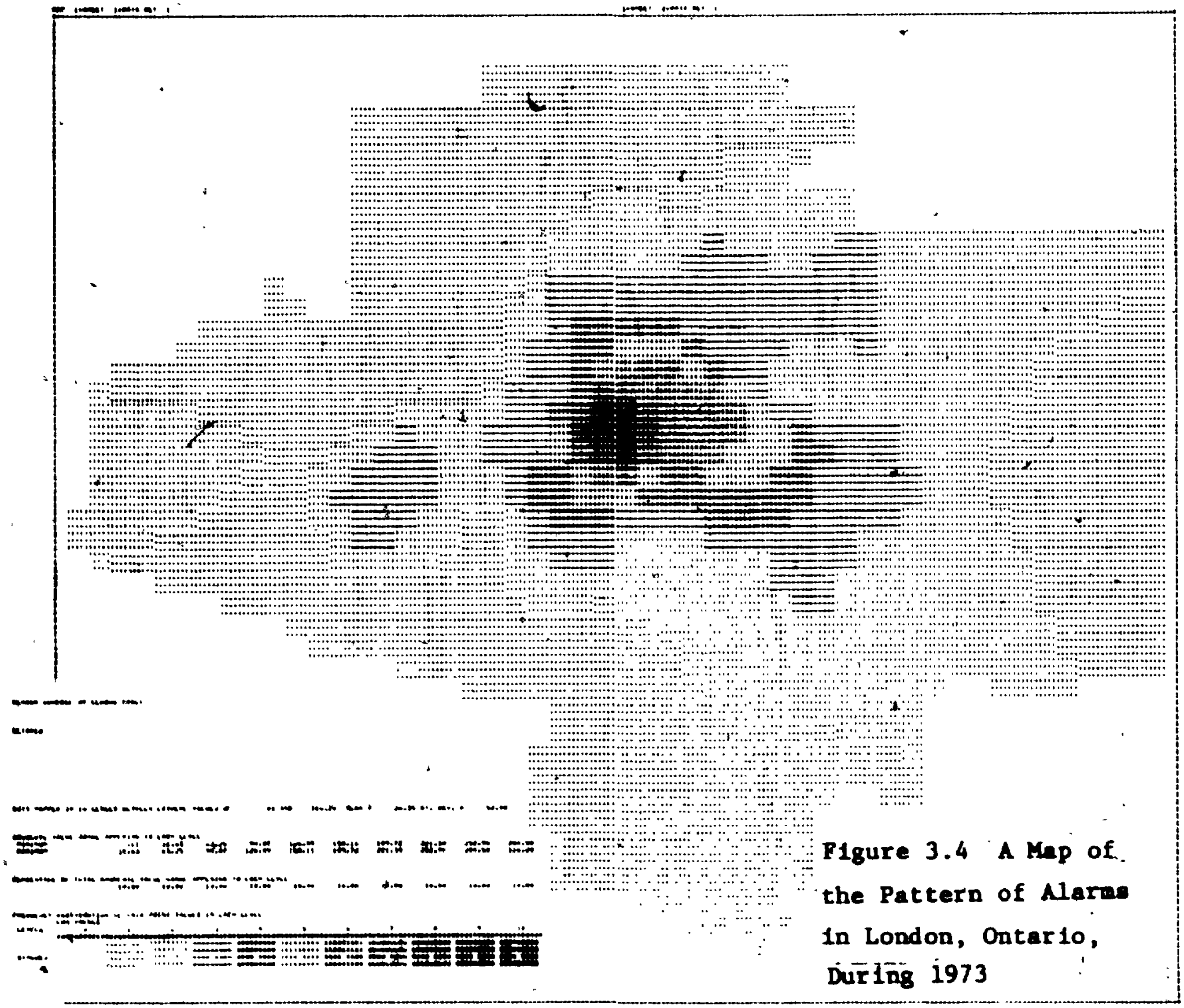


Figure 3.4 A Map of the Pattern of Alarms in London, Ontario, During 1973

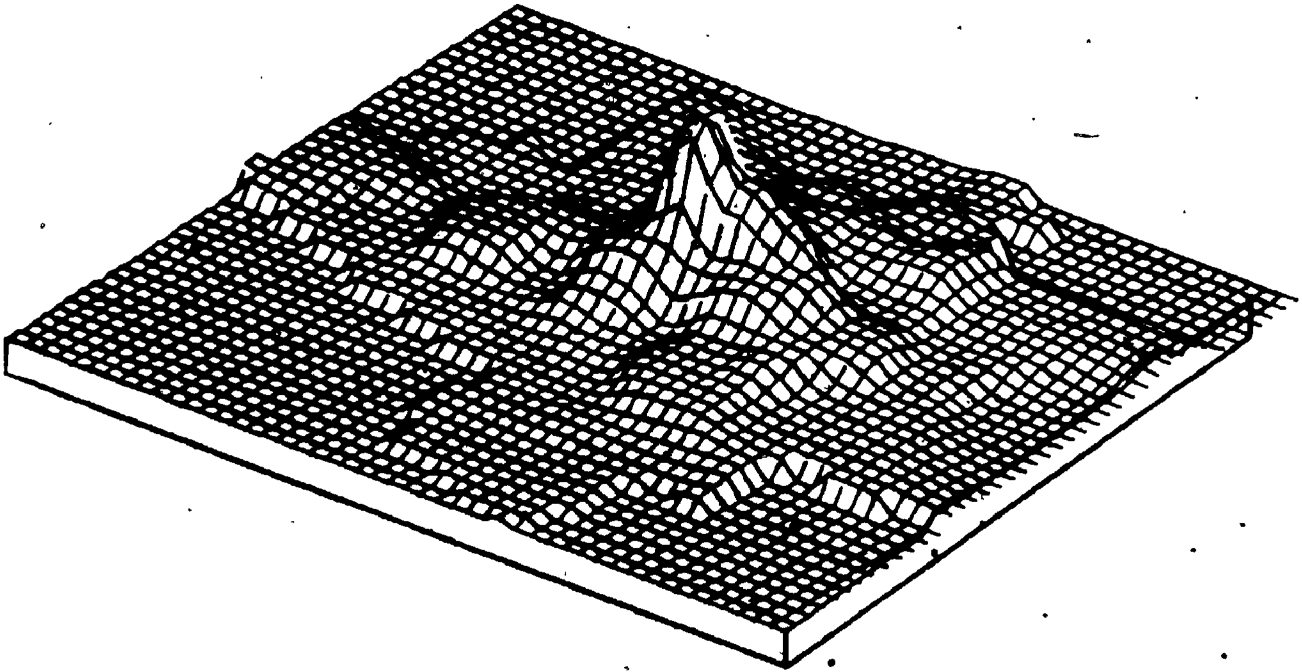


Figure 3.5 A Three Dimensional, Block Diagram of the Pattern of Alarms in London, Ontario, During 1973

This constant 'a' may be redefined as:

$$a = \log 2/b \qquad 3.2$$

And this gives:

$$z' = \sum_i z_i e^{-\log 2 r_i/b} / \sum_i e^{-\log 2 r_i/b} \qquad 3.3$$

where the terms are as above.

Thus, 'b' is the distance over which the influence weight of any one data point halves (Van Horik and Goodchild, 1975, p. 11). De Smith (personal communication) has pointed out that the expression may be reduced to:

$$z' = \sum_i z_i 2^{-r_i/b} / \sum_i 2^{-r_i/b} \qquad 3.4$$

With a small 'b' value only nearby points will affect the interpolation but with a larger 'b' the degree of smoothing or data generalization will increase correspondingly. In this example 'b' was set at 10 map units which is just under a tenth of a mile in the coordinate system used.

Global Generalization. To provide a global generalization of the spatial pattern a trend surface was fitted to the alarm data (again, part of this analysis was discussed in Waters, 1977). The recorded alarms were aggregated into cells 5,000 feet square (this being the grid size on the City Engineer's map). The number of alarms in each cell was then assigned to the centre of each square and in this manner a surface was created which was an estimate of annual demand for fire department services in the city. It was decided to fit the trend surface using non-orthogonal polynomials since the apparent lack of a spatial periodicity in the data made the use of a double Fourier series inappropriate. The polynomials were calculated by the computer program KWIKR8 (Esler, Smith and Davis, 1968). There is considerable advantage in using evenly spaced data because, as Norcliffe (1969) has pointed out, fitting a trend surface to clustered data can lead to spuriously good fits. Norcliffe also suggests that before fitting a trend surface the researcher should have sound, theoretical reasons for expecting a surface of a particular order. In this study, the a priori hypothesis was that the most appropriate model would be the quadratic or second order polynomial. The reason for supposing this is that generally, in the past, the urban core of most cities has had a high demand for fire department services while, at the same time, the demand tends to decline as one moves toward the periphery. Thus, the demand surface does bear some resemblance to an inverted bowl shape which is one form which the quadratic surface may also take.

In all, five polynomial equations were fitted and these explained approximately: 1%, 44%, 49%, 67% and 69% of the variation for the first to fifth order surfaces, respectively. All the models except the linear were found to be statistically significant at the 5% significance level. It should be noted here that the significance was measured by the F test and that the data does violate the assumptions of the test because of its high degree of spatial autocorrelation. This autocorrelation would reduce the degrees of freedom by an undetermined amount and would thus make the results of the test less conclusive. Bearing these considerations in mind it was also found that the quadratic surface gave a significant increase in explanation over the linear surface. Less obvious is the fact that the quartic surface yielded a significant increase in explanation over the cubic surface. As a result, the quartic surface, with its central peak and slight upturn at the periphery, may be regarded as the most appropriate model of the demand surface.

The original data used in the analysis is shown in Figure 3.6. The most striking aspect of the data is the heavy occurrence of alarms in the urban core. Also significant is the slightly higher demand on the western periphery of the town (which is probably due to a large number of brush and grass fires in this area). The extreme south also has a high demand in the industrial areas and this demand is likely to increase as industry continues to be drawn to this part of the town. Figures 3.7, 3.8, 3.9, and 3.10 show the second, third, fourth, and fifth order surfaces, respectively. Figure 3.11 shows the residuals from the quartic model. It is obvious that even the quartic model fails to adequately predict the very high number of alarms in the urban core, the evidence for this being the group of four very large positive residuals in the centre of the map. In addition, the model fails to estimate the steepness of the decline in the number of alarms around the core area and hence the ring of negative residuals around the city core.

In the second part of the study the alarms were split up into three groups: (i) the residential alarms, (ii) the alarms located in public, industrial and commercial buildings, and finally, (iii) minor alarms such as brush fires, garbage fires and automobile fires (namely those alarms with property codes 20A). These three demand surfaces were then analysed separately. This analysis tended to show

			6	4	6	12	14	15			
			14	7	71	18	38	13	10	2	1
1	10	10	11	39	59	77	61	53	50	11	3
26	13	10	15	36	203	192	99	40	27	24	4
29	24	10	34	64	142	142	75	78	28	16	2
1	0	44	18	25	31	40	53	34	35	19	1
		1	5	27	14	21	20	1	1	5	1
				0	13	29	17	0	0		
				0	7	15	11				

Figure 3.6 Data Used for the Trend Surface Analysis Based on Cell 5,000 Feet Square

TREND SURFACE ANALYSIS OF ALL 1973 FIRE ALARM DATA FOR LONDON, ONTARIO

```
YMIN =     0.0000 (TOP EDGE)       YMAX =   100.0000 (BOTTOM EDGE)     XMIN =     0.0000 (LEFT EDGE)
XMAX =   110.0000 (RIGHT EDGE)     PER  =    30.0000                   CON  =    10.0000
```

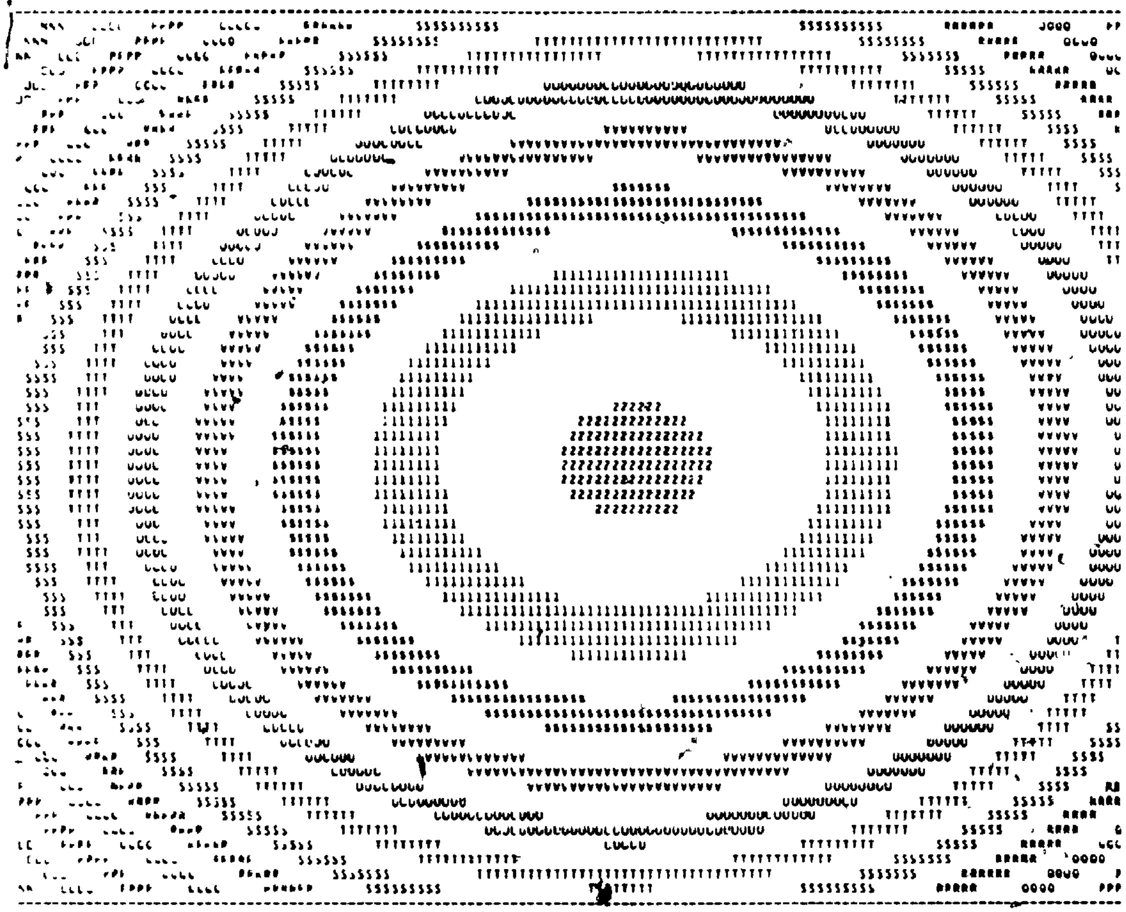


Figure 3.7 Quadratic Trend Surface Based on the Data in Figure 3.6

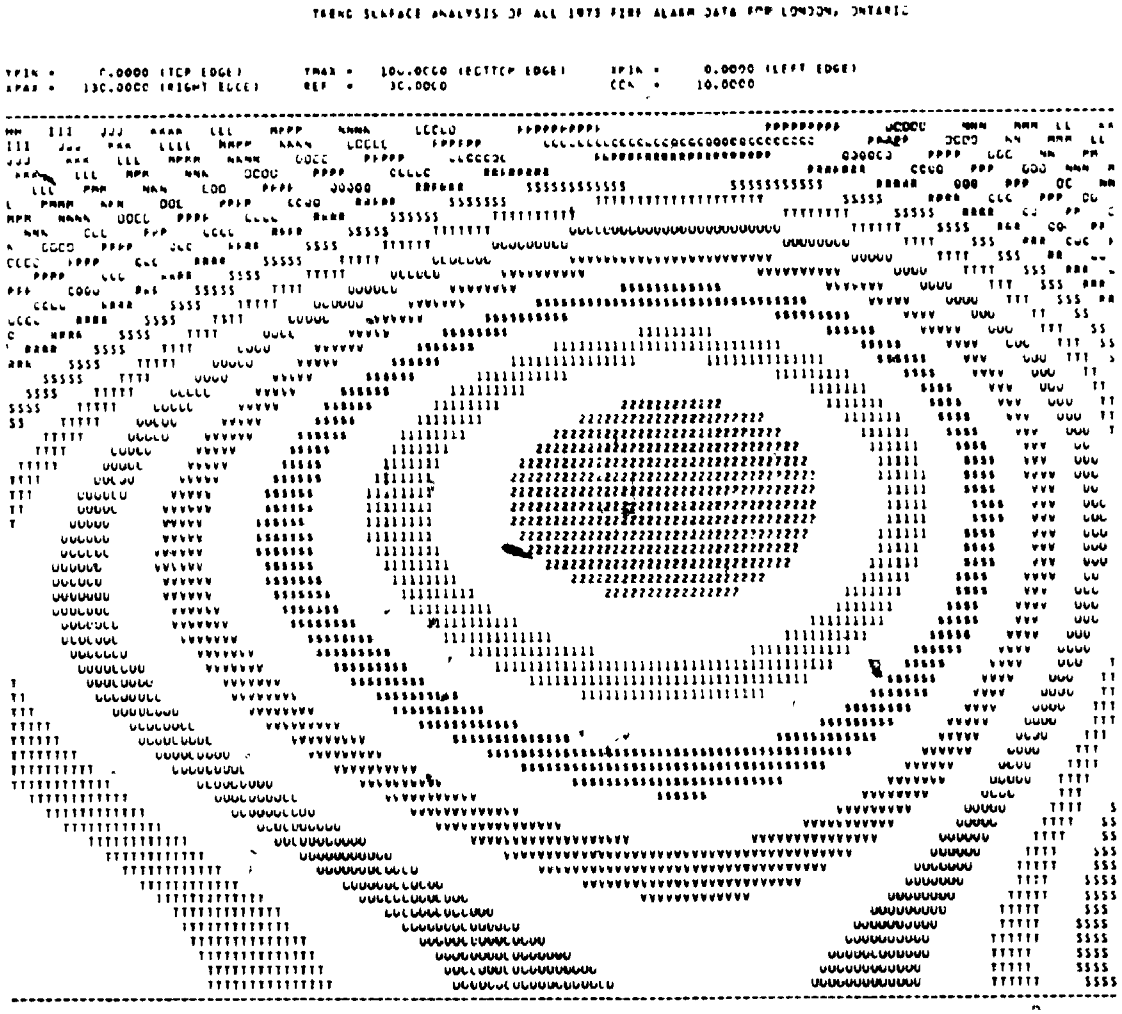


Figure 3.8 Cubic Trend Surface Based on the Data in Figure 3.6

```
                    TREND SURFACE ANALYSIS OF ALL 1973 FIRE ALARM DATA FOR LONDON, ONTARIO

YMIN =     0.0000 (TOP EDGE)      YMAX =   100.0000 (BOTTOM EDGE)      XMIN =     0.0000 (LEFT EDGE)
XMAX =   130.0000 (RIGHT EDGE)    REF  =    30.0000                    CON  =    10.0000
```

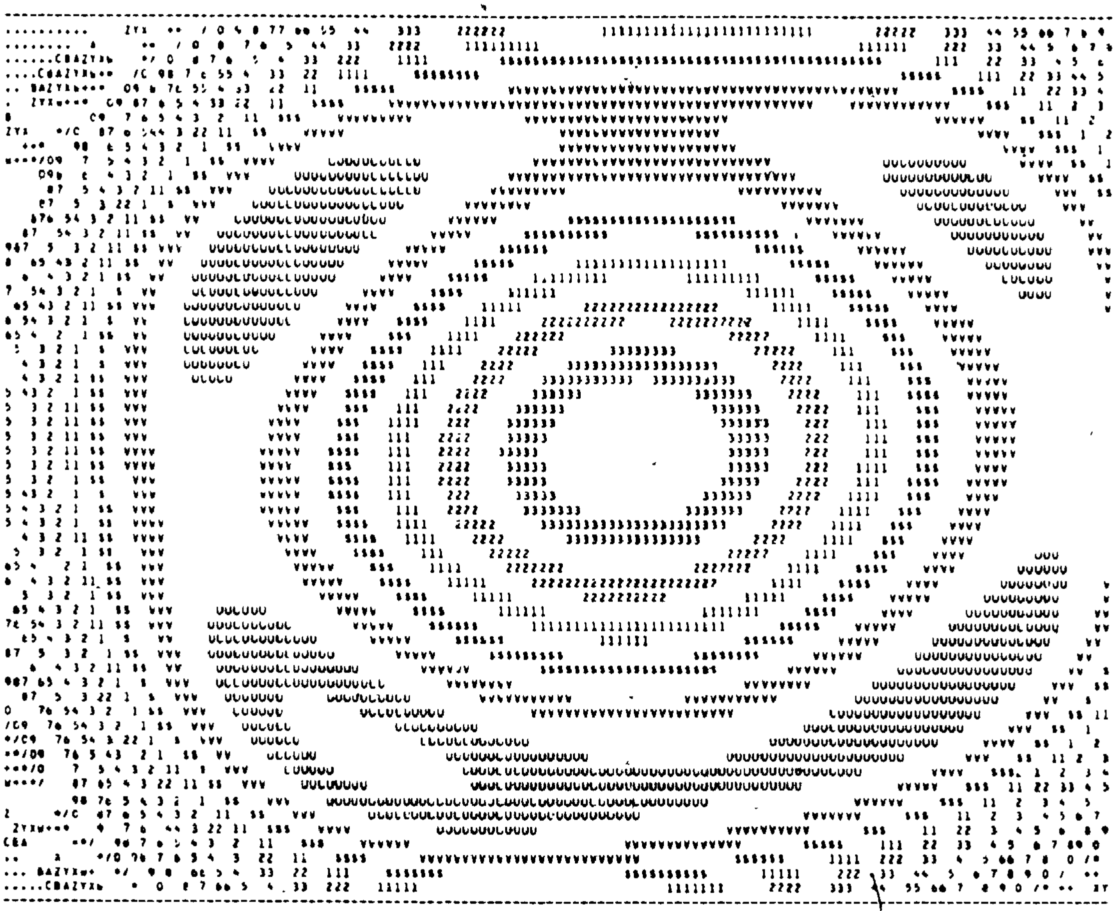


Figure 3.9 Quartic Trend Surface Based on the Data in Figure 3.6

```
TREND SURFACE ANALYSIS OF ALL 1973 FIRE ALARM DATA FOR LONDON, ONTARIO

YMIN =     0.0000 (TOP EDGE)        YMAX =   100.0000 (BOTTOM EDGE)     XMIN =     0.0000 (LEFT EDGE)
XMAX =   130.0000 (RIGHT EDGE)      REF  =    30.0000                   CIN  =    10.0000
```

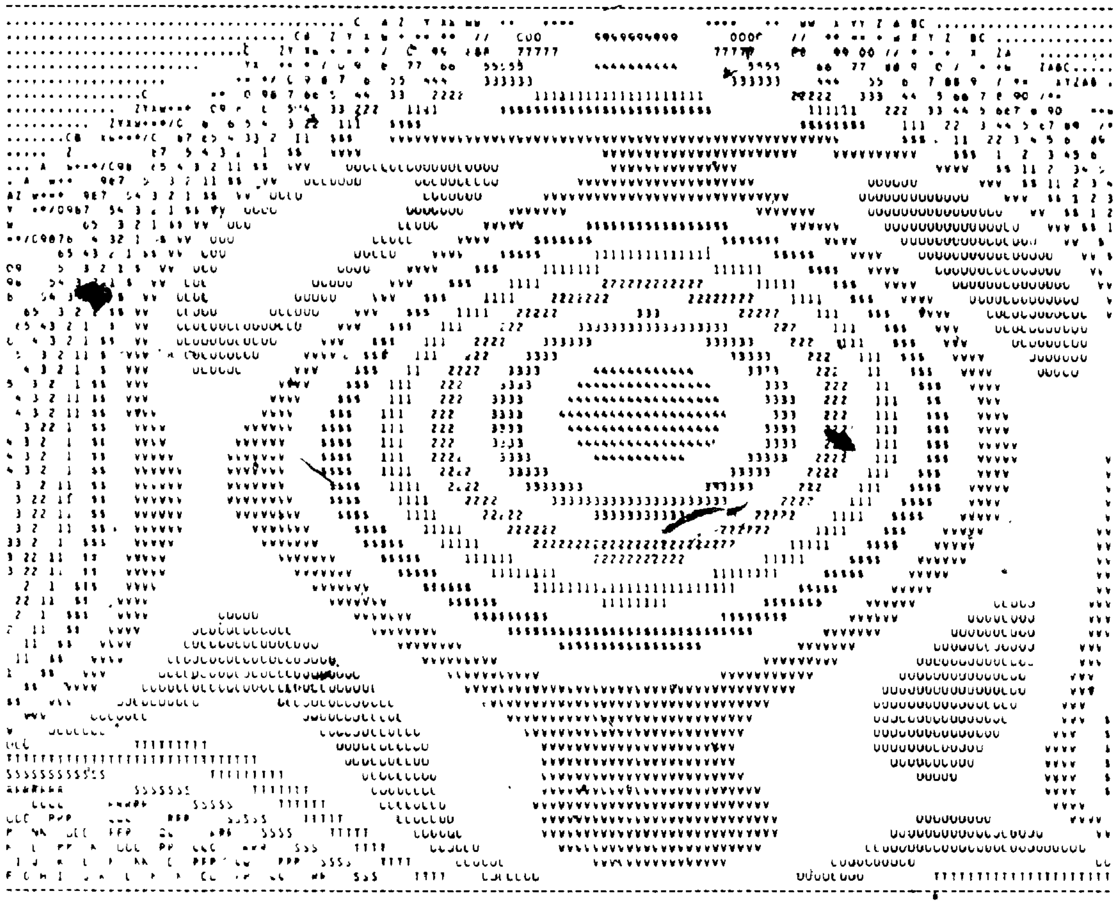


Figure 3.10 Quintic Trend Surface Based on the Data in Figure 3.6

TABLE 3.2 Cont'd.

49)	25.000
50)	10.560
51)	2.4700

that the third group of alarms had a more even distribution across the city than the other two types and the strong spatial concentration in the urban core was thus much less evident (a result which had been anticipated by the Fire Chief).

Tobler (1969, p. 236) has commented that there "appears to be a temptation to apply this model [trend surface analysis] rather indiscriminately to all sorts of geographical situations". However, Chorley and Haggett (1965) have listed at least four different uses for the model - two of which appear to be appropriate here. They suggest that it is useful because it yields a simplified model for describing a complex geographical pattern and, as a result, it allows easy comparison with other surfaces. Thus, in the present study the model could be used to compare the demand for fire department service in different cities and for the same city at different periods. Secondly, Chorley and Haggett suggest it may help in determining those processes which are responsible for the surface. Thus, in London, Ontario, the high demand for fire department service in the centre of the city is possibly due to the higher density of restaurants and hotels in this area and the greater age of the buildings. It is interesting to note that the older buildings are now gradually being torn down under a variety of urban renewal schemes and possibly the pattern of alarms may be quite different in the not too distant future.

This trend surface analysis suggests that it may be possible to build an alternative model of the spatial pattern of alarms. It appears that like many urban phenomena, the alarms exhibit a negative exponential decay away from some central point in the city.

Consequently, an attempt was now made to fit a negative exponential distance decay function to the alarm data. All the alarms were aggregated by census tract. This was done in order to facilitate the construction of the explanatory socio-economic model described in Chapter 4. The independent socio-economic variables for this model were only available by census tract. For each census tract the mean X and Y coordinate of the alarms was calculated since these coordinates were felt to provide the best estimate of the centre of the distribution of alarms in each tract. These data together with the number of fires per square mile in each census tract were used to fit the distance decay function. This function was fitted using the Time Series Processor package (Time Series Processor, 1975). The hypothesized equation given to the LSQ program was as follows:

$$F' = F_0 e^{-bd} \qquad 3.5$$

where F' is the predicted number of alarms

F_0 is the number of alarms when d is zero

e is the base of natural logarithms

b is the slope of the regression line

d is the distance between an unknown central point, $X_0 Y_0$, and the mean coordinates of the alarms in the census tract

This equation may be expanded to:

$$F' = F_0 e^{-b((X - X_0)^2 + (Y - Y_0)^2)^{\frac{1}{2}}} \qquad 3.6$$

In order to run the program the parameters F_0, X_0, Y_0 and b must be given reasonable initial values. All four of these parameters, including X_0 and Y_0, are to be fitted. The LSQ program fits an equation which minimizes the sum of the squared deviations from the line (barring entrapment in a local optimum). It does this using the Gauss-Newton iterative procedure to manipulate the four parameters until convergence is achieved. This occurs when the largest change of a parameter value is less than .01 or 1%.

Table 3.2 shows 51 values for the number of alarms per square mile together with the identification number of each census tract. The LSQ program converges rapidly in ten iterations to give the following equation:

$$F' = 318.4e^{-.0088((X - 714)^2 + (Y - 618)^2)^{\frac{1}{2}}} \qquad 3.7$$

This places the centre of the distribution a short distance to the north and west of the Dundas-Waterloo intersection. The explanation achieved by this simple model was surprisingly high: R and R^2 values were -.8604 and +.7403, respectively. Figures 3.12 and 3.13 represent a block diagram and contour map of the model surface. These figures were also produced by the SURF package using the Interpolate option and a 'b' value of 10. Figure 3.14 shows a plot of the actual and fitted values and Figure 3.15 shows a plot of residuals against distance. It is difficult to determine a pattern in the latter figure though to some extent it does have a funnel shape with the wide end corresponding to the small distances and the narrow end to the large distances. This would suggest that the model's greatest error lies near the centre of the alarm distribution. Census tract 22, lying right at the heart of the distribution, is still heavily under-predicted while census tracts 15 and 23 are seriously over-predicted.

TABLE 3.2 The Number of Alarms Per Square Mile in Each of London's 51 Census Tracts

1)	10.800	25)	78.670
2)	24.480	26)	33.710
3)	20.480	27)	11.310
4)	20.990	28)	34.290
5)	22.990	29)	38.300
6)	22.000	30)	75.000
7)	39.630	31)	124.07
8)	17.480	32)	200.00
9)	14.080	33)	220.93
10)	66.670	34)	161.22
11)	27.350	35)	37.500
12)	27.630	36)	51.920
13)	60.000	37)	36.250
14)	61.020	38)	41.130
15)	28.120	39)	85.110
16)	75.000	40)	70.000
17)	132.14	41)	83.720
18)	117.46	42)	90.200
19)	63.160	43)	93.650
20)	25.420	44)	29.250
21)	91.030	45)	42.190
22)	326.03	46)	53.570
23)	104.84	47)	35.380
24)	121.87	48)	60.000

TABLE 3.2 Cont'd.

49)	25.000
50)	10.560
51)	2.4700

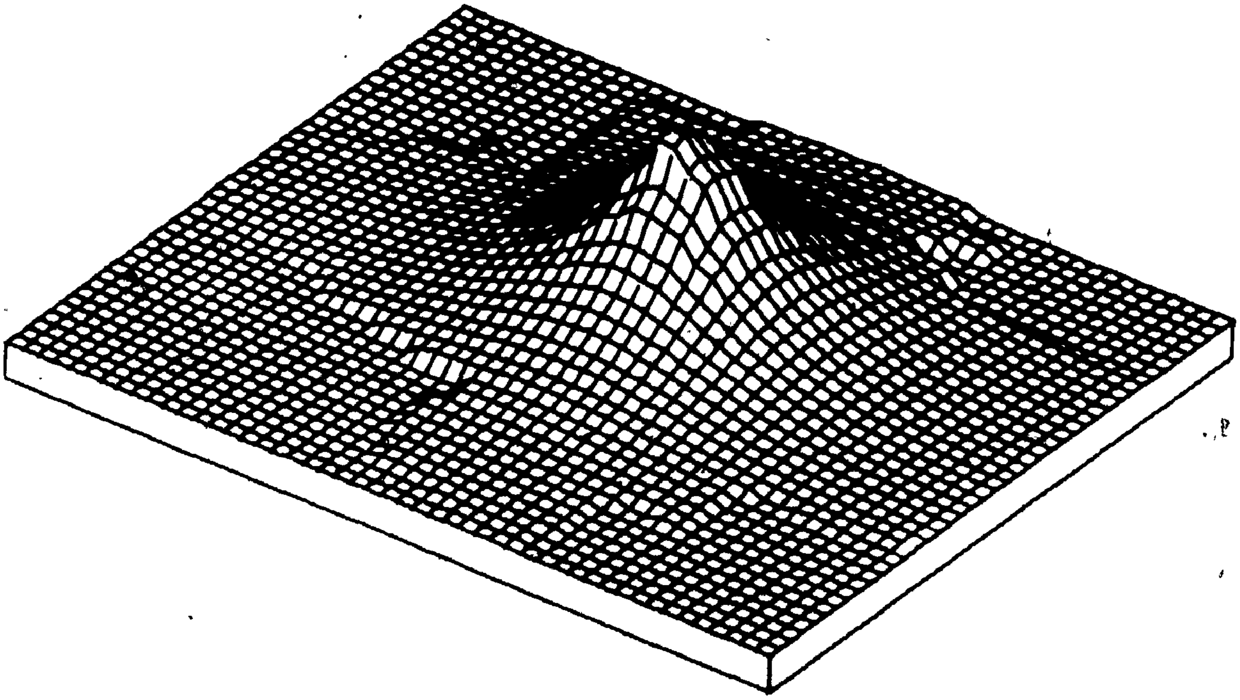


Figure 3.12. Block Diagram of the Distance Decay Model Produced by the LSQ Program from the Time Series Processor for the Data in Table 3.2

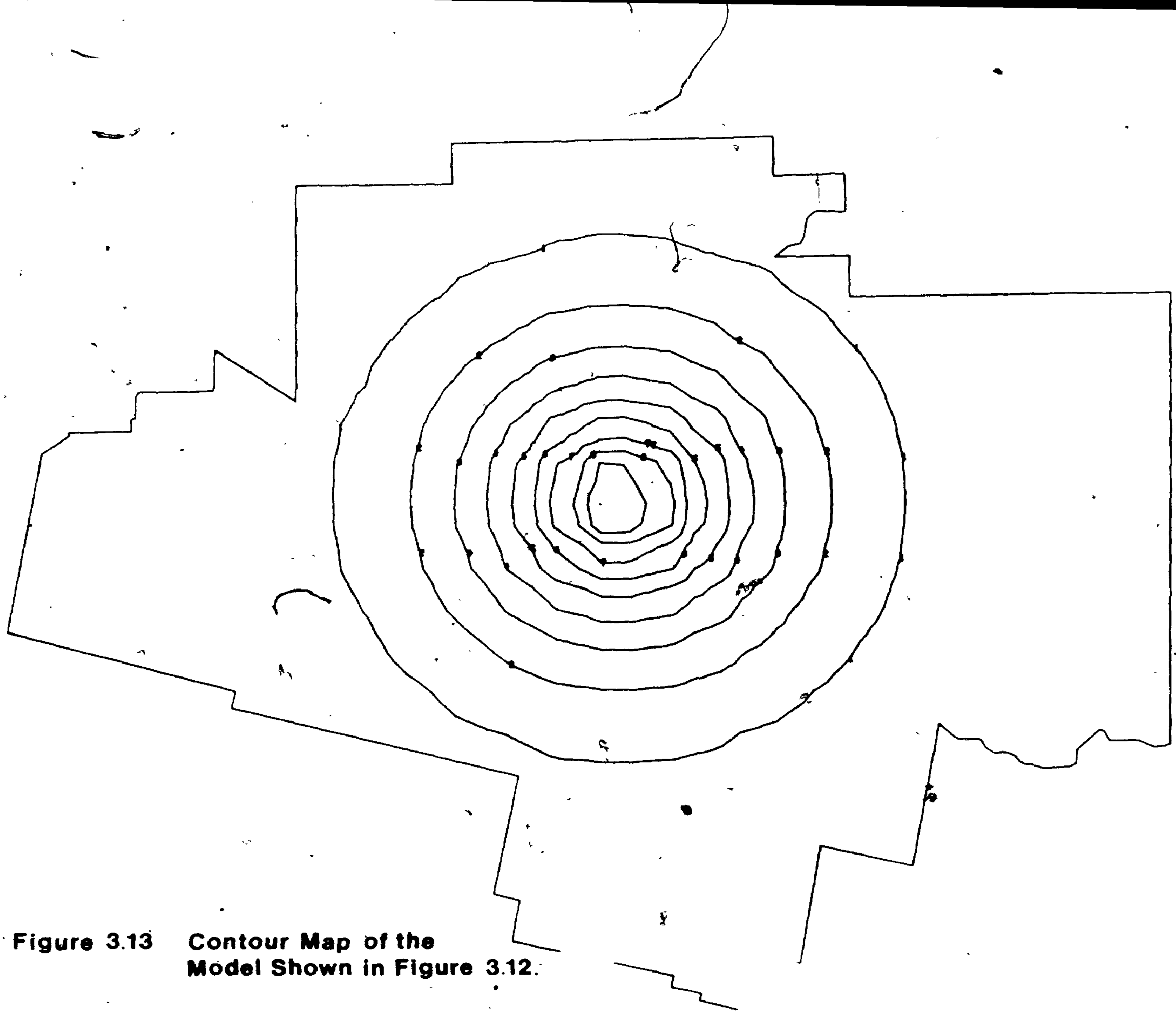
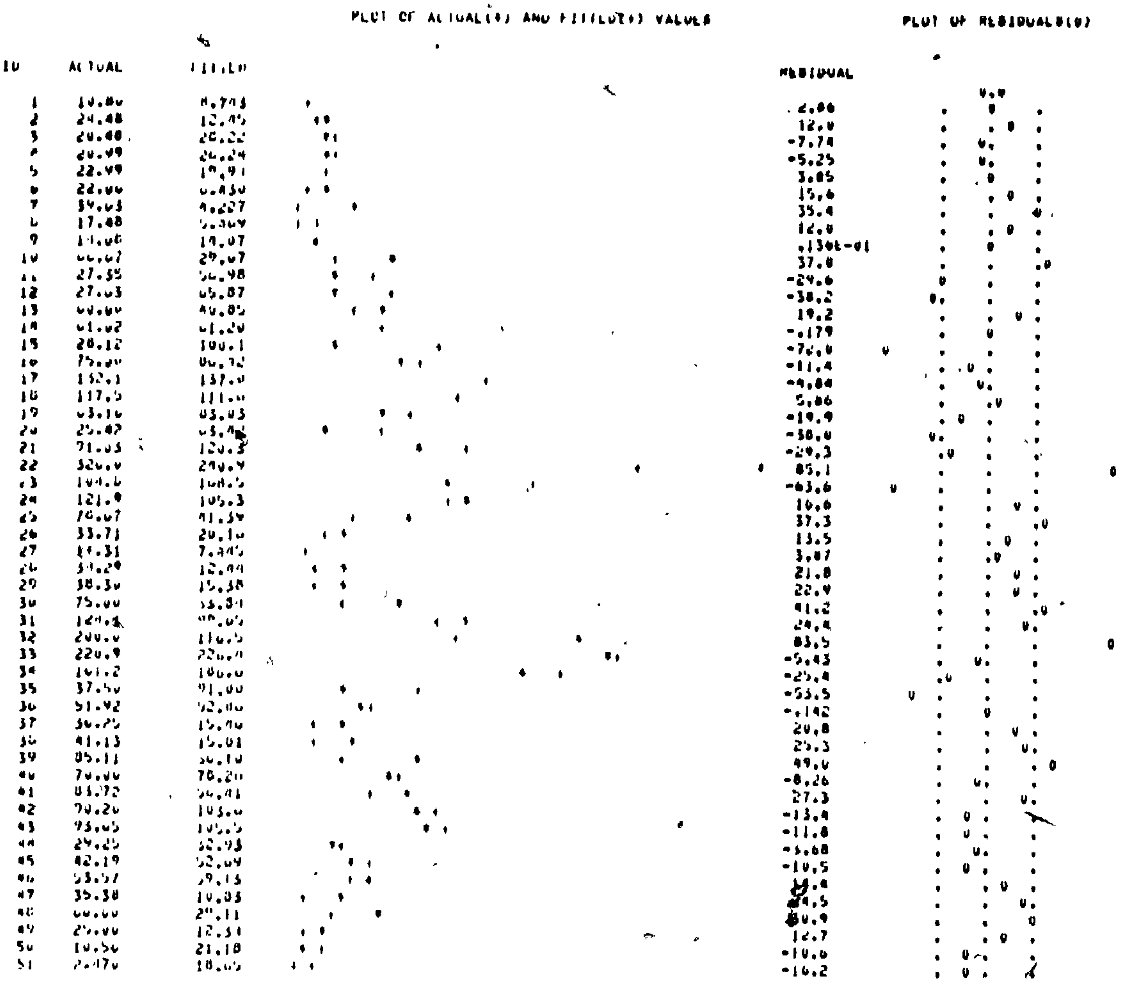


Figure 3.13 Contour Map of the Model Shown in Figure 3.12.



ID	ACTUAL	FITTED	RESIDUAL
1	10.80	8.743	2.06
2	24.48	12.45	12.0
3	20.48	28.22	-7.74
4	20.99	26.24	-5.25
5	22.99	19.14	3.85
6	22.00	6.430	15.6
7	44.63	9.227	35.4
8	17.48	5.369	12.1
9	14.08	14.07	.130E-01
10	66.67	29.07	37.6
11	27.35	56.98	-29.6
12	27.63	65.87	-38.2
13	60.00	40.85	19.2
14	61.02	61.20	-.179
15	28.12	100.1	-72.0
16	75.00	86.42	-11.4
17	132.1	137.0	-4.84
18	117.5	111.6	5.86
19	63.16	83.03	-19.9
20	25.47	63.4[illegible]	-38.0
21	91.03	120.3	-29.3
22	326.0	240.9	85.1
23	104.8	168.5	-63.6
24	121.9	105.3	16.6
25	78.67	41.39	37.3
26	33.71	20.16	13.5
27	11.31	7.445	3.87
28	34.29	12.49	21.8
29	38.30	15.38	22.9
30	75.00	33.84	41.2
31	124.[illegible]	99.65	24.4
32	200.0	116.5	83.5
33	220.9	226.3	-5.43
34	161.2	186.6	-25.4
35	37.50	91.00	-53.5
36	51.92	52.06	-.142
37	36.25	15.40	20.8
38	41.13	15.81	25.3
39	85.11	36.10	49.0
40	70.00	78.26	-8.26
41	83.72	56.41	27.3
42	90.20	103.6	-13.4
43	93.65	105.5	-11.8
44	29.25	32.93	-3.68
45	42.19	52.69	-10.5
46	53.57	39.15	14.4
47	35.38	10.85	24.5
48	60.00	29.11	30.9
49	25.00	12.31	12.7
50	10.56	21.18	-10.6
51	2.470	18.65	-16.2

Figure 3.14 Plot of the Actual and Fitted Values of the Distance Decay Model Shown in Figure 3.12

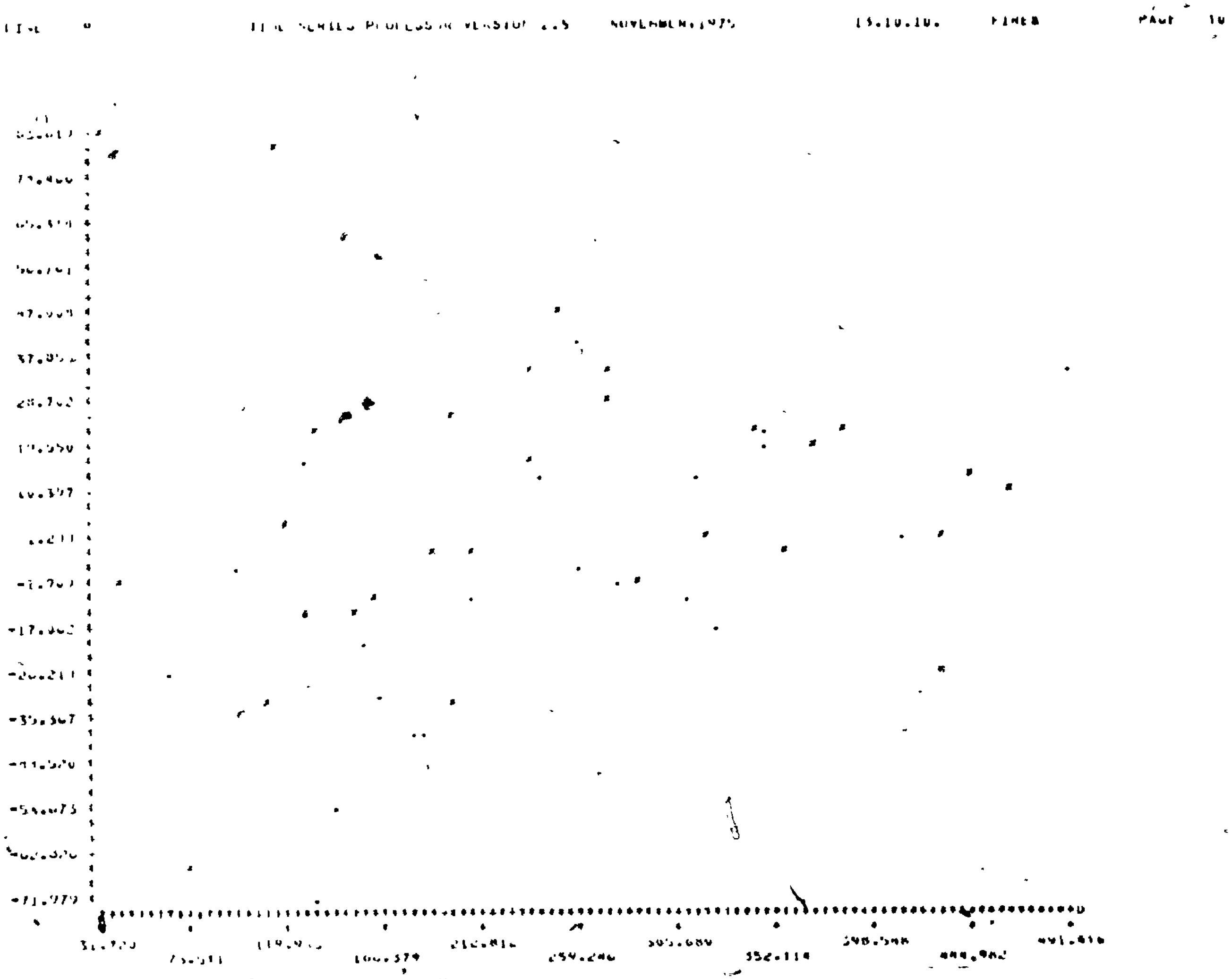


Figure 3.15 Plot of Residuals Against Distance from the Centre of the Distribution for the Distance Decay Model Shown in Figure 3.12

The pattern is similar to the one found with the trend surface model where there was a high positive residual at the centre and a ring of high negative residuals around it. The distribution is actually leptokurtic. There are, of course, some notable anomalies in the distribution of residuals. Thus census tract 35, which only contains Wolseley Barracks, has a high negative residual and census tract 32 has a high positive residual. The latter may possibly be explained by its location along the north side of the east London retail trade area. In larger cities it may be possible to detect several peaks in the alarm density pattern, each peak corresponding to a major retail trade area. Thus in some cities the alarm density pattern may also have "multiple nuclei".

It should be pointed out that in the above analysis two alternative models of the spatial distribution of alarms have been described. Firstly, there is the three-dimensional quartic trend surface equation. This model has the advantage that it can describe asymmetries in the alarm data which exist around the urban core. The shape of the model is basically that of a convex hill centred on the urban core with a slight rise on the periphery of the city. The second model is the two-dimensional negative exponential distance decay function. Because it is two-dimensional this model assumes that the alarm distribution is symmetrical about a central point and this is, of course, an inherent weakness. However, the basic shape of this model is that of a hill with concave slopes centred on the urban core and this does appear to be a more realistic approximation to the actual alarm distribution in London during 1973.

In order to establish which was the more appropriate model, the trend surface analysis was repeated using the same data set as was used to fit the distance decay equation (that is the alarm density in each of the 51 census tracts). The second, third, fourth, and fifth order surfaces yielded explanations of 39%, 46%, 59% and 62%, respectively. These trend surface equations were evaluated using the TREND option in the SURF program package and the same package was used to create block diagrams of the four models which are shown in Figures 3.16, 3.17, 3.18 and 3.19, respectively. These four diagrams bear out the remarks made above about the shape of the trend surface model. The central peak in alarms is always modelled with too gentle a decline away from the core. As a result, the distance decay function explains, in a more parsimonious manner (because it uses fewer terms), 12% more of the variation in the surface than the fourth order surface which was deemed the most appropriate trend surface model in the previous analysis. It may be concluded that for cities, such as London, where alarm densities are not markedly asymmetrical around the urban core, the negative exponential distance decay function is the most appropriate and parsimonious model of such densities. Where alarm densities are less symmetrical, for example, in cities with a strong sectoral land use pattern or a multiple nuclei land use pattern (presuming a relationship between land use and alarm densities) the trend surface model <u>may</u> be more appropriate. Obviously, in order to resolve this problem, further research will be required on larger cities with more complex land use structures.

So far, the preliminary analysis has analysed the pattern of alarm density in time and space. A third series of analyses were run

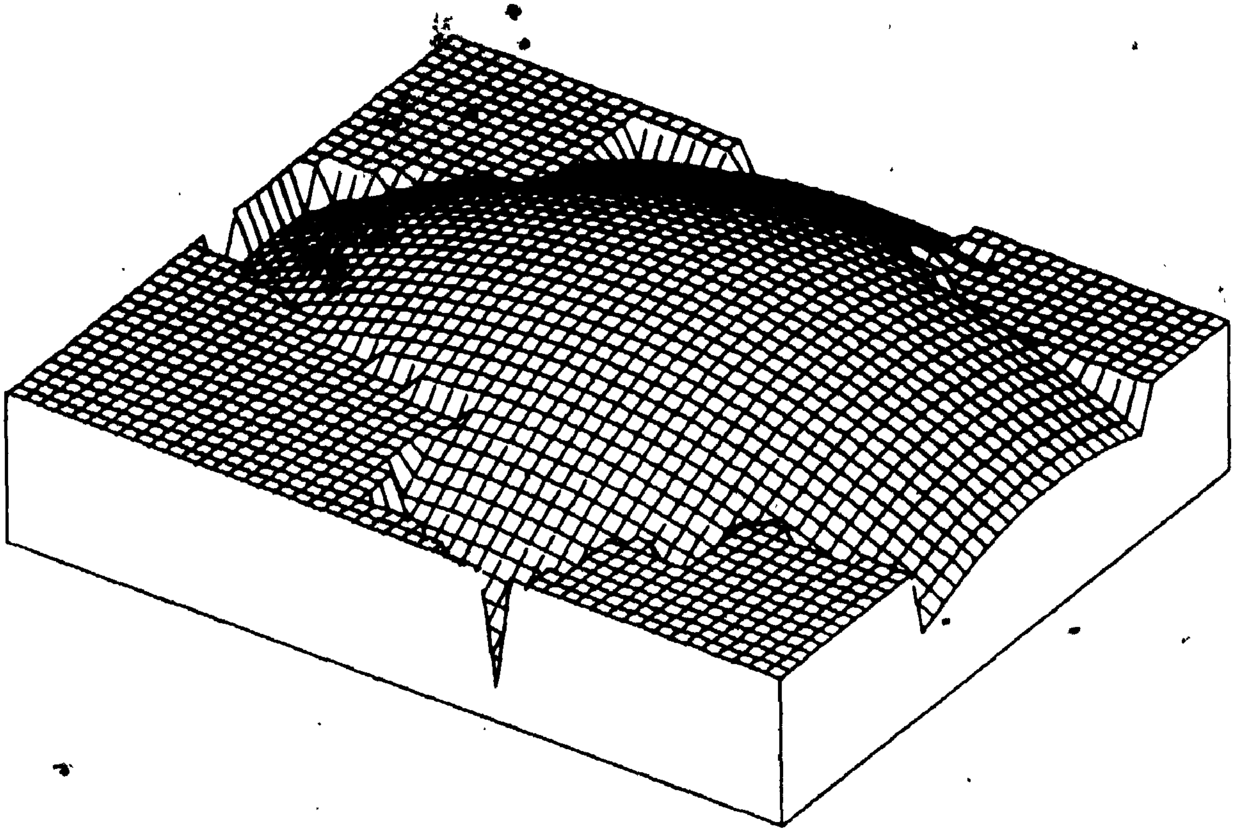


Figure 3.16 Block Diagram of a Quadratic Trend Surface Model Based on Data Shown in Table 3.2

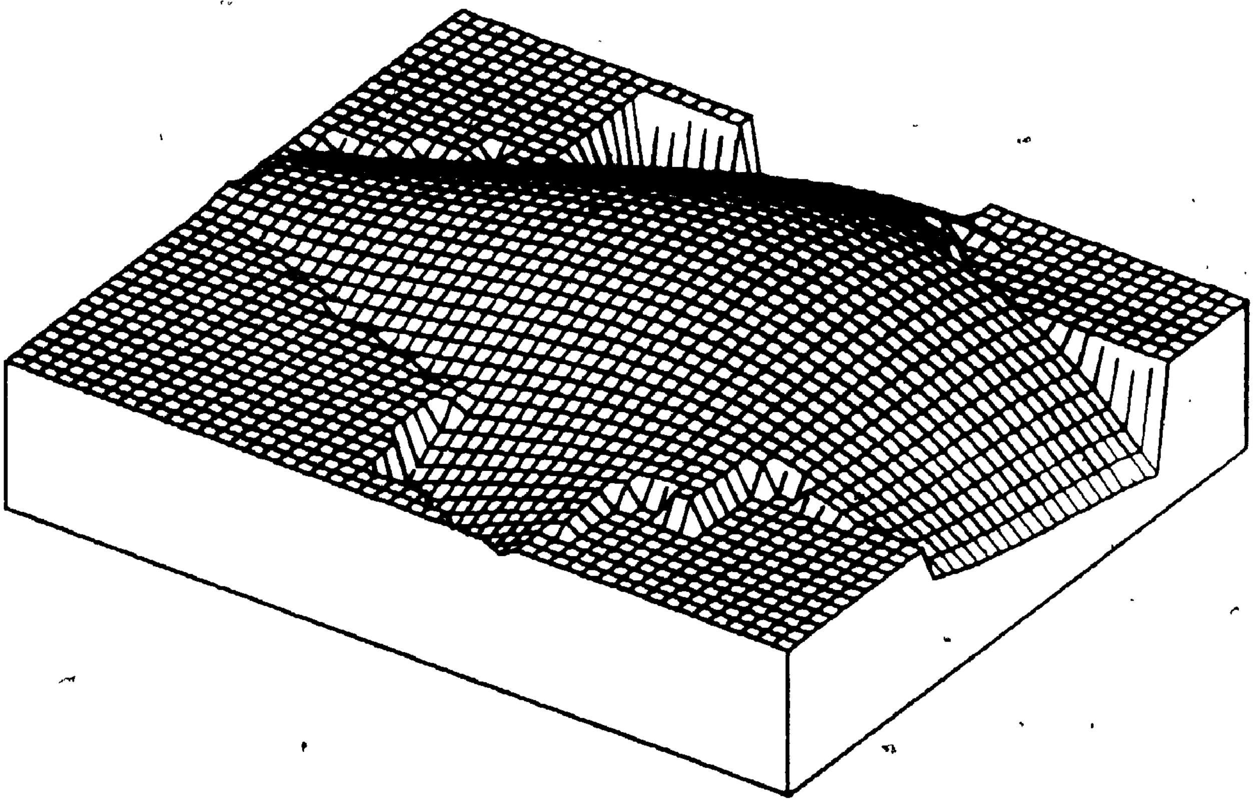


Figure 3.17 Block Diagram of a Cubic Trend Surface Model Based on Data Shown in Table 3.2

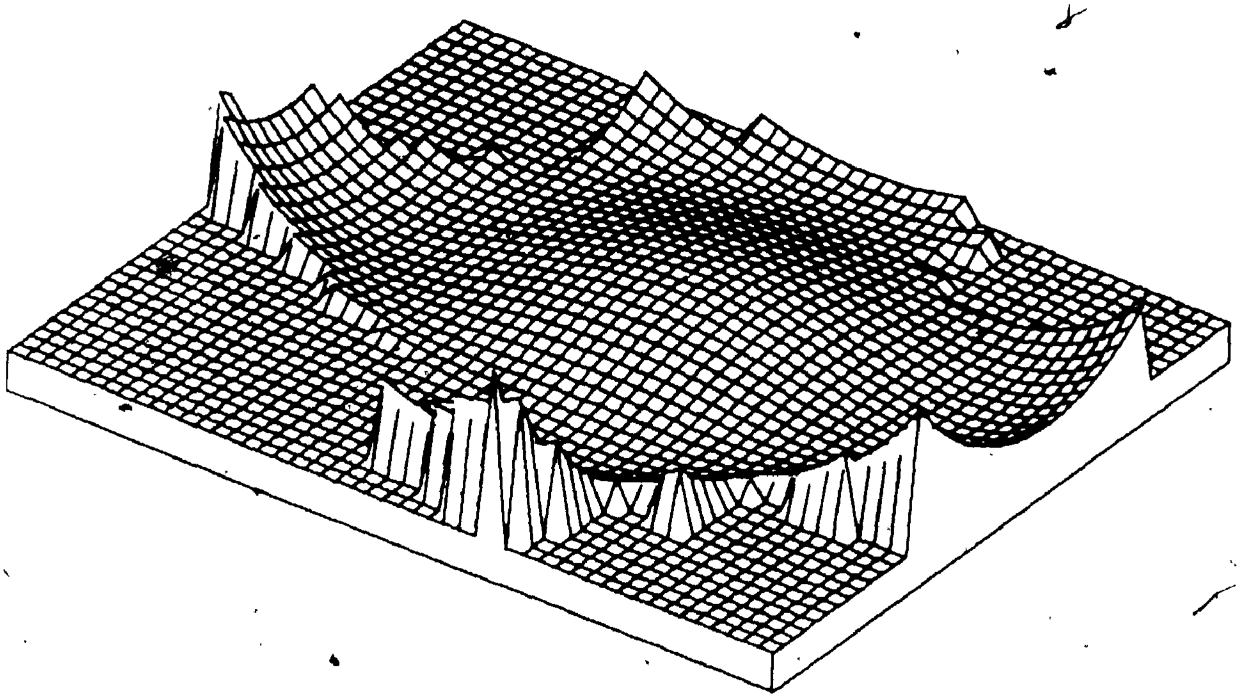


Figure 3.18 Block Diagram of a Quartic Trend Surface Model Based on Data Shown in Table 3.2

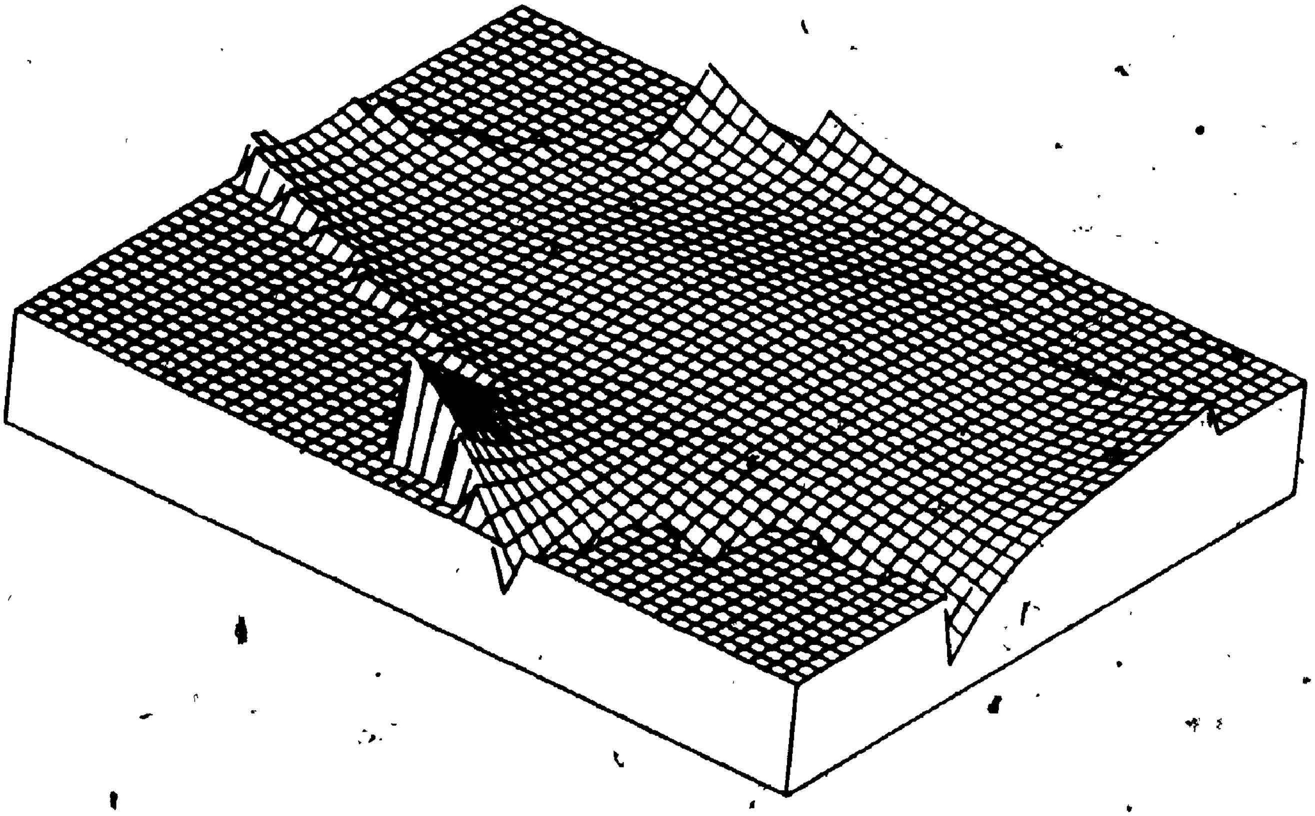
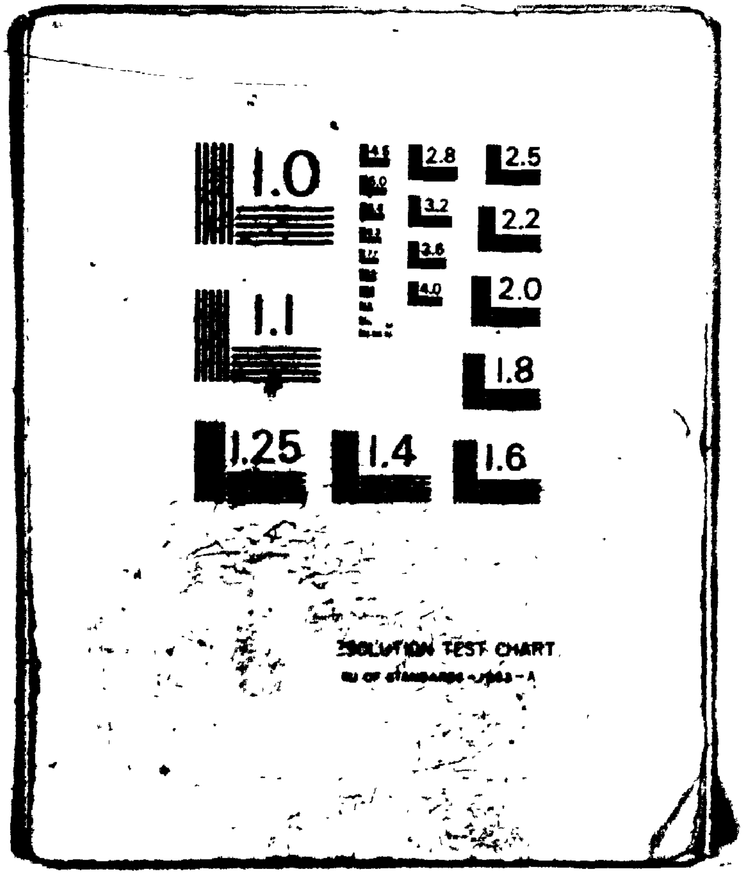


Figure 3.19 Block Diagram of a Quintic Trend Surface Model Based on Data Shown in Table 3.2

2


1.0
4.5
5.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
ESOLUTION TEST CHART
AU OF STANDARDS-1963-A

to determine whether there were any interaction effects. The distance decay function was now fitted to the data for each time period in turn. Figures 3.20, 3.21, 3.22 and 3.23 represent block diagrams drawn by the SURF program for each of the four time periods. The equations and R^2 terms for the four functions were as follows:

Time Period 1 $$F' = 69.0e^{-.0126((X-704)^2 + (Y-616)^2)^{\frac{1}{2}}} \qquad 3.8$$

$$R^2 = .67$$

Time Period 2 $$F' = 75.5e^{-.0115((X-712)^2 + (Y-618)^2)^{\frac{1}{2}}} \qquad 3.9$$

$$R^2 = .67$$

Time Period 3 $$F' = 99.2e^{-.0080((X-714)^2 + (Y-616)^2)^{\frac{1}{2}}} \qquad 3.10$$

$$R^2 = .74$$

Time Period 4 $$F' = 89.7e^{-.0074((X-709)^2 + (Y-626)^2)^{\frac{1}{2}}} \qquad 3.11$$

$$R^2 = .66$$

Although these results appear similar there are some significant differences between the first two and the last two periods. The F_0 terms varied simply because the total number of alarms in each period also varies. In each of the four periods the total number of alarms is, respectively, 336, 422, 862 and 839. More interesting is the difference between the b term in equations 3.8 and 3.9 as opposed to 3.10 and 3.11. The standard errors for the b terms in equations 3.10 and 3.11 are, respectively, .0008 and .0009. This, of course, indicates a significant difference (at the 5% level) between the b values in equations 3.10 and 3.11 and those in equations 3.8 and 3.9. More simply the fire alarm density slope is steeper before noon than after noon. It is difficult to determine the exact reason for this. To provide further insight a cross tabulation was performed by census

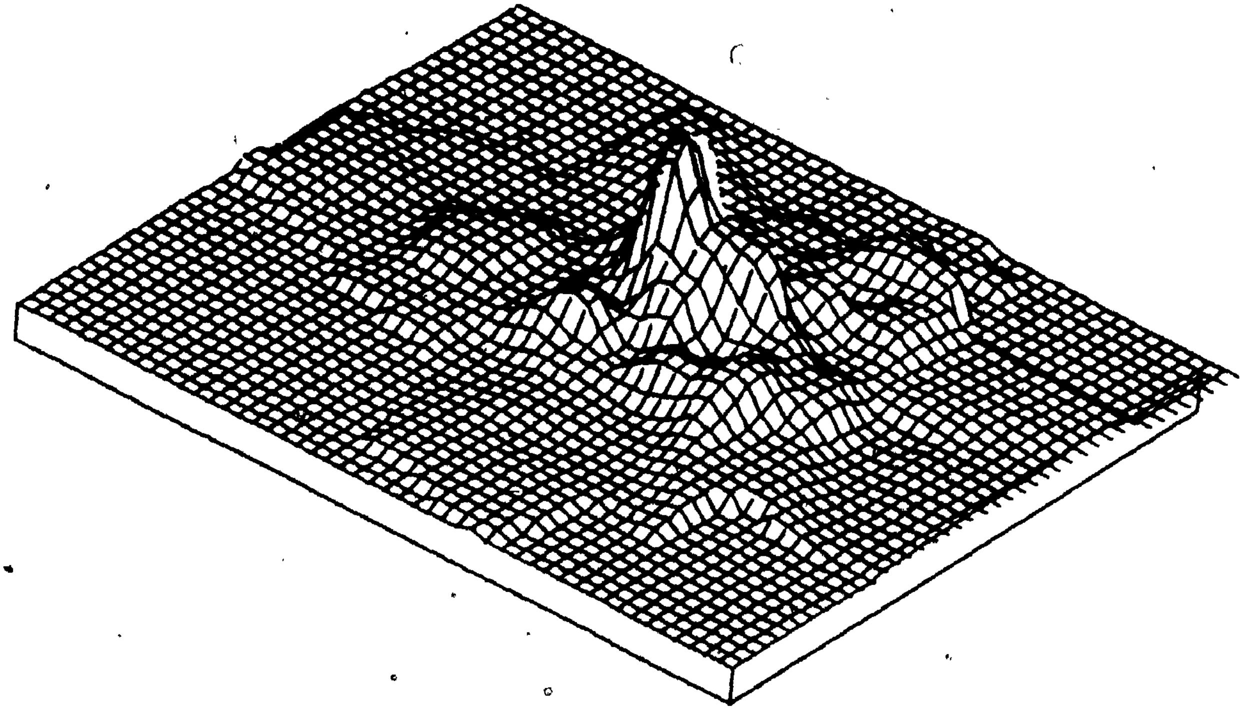


Figure 3.20 Block Diagram Showing the Distribution of Alarms During the First Time Period for 1973

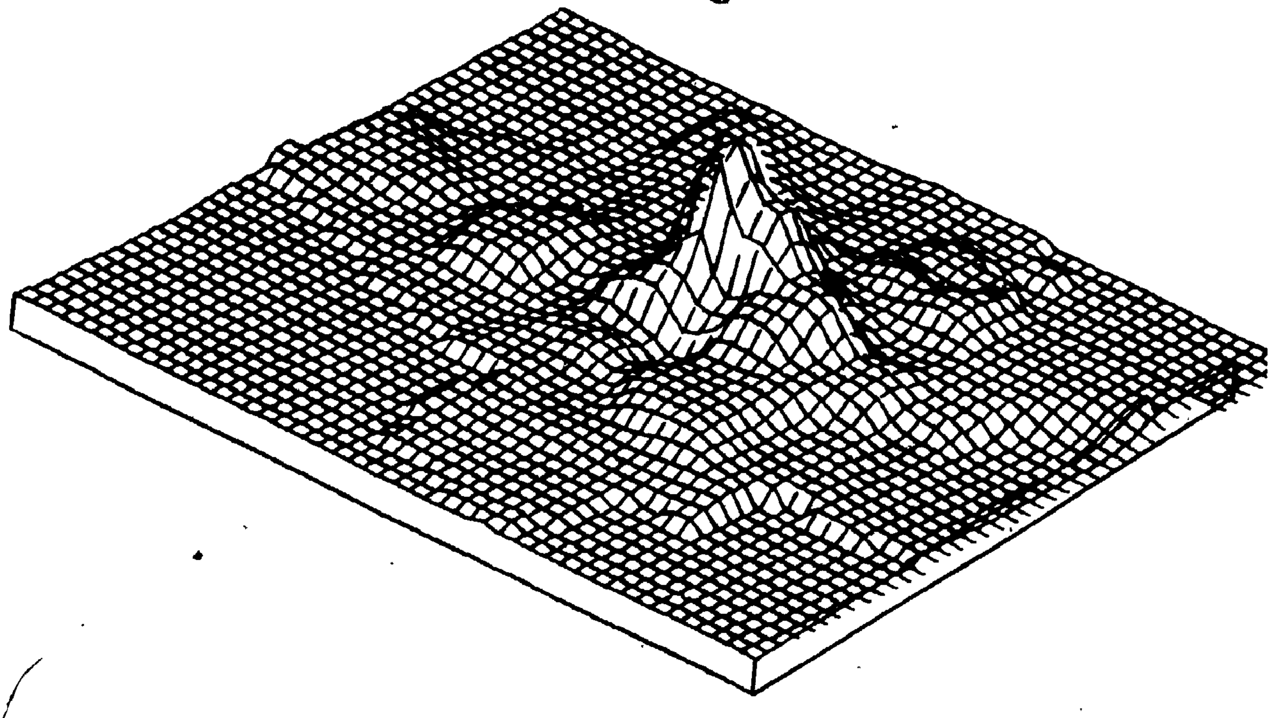


Figure 3.21 Block Diagram Showing the Distribution of Alarms During the Second Time Period During 1973

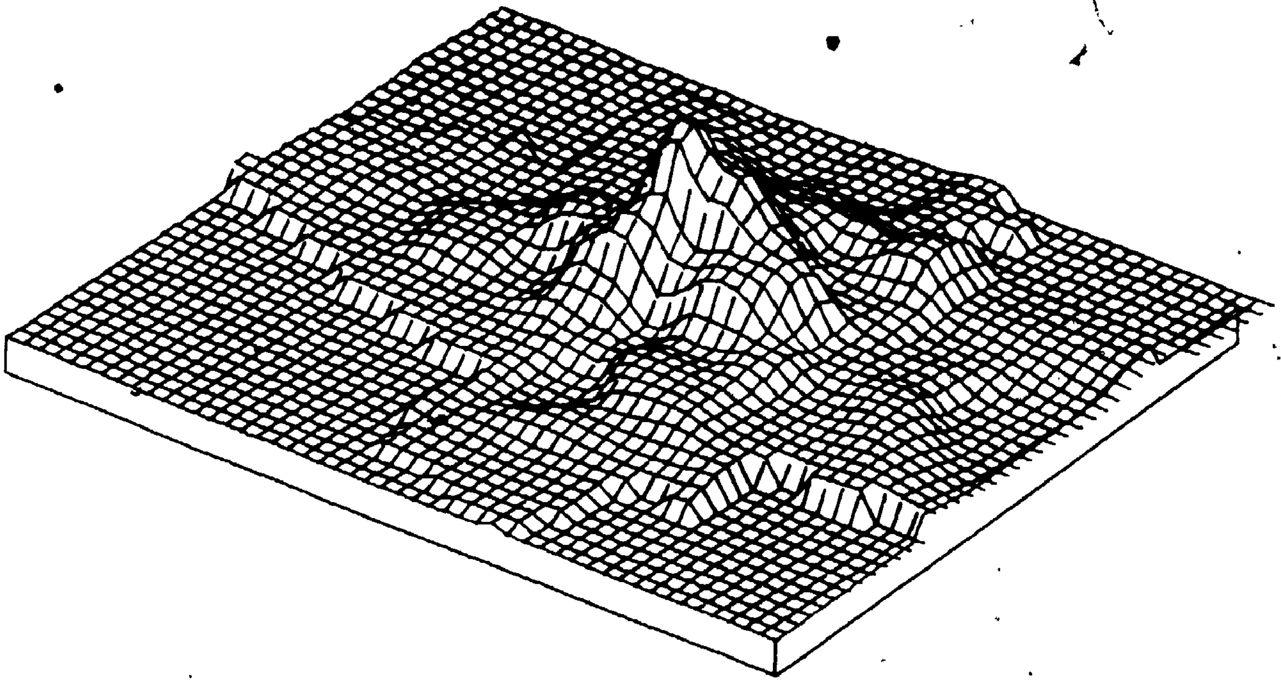


Figure 3.22 Block Diagram Showing the Distribution of Alarms During the Third Time Period for 1973

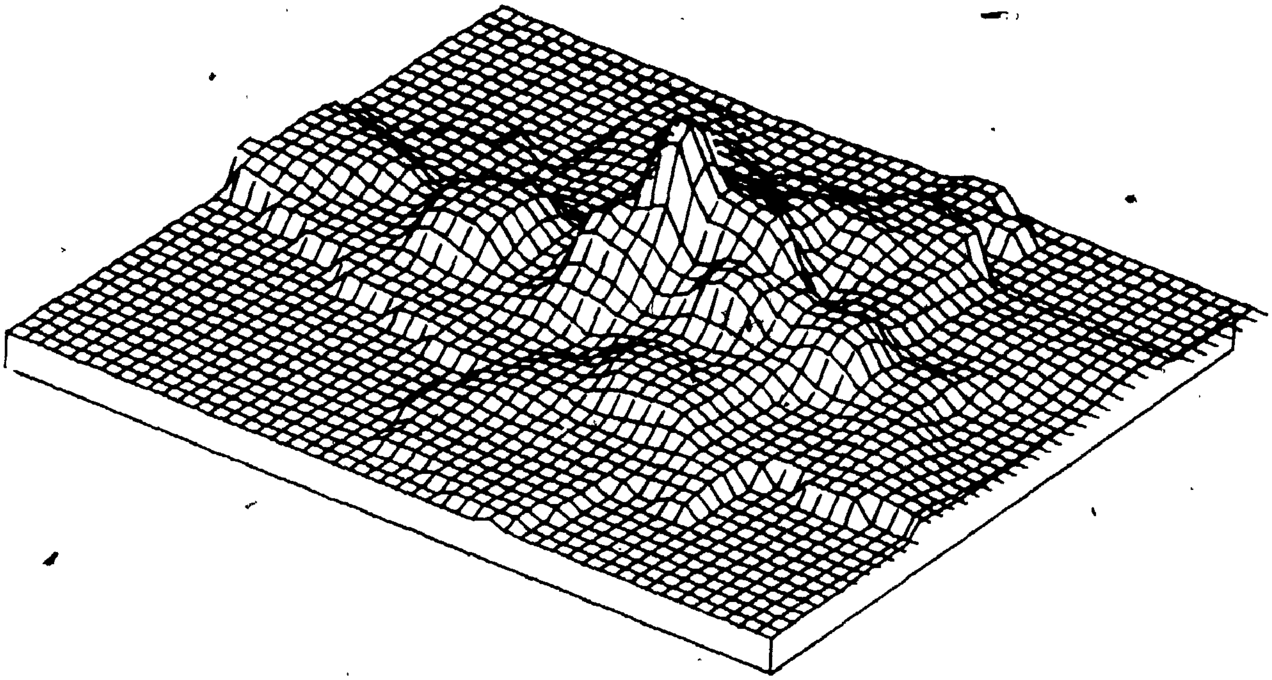


Figure 3.23 Block Diagram Showing the Distribution of Alarms During the Fourth Time Period During 1973

tract and time period using the SPSS program CROSSTABS (Nie et al., 1975). The results of this analysis are displayed in Appendix 1. As can be seen the raw chi-square value is high and significant at less than the 5% level. Cramer's V, however, is low and so the strength of the association is not great. The pattern is still indistinct though and it is possible to do little more than point to such features as the decline in the percentage share enjoyed by the core tract, number 22. Thus, though census tract 22 has more alarms in the last two time periods, its percentage share in these periods is only 2/3 of its share in the first two periods. A likely reason for the confusion in these patterns is that different types of alarms have different time-space patterns. In order to determine whether this was indeed the case the analysis was repeated for emergency alarms, the various types of false alarms, and the miscellaneous category of alarm codes. In none of these analyses was the chi-square value significant. There are probably at least two reasons for this disappointing result. Firstly, the alarm code is in all likelihood too coarse and consequently still groups the alarms into rather heterogeneous classes whose members may still have very different time-space distributions. Secondly, since there are 204 classes in the chi-square table (51 census tracts times four time periods) the data, when it is split into different alarm types, becomes too sparse for a meaningful analysis. This second problem, of course, exacerbates the solution to the first since that would require an even finer breakdown of alarm types thus making the data more thinly distributed over a larger number of categories. Any researcher investigating emergency services is likely to be faced with this problem of data scarcity and future analyses which attempt to build predictive and explanatory models of the time-space distributions of alarm types should be based on very large data sets. Needless to say such large data sets can only be built up over a number of years (this being especially true of small towns) and, of course, over a number of years the nature of the distribution may change. Chaiken and Rolph (1971) have noted that even using a data set containing 1½ million alarms, they still, in some situations, encountered problems relating to sample size.

Finally, the CROSSTABS program was run on the five alarm codes as they were distributed across the 51 census tracts to determine whether there was a spatial distribution to these alarm types (thus in this analysis the time component which had aggravated the data sparseness was ignored). The raw chi-square value was over 353 with 200 degrees of freedom and this is significant at the 95% confidence level. Cramer's V was still only 0.19 which again indicates that the strength of the relationship is weak. The five alarm code distributions are shown in Figures 3.24, 3.25, 3.26, 3.27 and 3.28 and the five best fit equations describing these distributions are as follows:

$$\text{ACODE1}' = 45.5e^{-.0074((X-756)^2 + (Y-627)^2)^{\frac{1}{2}}} \qquad 3.12$$

$$R^2 = .71$$

$$\text{ACODE2}' = 34.1e^{-.0203((X-707)^2 + (Y-617)^2)^{\frac{1}{2}}} \qquad 3.13$$

$$R^2 = .73$$

$$\text{ACODE3}' = 61.4e^{-.0246((X-690)^2 + (Y-616)^2)^{\frac{1}{2}}} \qquad 3.14$$

$$R^2 = .80$$

$$\text{ACODE4}' = 30.0e^{-.0119((X-711)^2 + (Y-621)^2)^{\frac{1}{2}}} \qquad 3.15$$

$$R^2 = .59$$

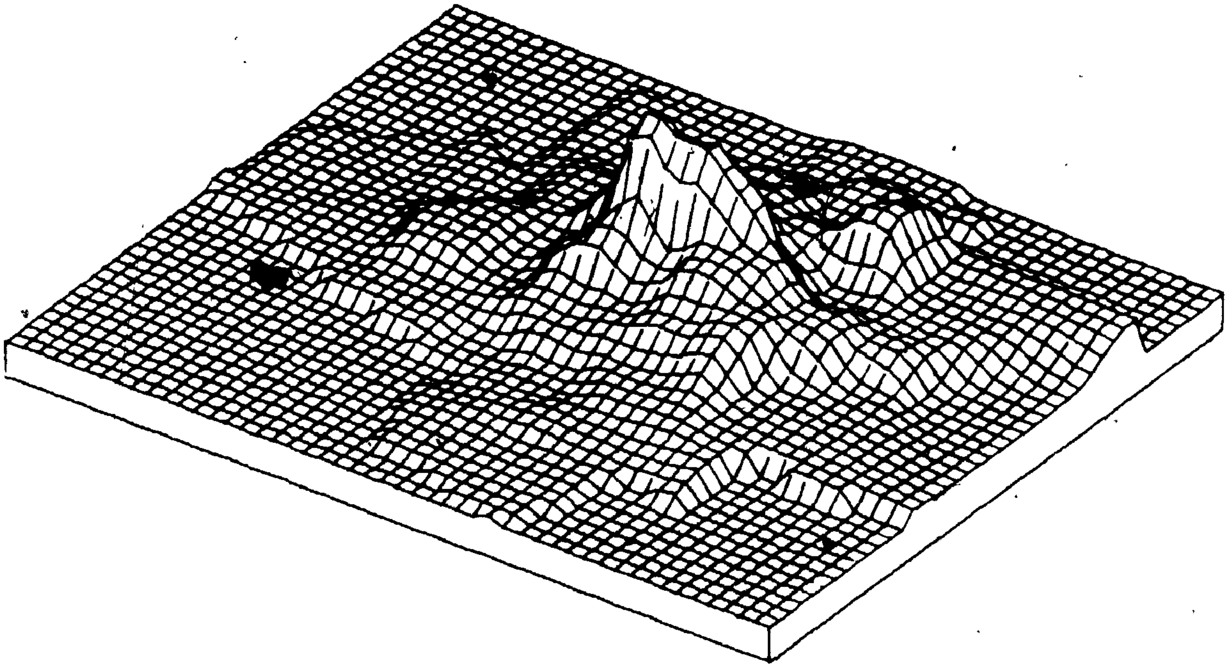


Figure 3.24 Block Diagram Showing the Distribution of Emergency Alarms During 1973

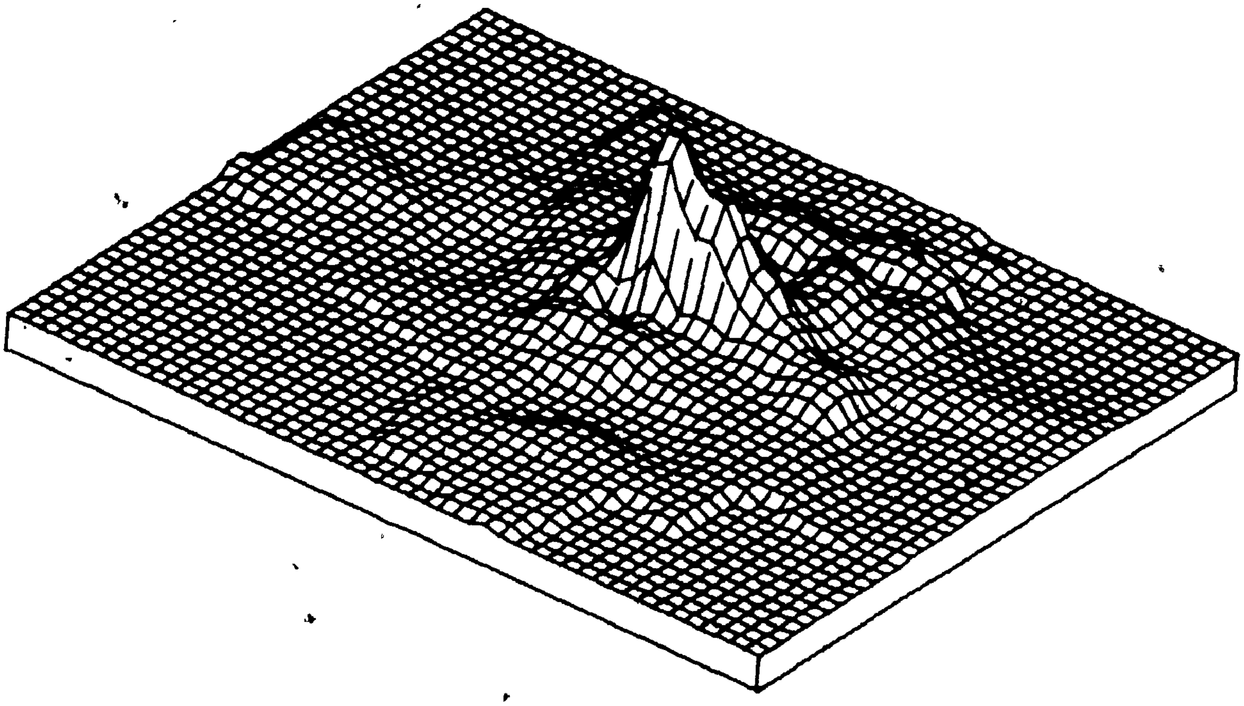


Figure 3.25 Block Diagram Showing the Distribution of Good Intent False Alarms During 1973

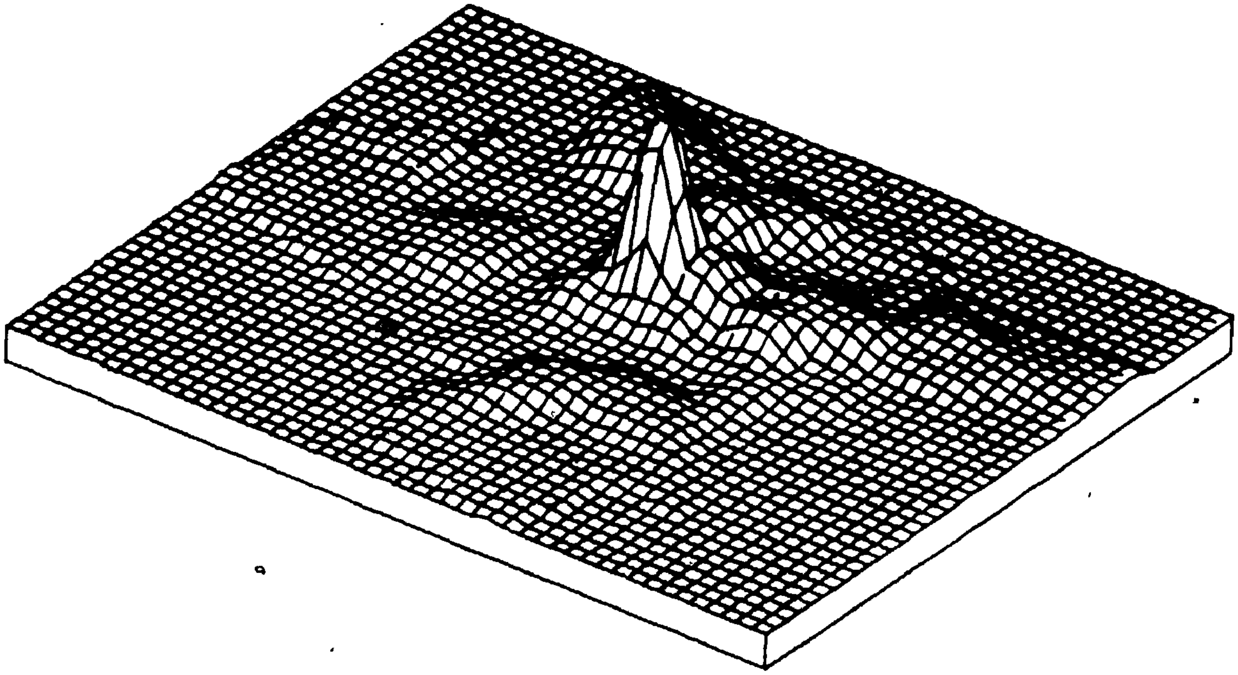


Figure 3.26 Block Diagram Showing the Distribution of Mechanical and Accidental False Alarms During 1973

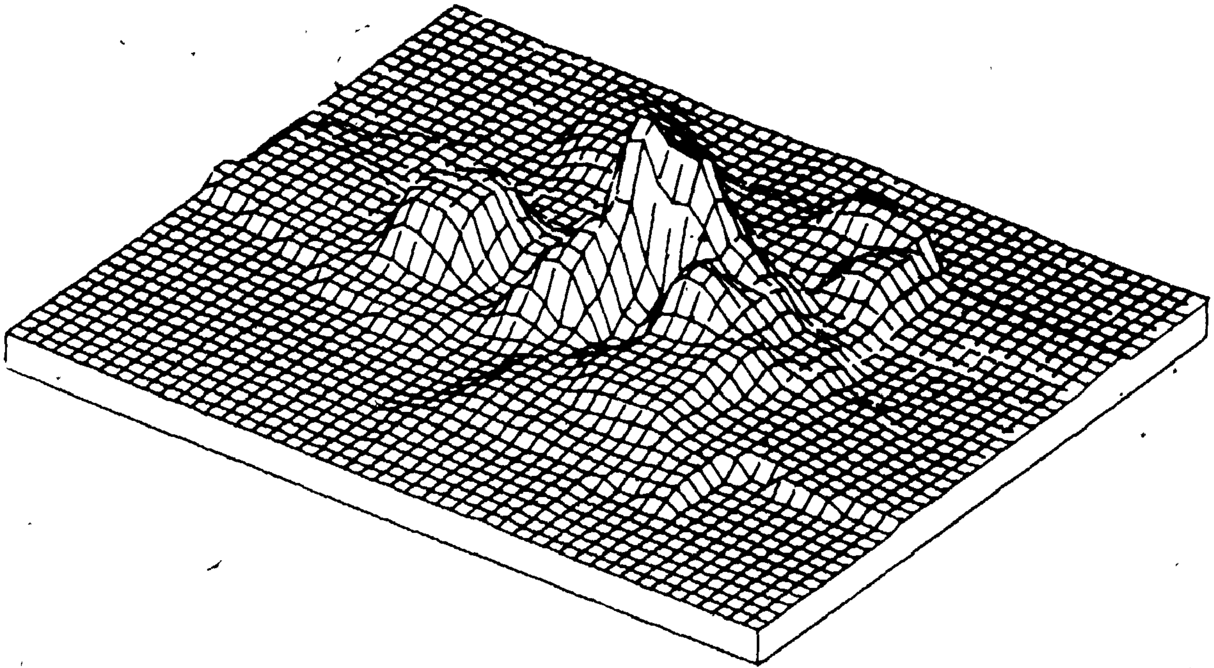


Figure 3.27 Block Diagram Showing the Distribution of Malicious False Alarms During 1973

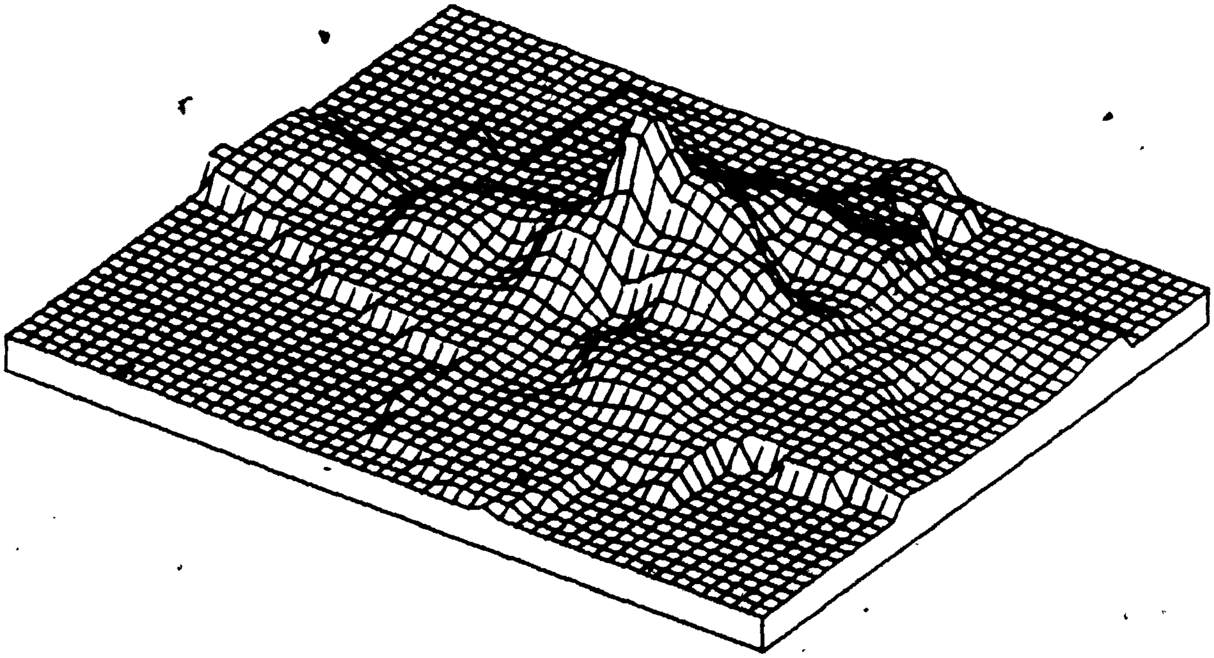


Figure 3.28 Block Diagram Showing the Distribution of Alarms Other Than Emergency and False Alarms During 1973

$$ACODE5' = 185.1e^{-.0077((X-712)^2 + (Y-622)^2)^{\frac{1}{2}}} \qquad 3.16$$

$$R^2 = .71$$

where ACODE1' to ACODE5' represents the predicted number of alarms of code 1 to code 5 respectively.

The five block diagrams provide some assistance in interpreting these distributions. However, when interpreting the patterns it must be remembered that these distributions are expressed as densities per square mile for each census tract. Thus census tract 44 which contains the University, its residences and the new University Hospital, generates many malicious and mechanical/accidental false alarms but because this census tract is large the density of these alarms is reduced and they show only as mild bulges on Figures 3.27, and 3.26, respectively. Interestingly enough the miscellaneous category, Figure 3.28, does tend to show a somewhat more even distribution across the city than the three types of false alarms.

The main value of this analysis is that it provides a simple model for predicting the spatial distribution of alarms by type. When refined such models might then be used to generate surfaces which could be used as the data input for location-allocation studies.

Analysis of Response Times

The literature on the modeling of fire department operations has discussed in some detail the relationship between response times and distance (Kolesar and Walker, 1974). One of the main aims in the present study was to determine what spatial and temporal variations existed in the response times. As a preliminary step in this analysis, the response times were mapped using the SURF package. The response time surface was then printed out as an isopleth map on the line printer again using a 'b' value of 10 and ten equal intervals on the map scale. This map is shown in Figure 3.29. Figure 3.30 is the three-dimensional representation of the map and Figure 3.31 is the contour map. All three figures illustrate a number of points very clearly. Firstly, it is apparent that the broad, overall shape of the distribution is "bowl-shaped". There is a general depression in the middle of the city and a rim around the periphery. This is not unreasonable considering the concentration of Fire Stations 1, 2, 3 (old location), 4 and 5 in and around the city core. However, a closer examination of the figures also shows that there are a number of local depressions outside the core area. This can be seen in the south of the city (corresponding to the location of Fire Station 9), in the extreme west (corresponding to Fire Station 6), in the northwest (where Fire Station 8 is located) and, finally, in the central east (where Station 7 is located). It should be noted that the depressions around Stations 7 and 8 (which are highlighted by the inclusion of both stations inside the first contour which means a response time of 1.98 minutes) do in fact join up with the main, central depression. The first contour also encloses Stations 6 and 9 which are completely isolated and represent two pits in the surface. A number of the values in the surface can be readily identified as corresponding to the major thoroughfares in the city. This is true, for example, for Wellington Road South which almost allows the first contour to break through to the pit around Fire Station 9 and for Commissioners Road West which elongates the pit around Fire Station 6

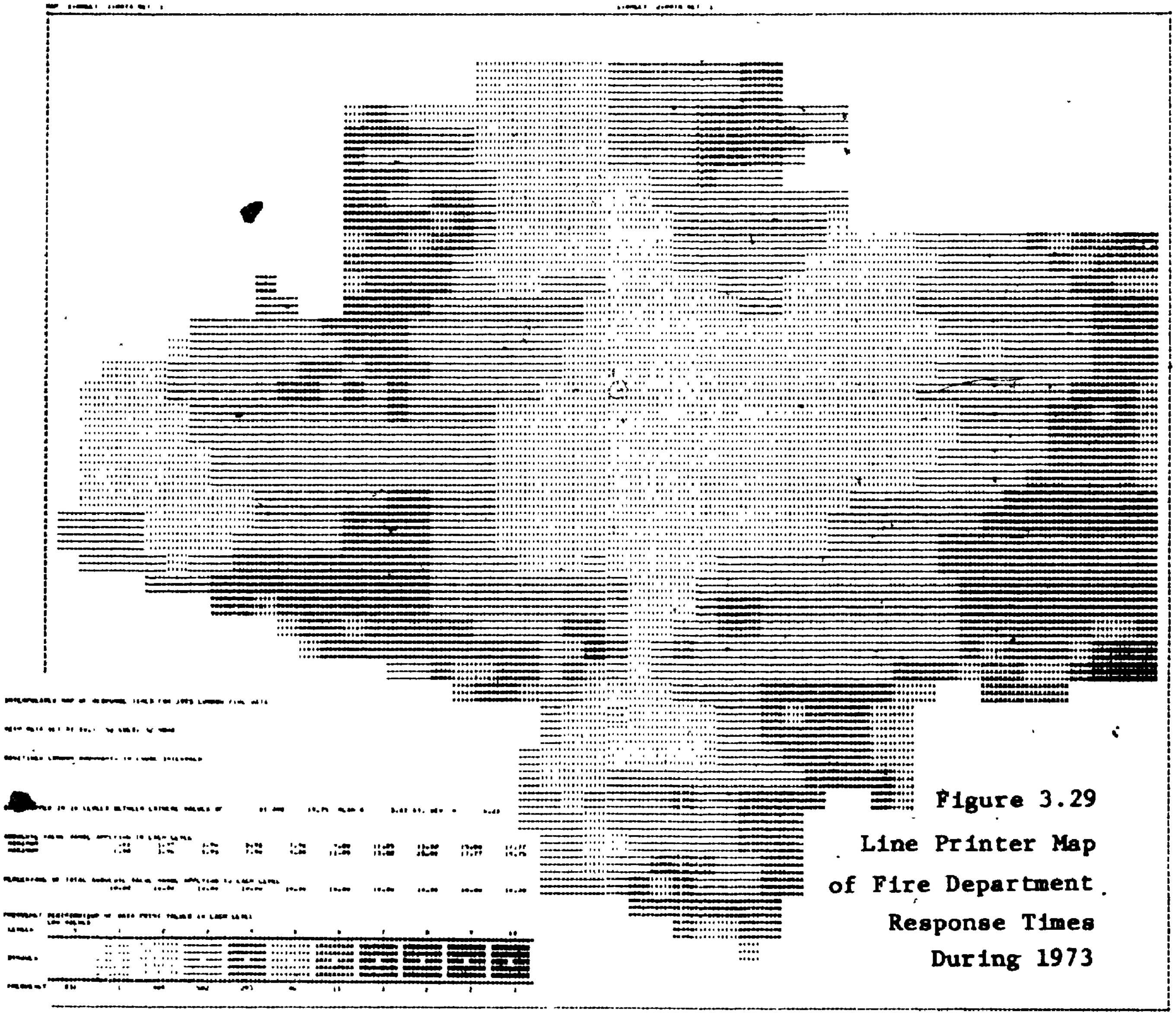


Figure 3.29
Line Printer Map
of Fire Department
Response Times
During 1973

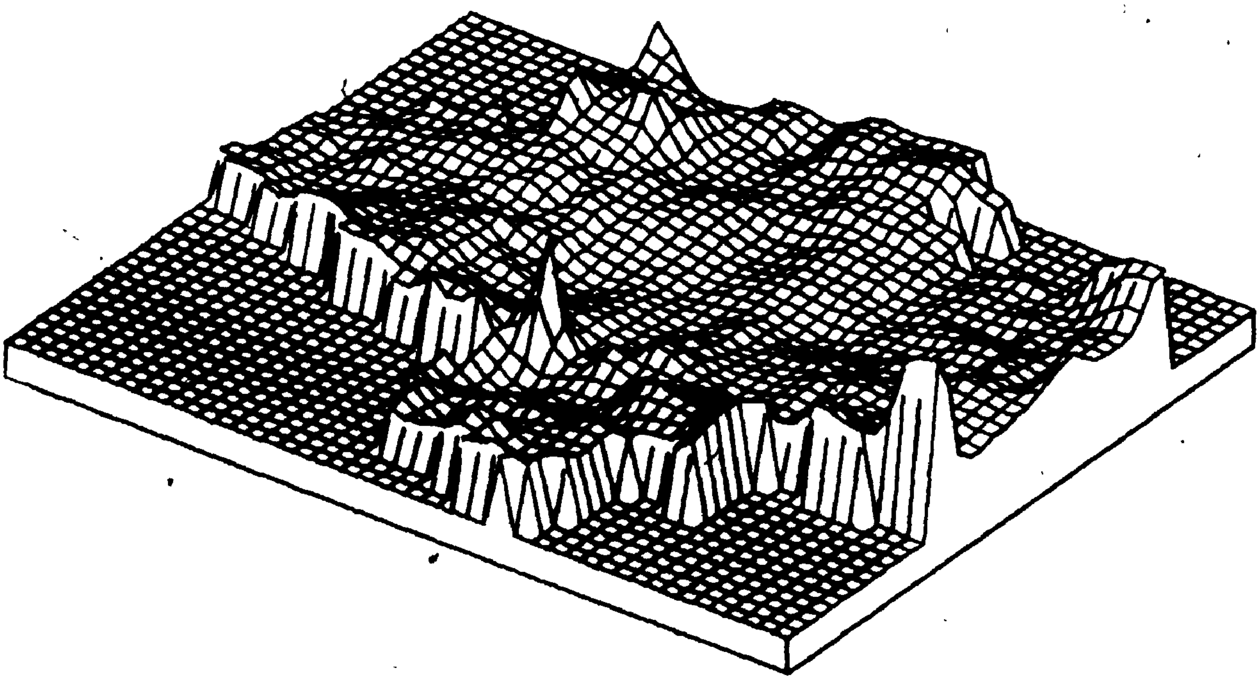


Figure 3.30. Block Diagram of the Data Shown in Figure 3.29

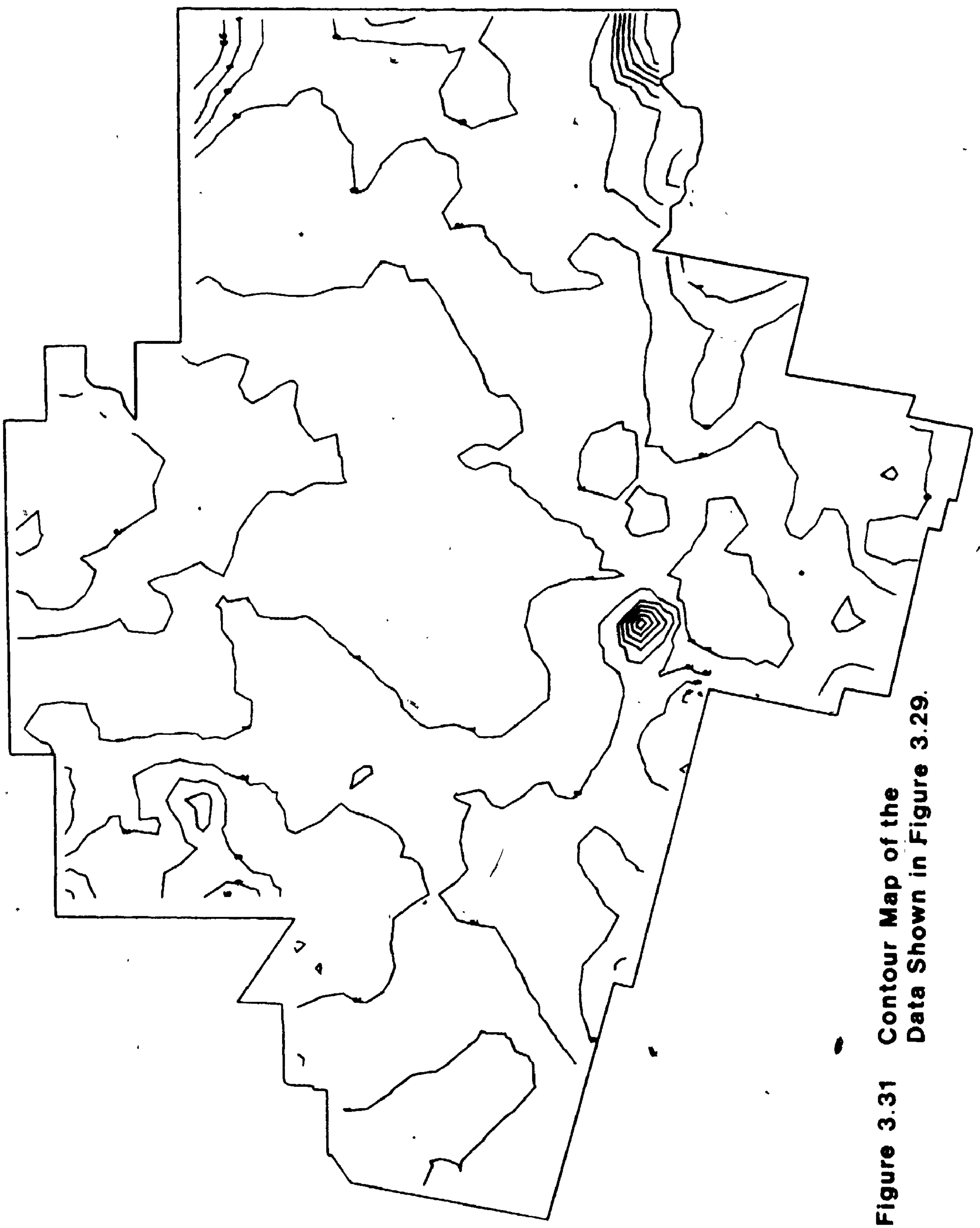


Figure 3.31 Contour Map of the Data Shown in Figure 3.29.

> Responses made when returning from an earlier run or from a position in the field were not included, because of the difficulty of recording accurately times, distances, and locations at time of dispatch ....
>
> ...the need for odometers that recorded in tenths of miles was a limiting factor; only ladder companies and Battalion Chiefs participated since no engines had such odometers. (Our failure to include engines in the experiment would introduce an element of bias in the results, since engines are generally smaller than ladders and are able to manoeuver more easily in traffic and narrow streets, so that they may travel slightly faster.) ...
>
> Editing the Data. The raw data were edited to eliminate obviously erroneous records. We used a number of consistency checks in this process. For example, we eliminated records for which the average velocities attained were higher than 60 m.p.h. In addition, observations for runs to the same alarm box were grouped and, if distances varied by more than ¼ miles, an independent check of the possibility of such readings was made. Less than 5% of the original data were eliminated by this process.

Some of the features of this experiment are obviously an improvement on the analysis reported in the present study. Thus it would have been preferable if in this analysis those runs not made from quarters could have been eliminated. Similarly, editing of the data for patently erroneous results would no doubt have improved the explanation afforded by the model. Other aspects of the Institute's experiment are somewhat less exemplary. For example, the distances are measured accurately only to the nearest tenth of a mile. In cities such as New York and London, where the streets follow basically a grid iron pattern, it is probably more accurate to evaluate distances using the approach adopted here (namely, to locate the alarm source and fire station location on a finely defined grid and evaluate the distance between them using a Manhattan metric). Thus future studies in such cities might well use a methodology which is a compromise of the two described here. Models which measure time

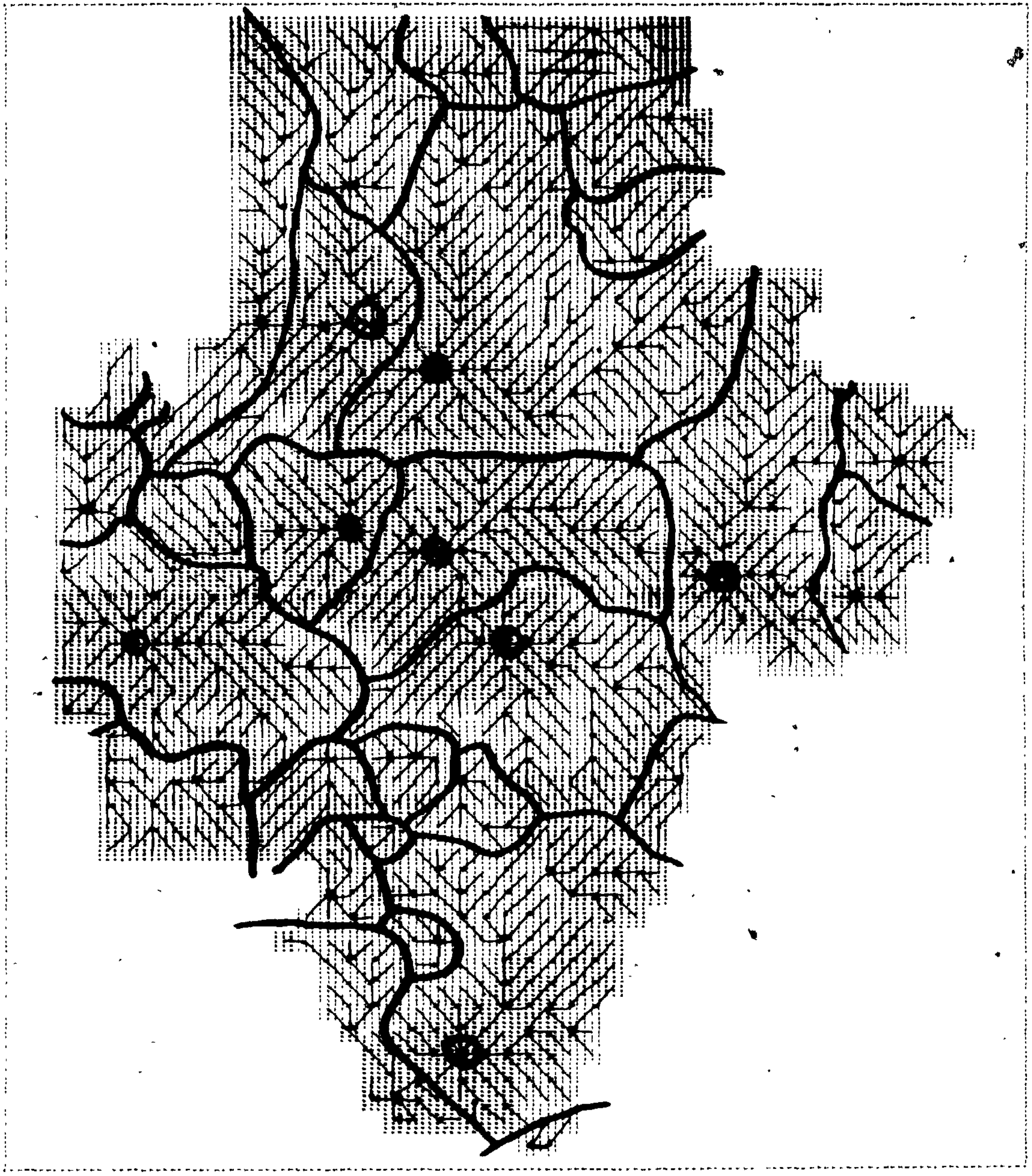


Figure 3.32 Pits and Ridges for the 1973 Response Time Surface

two or more stations responded). Distance was measured as Manhattan or "city block" distance which is given by the following formula:

$$D = |X_1 - X_2| + |Y_1 - Y_2| \quad 3.17$$

where D is the Manhattan distance between the alarm and the station

X_1Y_1 represent the coordinates of the alarm

X_2Y_2 represent the coordinates of the fire station

$||$ indicates the absolute value

It was felt, intuitively, that London's grid street pattern would make the Manhattan metric more appropriate since the fire trucks could not travel in a straight line towards the alarm. To produce a simple regression and scattergram between the response times (measured in minutes) and distances (measured in units of 50 feet) the SPSS program SCATTERGRAM was used. The results are shown in Figure 3.33 which is the scattergram of the relationship, and Table 3.3 shows the statistics describing the relationship. The correlation of 0.55 is not very large and the main reason for this is that the data set used includes all alarms, both the emergencies and the less serious alarms. The response times to some of these less serious alarms were quite considerable. Towards the end of the year a number of houses in the city experienced flooding problems and the department's response times for these situations were frequently lengthy. In order to provide a meaningful data set a second analysis was carried out using only the emergency alarms. Figure 3.34 and Table 3.4 show the results of this analysis. The correlation is now 0.69 and the explanation has jumped from 30% to almost 50%. It was still not clear, however, that the

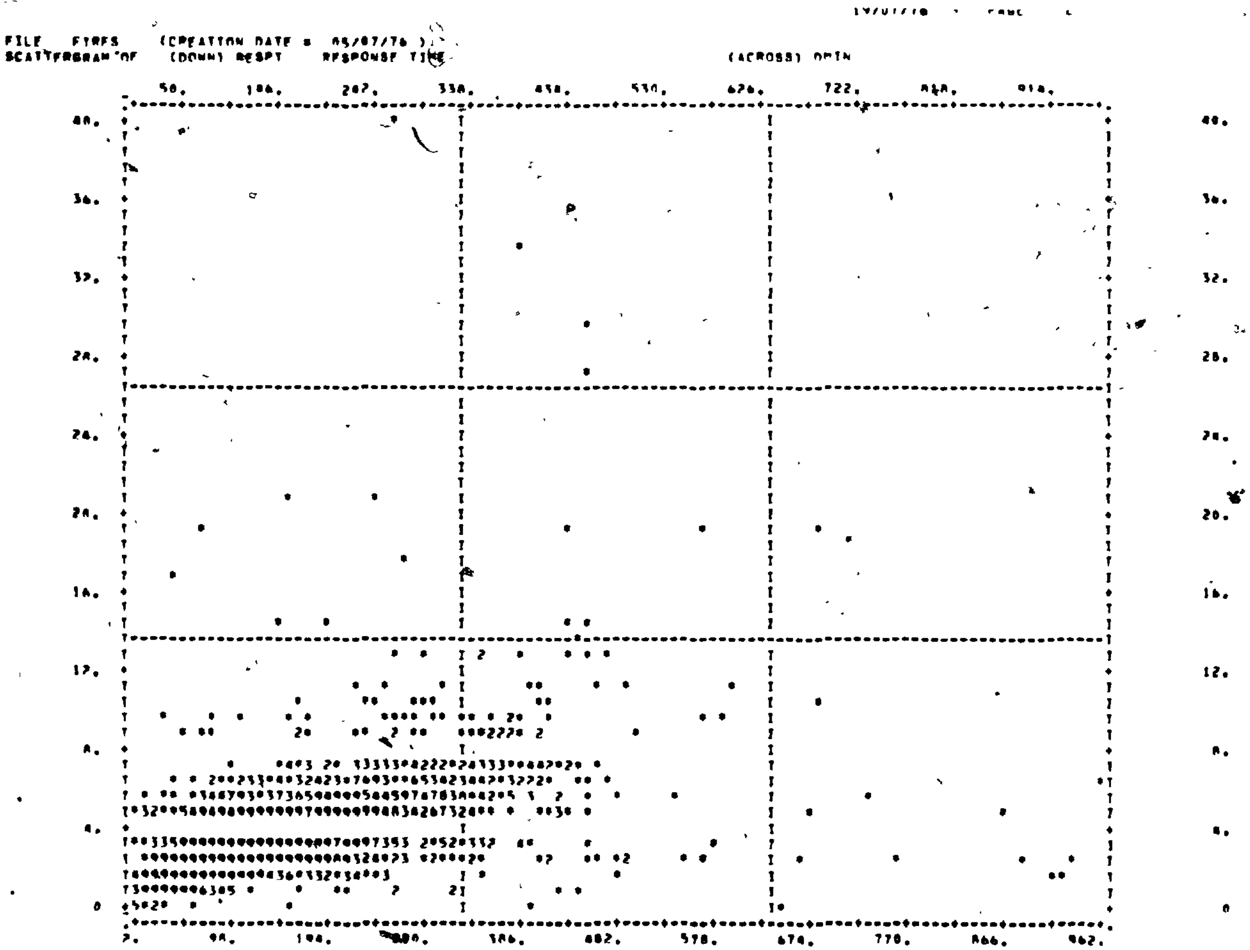


Figure 3.33 Scattergram of the Relationship between Response Time (y axis) and Manhatten Distance (x axis) for all 1973 Alarms

Table 3.3: Relationship Between Response Time and Manhattan Distance for All 1973 Alarms

Correlation (R) -	.55027	R^2 -	.30280	Significance R -	.00001
Std. Err. of Est. -	2.15948	Intercept (A) -	2.15850	Std. Err. of A -	.07076
Significance A -	.00001	Slope (B) -	.01244	Std. Err. of B -	.00038
Significance B -	.00001				
Plotted Values -	2441	Excluded Values -	0	Missing Values -	18

Table 3.4: Relationship Between Response Time and Manhattan Distance for 1973 Emergency Alarms

Correlation (R) -	.68912	R^2 -	.47488	Significance R -	.00001
Std. Err. of Est. -	1.36149	Intercept (A) -	1.72585	Std. Err. of A -	.12016
Significance A -	.00001	Slope (B) -	.01397	Std. Err. of B -	.00075
Significance B -	.00001				
Plotted Values -	390	Excluded Values -	0	Missing Values -	4

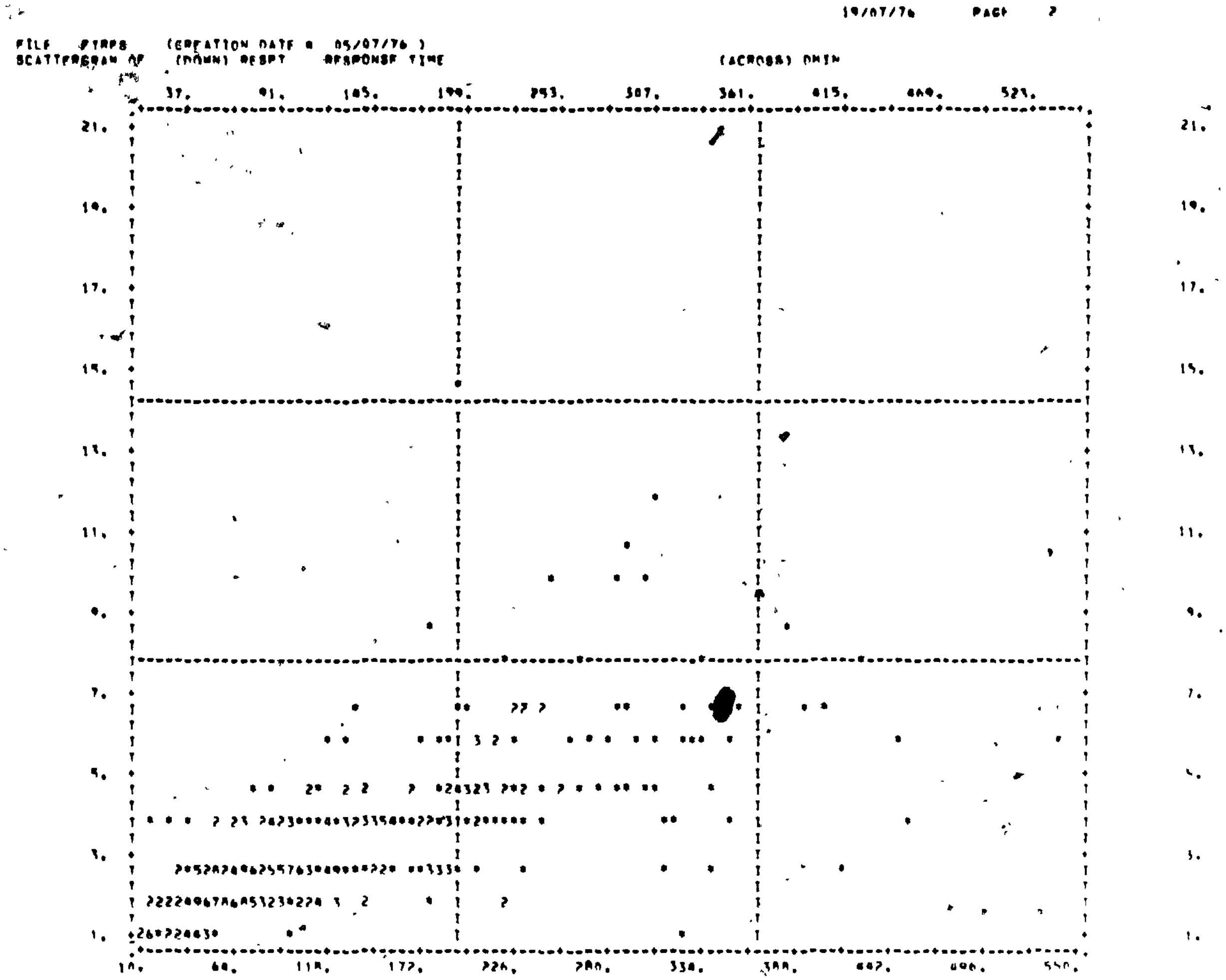


Figure 3.34 Scattergram of the Relationship between Response Time (y axis) and Manhattan Distance (x axis) for 1973 Emergency Alarms

Manhattan metric was the best approximation to the distance travelled by the fire trucks and so this last analysis was repeated using straight line, Euclidean distances as the X values. The results were statistically indistinguishable at the 5% significance level. The only parameter of the regression in which there was a significant change was the slope of the line and this was to be expected since the straight line distance provided a shorter estimate than the Manhattan of the actual distance travelled. Thus the slope in the last regression is significantly steeper (theoretically by a factor of 1.273, i.e. $4/\pi$).

At first sight it might appear curious that there is not a better relationship between response time and distance. After all the regression has only explained approximately 50% of the variation in the response times. There are probably a number of reasons for the failure of the regression to do better. Firstly, the distances are at best only crude estimates of the true distance travelled by each truck. In the newer housing subdivisions neither the Manhattan metric nor the straight line distance would provide a good estimate of the actual distance travelled. Secondly, the response times are only accurate to the nearest minute and this in itself is not a very precise estimate when one is dealing with response times which average, approximately, only 4 minutes. Ideally, these times should be collected by stop watch accurate to the nearest second. An examination of some of the observations with large negative and positive residuals reveals a number of other reasons for the low degree of fit. In one instance the fire truck was sent to the wrong address and thus the response time was too large and a high positive residual resulted.

In another situation a fire rekindled and a truck was recalled to the scene of the fire before it had returned to quarters. Because the distance was now underestimated a high negative residual occurred. On another occasion a truck from Station 1 was called from one alarm to another and thus the present analysis overestimated the distance travelled. A high positive residual resulted from a response to an alarm in a subdivision and this was presumably due to the circuitous path travelled by the truck. Furthermore, some of the alarm locations on the periphery of the city may not have been accurate (for example, the brush fires). A possible way around these problems would be to edit the data for obviously erroneous results. This option is discussed below. A final reason for the present model's fairly low degree of fit is the occurrence of time-space variations in the relationship between distance travelled and response time. A number of researchers (Kolesar and Walker, 1974; Hendrick and Plane et al., 1975; and Larson, 1971) have attempted, usually with little success, to determine whether there are spatial and/or temporal differences in the relationship between the two variables. It is interesting to compare the methodology used in the present study with that used by Kolesar and Walker in their study. These researchers (Kolesar and Walker, 1974, p. 2-6) describe in the following section the mechanics of their analysis, which, with the extensive resources at their disposal, were both thorough and exhaustive:

> Fifteen units participated in the experiment: thirteen ladder companies and two Battalion Chief's cars. Each unit had an odometer that read tenths of miles, so that reasonably accurate distance records could be produced
> . . .
> Each unit was provided with a stop watch and copies of a form to keep a record of all responses made <u>from quarters</u>.

> Responses made when returning from an earlier run or from a position in the field were not included, because of the difficulty of recording accurately times, distances, and locations at time of dispatch ....
>
> ...the need for odometers that recorded in tenths of miles was a limiting factor; only ladder companies and Battalion Chiefs participated since no engines had such odometers. (Our failure to include engines in the experiment would introduce an element of bias in the results, since engines are generally smaller than ladders and are able to manoeuver more easily in traffic and narrow streets, so that they may travel slightly faster.)
>
> ...
>
> Editing the Data. The raw data were edited to eliminate obviously erroneous records. We used a number of consistency checks in this process. For example, we eliminated records for which the average velocities attained were higher than 60 m.p.h. In addition, observations for runs to the same alarm box were grouped and, if distances varied by more than ¼ miles, an independent check of the possibility of such readings was made. Less than 5% of the original data were eliminated by this process.

Some of the features of this experiment are obviously an improvement on the analysis reported in the present study. Thus it would have been preferable if in this analysis those runs not made from quarters could have been eliminated. Similarly, editing of the data for patently erroneous results would no doubt have improved the explanation afforded by the model. Other aspects of the Institute's experiment are somewhat less exemplary. For example, the distances are measured accurately only to the nearest tenth of a mile. In cities such as New York and London, where the streets follow basically a grid iron pattern, it is probably more accurate to evaluate distances using the approach adopted here (namely, to locate the alarm source and fire station location on a finely defined grid and evaluate the distance between them using a Manhattan metric). Thus future studies in such cities might well use a methodology which is a compromise of the two described here. Models which measure time with a high and distance with a low degree of sensitivity or vice versa will not yield the best results. If the cruising velocity is 39 miles per hour or just over 57 feet per second (as Kolesar and Walker established for New York City) or nearly 41 m.p.h., which is just over 59 feet per second (as the cruising velocity for emergency alarms has been established in this study), then it would appear that units of seconds for time and 50 feet intervals for distance are the most appropriate levels of measurement which will ensure similar levels of sensitivity.

The model which Kolesar and Walker found to give the best fit to their data was "a piece wise square root - linear function with a continuous first derivative". This model, which was fitted to the *average* travel times for each distance, is shown in Figure 3.35 (from Kolesar and Walker, 1974, p. 27). The square root function is appropriate for response distances less than or equal to 0.88 miles while the linear function is appropriate for greater distances. (Note that fitting the model to the averaged times partially overcomes the problem of non-heteroscedasticity and also gives the appearance of a better fit). The reassuring aspect about the linear piece of their model is its remarkable similarity to the model established in the present study for emergency alarms using Manhattan distances. Expressed in the same units of distance the two models are:

$$T = 1.35 + 1.53D \quad \text{(Kolesar and Walker, 1974, p. 27)} \qquad 3.18$$

$$T = 1.73 + 1.48D \qquad 3.19$$

where T is measured in minutes

D is measured in miles

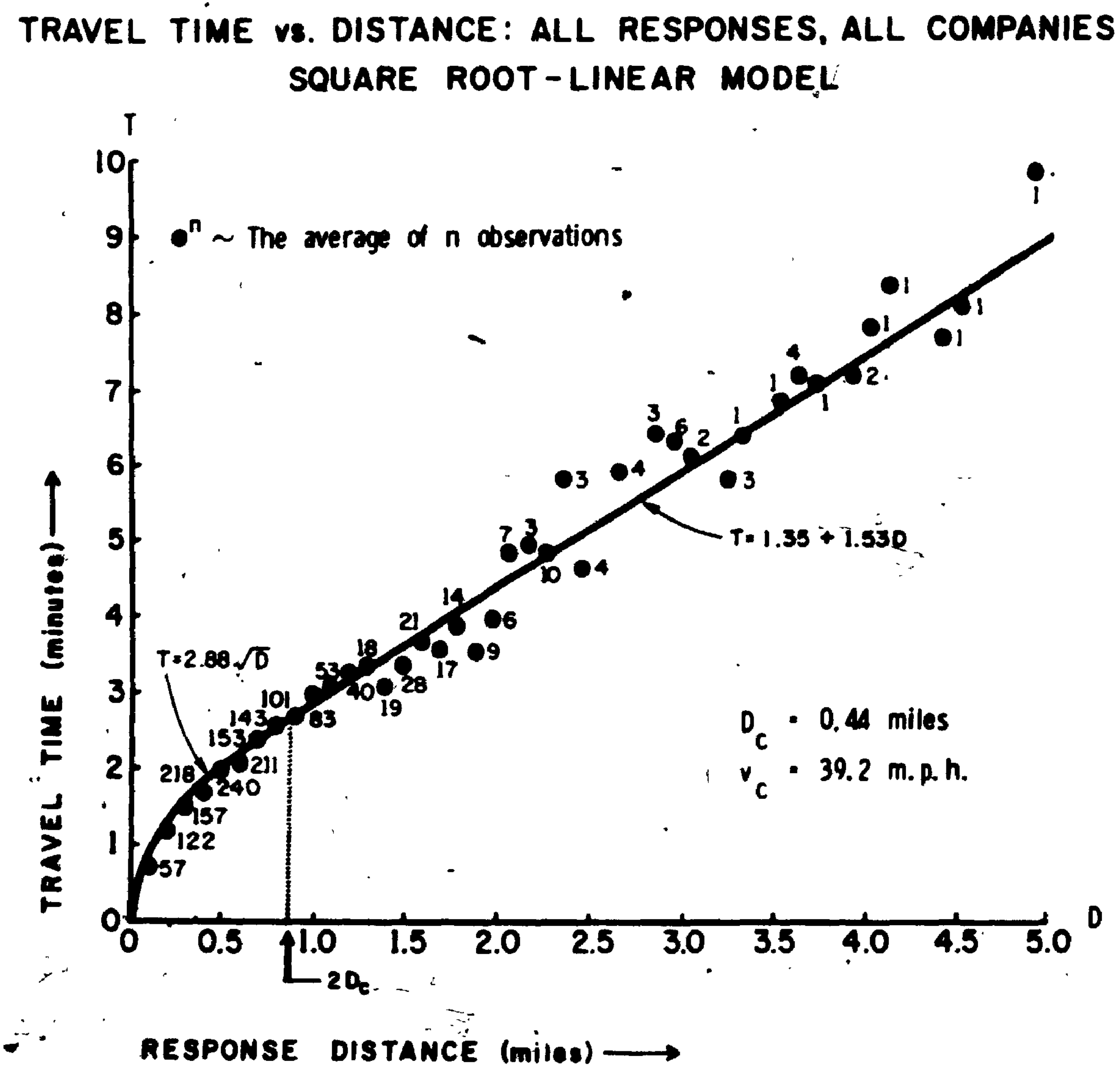


Figure 3.35 A Piece Wise Square Root - Linear Function for the Relationship between Response Time and Distance in New York City (Kolesar and Walker, 1974, p. 27)

The slope of the second model is not significantly different from the first (at the 5% level) but the intercept is just significantly different and this probably reflects the coarseness of the measurement of time in the present study.

Kolesar and Walker (p. 30) note that in New York City the relationship of response times with distance has the following temporal insensitivities:

> First, there is no practical difference between travel velocities under conditions of daylight and darkness. Second, while velocities are lower during rush hours, they are not as much lower as we or the Department expected. The reduction in average velocity (of about 20%) is greatest during the 8 a.m. - 9 a.m. period.

In order to try and determine whether there were any temporal differences in the relationship between response times and distances in London, the analysis was repeated using the Manhattan metric (since this was marginally better than the straight line distance), and the emergency alarms separately for each of the four six hour time periods identified in the autocorrelation analysis described above. Tables 3.5, 3.6, 3.7 and 3.8 show the results of these analyses. Obviously there are significant differences between the regressions but it is difficult to provide rational explanations for the differences in the amount of explanation, the intercept or the slope of the four regressions. Some results do appear to be reasonable. Thus the highest intercept occurs in the first time period when it would be expected that the firemen would be slightly less alert and would consequently have a higher turnout time. These analyses were repeated for the morning and evening "rush-hours" which were defined as lasting from 6:30 to 9:30 a.m. and 3:30 to 6:30 p.m., respectively.

Table 3.5: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Before 6:00 a.m.

Correlation (R) -	.60263	R^2 -	.36317	Significance R -	.00001
Std. Err. of Est. -	1.77184	Intercept (A) -	2.10093	Std. Err. of A -	.40531
Significance A -	.00001	Slope (B) -	.01423	Std. Err. of B -	.00245
Significance B -	.00001				
Plotted Values -	61	Excluded Values -	0	Missing Values -	0

Table 3.6: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Between 6:00 a.m. and Noon

Correlation (R) -	.70514	R^2 -	.49722	Significance R -	.00001
Std. Err. of Est. -	1.22550	Intercept (A) -	1.92475	Std. Err. of A -	.24104
Significance A -	.00001	Slope (B) -	.01231	Std. Err. of B -	.00147
Significance B -	.00001				
Plotted Values -	73	Excluded Values -	0	Missing Values -	1

Table 3.7: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Between Noon and 6:00 p.m.

Correlation (R) -	.68936	R^2 -	.47522	Significance R -	.00001
Std. Err. of Est. -	1.32555	Intercept (A) -	1.62870	Std. Err. of A -	.19414
Significance A -	.00001	Slope (B) -	.01368	Std. Err. of B -	.00124
Significance B -	.00001				
Plotted Values -	137	Excluded Values -	0	Missing Values -	1

Table 3.8: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Between 6:00 p.m. and Midnight

Correlation (R) -	.74868	R^2 -	.56053	Significance R -	.00001
Std. Err. of Est. -	1.21850	Intercept (A) -	1.51972	Std. Err. of A -	.20113
Significance A -	.00001	Slope (B) -	.01519	Std. Err. of B -	.00124
Significance B -	.00001				
Plotted Values -	119	Excluded Values -	0	Missing Values -	2

The results are shown in Tables 3.9 and 3.10. The morning period has a more gentle slope and this might be, tentatively explained as a result of the traffic conditions. In the morning the fire trucks (being largely located in the centre of the city) are probably, for the main part, moving against the flow of traffic bound for the city centre while in the evening the converse is probably true.

It should be realized that these results conflict with those of Kolesar and Walker (noted above) who found the morning rather than the evening rush hour to be the period in which cruising velocity was slowest. In the evening rush-hour in London the slope of the regression line indicates a cruising velocity of 37 m.p.h., which is just over 54 feet per second. This represents a reduction of only 9% over the global figure for all emergency alarms which is considerably less than Kolesar and Walker found for their more narrowly defined morning rush-hour. It might be speculated that further decentralisation of the fire stations (as occurred in the case of Fire Station 3 and may occur with Fire Station 5) could well restore evening rush hour response times to the global average. Alternatively if temporal differences are marked in this manner it may indicate that fire station response districts should change according to time of day. This might mean, for example, that in the morning rush-hour central fire stations would have their response districts expanded outwards while in the evening rush-hour they would contract inwards to take account of the inflow and outflow of commuter traffic. It must be admitted, though, that the data in these rush-hour examples is coarse and the samples are small and so these comments should merely be noted as a basis for further research.

Table 3.9: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Between 6:30 a.m. and 9:30 a.m.

Correlation (R) -	.59324	R^2 -	.35194	Significance R -	.00112
Std. Err. of Est. -	.92956	Intercept (A) -	2.03800	Std. Err. of A -	.37766
Significance A -	.00001	Slope (B) -	.01171	Std. Err. of B -	.00339
Significance B -	.00112				
Plotted Values -	24	Excluded Values -	0	Missing Values -	1

Table 3.10: Relationship Between Response Time and Manhattan Distance for Emergency Alarms Occurring Between 3:30 p.m. and 6:30 p.m.

Correlation (R) -	.72246	R^2 -	.52194	Significance R -	.00001
Std. Err. of Est. -	1.39063	Intercept (A) -	1.50345	Std. Err. of A -	.25170
Significance A -	.00001	Slope (B) -	.01532	Std. Err. of B -	.00163
Significance B -	.00001				
Plotted Values -	83	Excluded Values -	0	Missing Values -	0

A number of analyses were carried out in which the data were separated out into core area and peripheral alarms. The aim was to see whether there were spatial differences in response speeds. The results were not conclusive but the regression slope for the core area alarms was steeper, suggesting that the truck speeds were slower in the core area than in the less congested periphery of the city. These results thus lend support to the Fire Department's decision to install the system allowing approaching fire trucks to change, automatically, the traffic lights in the core to green.

The results of this spatial analysis are also confirmed by the work of Hendrick and Plane et al. (1975) in Denver, Colorado. Their research procedure in analysing the relationship between response time and distance was very similar to the procedure used in the present study. In their specially conducted experiment they were, however, able to make two improvements. Firstly, they were able to measure response times very accurately using an electric timer with a digital readout accurate to .01 minutes and, secondly, they were able to use a Census Bureau address matching program to obtain the X and Y coordinates for the stations and the alarm incidents. However, the temporal analyses were inconclusive. This was possibly due to the fact that only 1600 alarms were used. Thus they too faced problems of data scarcity since over 160 time period - station combinations were possible. Indeed some combinations could not be tested owing to sample sizes of two or fewer observations. Their spatial analysis was, however, much more rewarding and, as mentioned above, tends to support the findings of the present research. Hendrick and Plane et al. were thus able to derive two regression equations - one for the downtown area of the city and one for the periphery. These were as follows:

Downtown: $T = 18.213 + .022846\,D$ 3.20

Periphery: $T = 26.292 + .019326\,D$ 3.21

Thus, the downtown situation is characterised by a more rapid turnout and a slower cruising velocity and these are results which do conform to intuitive expectations.

In some ways the results of the present analysis of response times have been slightly discouraging. The high intercepts (high when compared to the results of other researchers) are almost certainly due to the coarsness of the response time data. More encouraging, however, is that for middle and higher order distances the present models appear comparable to those already published. Perhaps most encouraging is the fact that some tentative spatial and temporal system insensitivities have been discovered.

Conclusion

The aim of this chapter has been to present some preliminary analysis of the spatial and temporal patterns of the fire department alarms and response times. Other researchers (Chaiken, Ignall and Walker, 1975c) have emphasized the importance of such descriptive analysis. This chapter has thus been devoted to describing the geography of alarms and response time patterns. Chapter 4 concentrates on procedures for building an explanatory model of the alarm demand surface.

CHAPTER 4

Towards an Explanatory Model of the Spatial Pattern of Fire Alarms

It was originally intended to build a multiple regression model which would explain the spatial pattern of urban fires and fire alarms. The aim was to produce a model in which the number of urban fires, or fire alarms, was the dependent variable. The variation in this dependent variable would then be "explained" by a series of independent variables.

Ahlbrandt's Model

Ahlbrandt (1973) is one of the few researchers who has attempted to build such a multiple regression model. Ahlbrandt's objectives, however, were different from those described above. He attempted to build a multiple regression model which would predict and explain the cost of operating a fire department. His aim was to compare the actual cost of operating a fire department with the empirical cost function suggested by the regression model. This would allow the researcher to evaluate the cost-efficiency of a fire department and thus it would be possible to determine whether a bureaucratic monopoly or a competitive producer could provide more efficient municipal fire protection.

The basic regression model was specified as follows, (Ahlbrandt, 1973, p. 25):

$$\begin{aligned} \ln y = a_0 &+ a_1 \ln X_1 + a_2 \ln X_2 \\ &+ a_3 \ln X_3 + a_4 \ln X_4 + a_5 \ln X_5 \\ &+ a_6 \ln X_6 + a_7 \ln X_7 + a_8 \ln X_8 \end{aligned}$$

$$+ a_9 \ln X_9 + a_{10} \ln X_{10} + a_{11} \ln X_{11} \quad 4.1$$

where y is the cost per capita in dollars

X_1 is the population from 1970 census in 1000s

X_2 is the area in square miles

X_3 is the assessed value in millions of dollars

X_4 is the percentage of housing units lacking all or some plumbing facilities (1970 census data)

X_5 is the adjusted wage index

X_6 is the fire insurance rating index

X_7 is the number of aerial ladder trucks

X_8 is the number of first aid cars or ambulances

X_9 is the number of volunteers

X_{10} is the number of fire stations

X_{11} is the number of full time personnel

a_0 is a constant

a_1 to a_{11} are the regression coefficients

Some of Ahlbrandt's variables have little relevance to the present study. Others, however, were incorporated into the present model in order to explain increased demand for fire department service. This latter group of variables includes: X_1, X_2, X_4 and X_7. Discussing the influence of these variables, which he refers to as "environmental factors", Ahlbrandt states (Ahlbrandt, 1973, p. 24):

> Factors such as population density, multi-storied structures, and the age and condition of the buildings affect the cost of supplying fire services. Population density was taken into account by including both

> population and area in the regression equation. The number of aerial ladder trucks operated by the fire department serves as a proxy for high-rise buildings and also captures some of the effects of population density.
>
> One would expect a city having many buildings with faulty wiring and few sprinkler systems to have commensurately higher fire protection costs for the same quality service than a comparable city with a higher percentage of more modern buildings. Differences in structural conditions between communities were incorporated into the regression equation by a variable showing the percentage of housing units lacking all or some plumbing facilities.

Ahlbrandt's study was most successful in explaining the variation in the expenditure on fire prevention services. In three different applications of the basic multiple regression model (Equation 4.1) with 32, 24 and 25 degrees of freedom the coefficients of multiple determination were .910, .961 and .962 respectively. It is also worth noting that in the third application independent variable X_7 was dropped since its affect on the model was not statistically significant.

Attempts to Build an Explanatory Model

In the present study it was considered necessary to build several multiple regression models in order to predict the spatial pattern of occurrence of all alarm types. The aim was to use one model to predict residential fires and a second model to predict commercial and industrial fires. Additional models would be necessary to predict other alarm types such as false alarms, garbage fires and other categories. As will be seen below, the disappointing results obtained with the multiple regression model for residential fires discouraged any attempts to build the subsequent models.

The first step in building the residential fire alarm regression model involved aggregating the 1973 fire alarms and also the company time by enumeration area and census tract. This was done for all alarms with a property code of 4 or less (i.e. residential alarms) using a specially written fortran program. The number of fire alarms and the company time were then attached to an SPSS data file which contained socio-economic data for the City of London, Ontario, which had been retrieved from the 1971 census tapes prepared by Statistics Canada. These census tapes contained information on 388 socio-economic variables for each of the 460 enumeration areas in the city.

After extensive background reading into the urban fire problem (Ahlbrandt, 1973; Barlay, 1972; Czamanski, 1975; Hamilton and Barnard, 1975; Smith, 1973) it was felt that certain of these socio-economic variables would have a significant influence on the number of residential alarms. Smith (1973, p. 64 and p. 195), for example, suggests that poverty is an important influence:

> Like crime and disease, fire victimizes the poor most.
>
> What most fire fighters do not know is that a good case for economic determinism can be made . . . Poverty is manifested in fire statistics - that's a safe generalization.

A number of the socio-economic variables recorded by Statistics Canada do measure various aspects of urban poverty and economic distress. However, it should be pointed out that the London Fire Prevention Officer (personal communication) demurred from Smith's 'economic determinism' thesis. He suggested that residential fires were primarily the result of carelessness which presumably affects all economic groups to the same extent. Judging by the rather disappointing results described below, the concept of economic determinism is probably more applicable to cities with extensive slum and ghetto areas than to small regional centres such as London.

The 23 extensive socio-economic variables which were felt, on a priori reasoning, to have some correlation with residential fires (also an extensive variable) are recorded in Table 4.1. An explanation of the relevant census terms may be found in Appendix 2. As a preliminary analysis the socio-economic variables in Table 4.1 were correlated with the number of residential alarms per enumeration area (this variable was labelled COUNT) and the total company time spent answering these alarms (this variable was labelled TIME) using the SPSS program PEARSON CORR. COUNT and TIME were also correlated with ~~each~~ other and, as might be expected, had a high correlation of +.737. The correlation between these two variables and the socio-economic variables varied but generally COUNT correlated more strongly with the census variables than did TIME. As a result the test of the discussion will merely consider the correlation between the socio-economic variables and COUNT. These correlations along with their significance levels are shown in Table 4.2. While these correlations are, for the main part, fairly weak, a number are significant at the 5% level or better. The correlation between COUNT and the total number of dwellings (VAR005) is fairly high, as might be expected for residential alarms. The correlation is also high between COUNT and the total number of rented dwellings (VAR007) but it is not significant between the total number of owned dwellings (VAR006) and COUNT. This, perhaps, gives further credence to Smith's economic determinism thesis. The correlation is high between COUNT and VAR010 which represents the number of apartments in each enumeration area. A possible explanation of this result is that in some areas of the city apartment blocks are plagued by malicious false alarms which, under these circumstances, are then classified as residential alarms. The

TABLE 4.1: 23 Extensive Socio-economic variables thought to have some relationship with the number of residential alarms

1.	VAR005	Total number of dwellings
2.	VAR006	Total number of dwellings owned
3.	VAR007	Total number of dwellings rented
4.	VAR008	Total number of single detached houses
5.	VAR010	Total number of apartments
6.	VAR038	Total population
7.	VAR085	Total number of households
8.	VAR123	Total number of lodgers in households
9.	VAR143	Total number of female heads of household
10.	VAR187	Total number maintaining own household
11.	VAR188	Total number not maintaining own household
12.	VAR193	Total number of female heads of family
13.	VAR194	Total number of married heads of family
14.	VAR205	Total number of heads of family never married
15.	VAR230	Total number of dwellings constructed before 1946
16.	VAR231	Total number of dwellings constructed from 1946 to 1950
17.	VAR232	Total number of dwellings constructed from 1951 to 1960
18.	VAR233	Total number of dwellings constructed from 1961 to 1965
19.	VAR234	Total number of dwellings constructed from 1966 to 1971
20.	VAR235	Total number of dwellings constructed during first 5 months of 1971
21.	VAR264	Total number of dwellings with no automobiles
22.	VAR269	Total number of dwellings with vacation homes
23.	VAR320	Total number of families with no income recipients

TABLE 4.2: Pearson product-moment correlations between COUNT and selected, extensive socio-economic variables

Variables	Correlation	Significance level
COUNT with VAR005	+.226	.000
COUNT with VAR006	+.024	.301
COUNT with VAR007	+.188	.000
COUNT with VAR008	+.020	.338
COUNT with VAR010	+.157	.000
COUNT with VAR038	+.154	.000
COUNT with VAR085	+.221	.000
COUNT with VAR123	+.310	.000
COUNT with VAR143	+.175	.000
COUNT with VAR187	+.132	.002
COUNT with VAR188	+.074	.057
COUNT with VAR193	+.295	.000
COUNT with VAR194	+.116	.007
COUNT with VAR205	+.167	.000
COUNT with VAR230	+.233	.000
COUNT with VAR231	-.034	.231
COUNT with VAR232	-.100	.020
COUNT with VAR233	+.017	.355
COUNT with VAR234	+.021	.328
COUNT with VAR235	+.105	.012
COUNT with VAR264	+.240	.000
COUNT with VAR269	+.023	.311
COUNT with VAR320	+.015	.372

university residences are a good example of this. There is also a high correlation between COUNT and the total population (VAR038) and between COUNT and the total number of households (VAR085). These correlations appear to be intuitively reasonable. The high positive correlations between COUNT and the total number of lodgers in households (VAR123), the number of female heads of household (VAR134), the number of female heads of family (VAR193), the number of family heads never married (VAR205), the number of dwellings constructed before 1946 (VAR230) and the number of dwellings without automobiles (VAR264) all add further support to the theory that the poor areas have a higher demand for fire department service. However, other correlations suggest the converse might be true. Thus there are also high positive correlations with the number of families maintaining their own household (VAR 187) and the number of married heads (VAR194).

Those variables which yielded the highest correlations were entered into the SPSS stepwise multiple regression program, REGRESSION. In this analysis the dependent variable was COUNT divided by the total number of dwellings per enumeration area (VAR005). This gave a new, intensive variable which represented the average number of residential alarms per dwelling in 1973. The new variable was labelled VAR900. The independent variables which had provided the highest simple correlations with COUNT were also divided by VAR005. Thus both dependent and independent variables were now intensive measures. The new set of variables are shown in Table 4.3. Table 4.4 summarizes the results of this stepwise regression. It appears, from this table, that the model provides a useful level of explanation but this apparent success is, in all likelihood, a statistical illusion. One variable (VAR903) is providing most of the explanation. This variable represents the number of dwellings constructed in the first five months of 1971 divided by the total number of dwellings in each enumeration area. Obviously, in many of the 460 enumeration areas this number will be zero and since the number of residential alarms is also zero in many of the enumeration areas, the high simple correlation is probably, largely a result of the sparseness of the data. However, much of the new construction took place in the outer suburbs of the city where a large number of minor fires did occur. Thus it would be wrong to assume that this correlation was entirely spurious. The program was also run without variable VAR 903. The results are summarized in Table 4.5. The explanation provided by the model is now depressingly low. The explanation is in fact under 10% when the six independent variables which are significant at the 5% level are included. It is somewhat encouraging, though, that the variable which now provides the largest share of the explanation is VAR912 (the number of rented dwellings divided by the total number of dwellings). Again this is a weak but positive affirmation of Smith's ideas.

In order to determine how serious the problem of data scarcity was, the multiple regression model was reformulated at the census tract level. Due to the disappointing results obtained with the more sensitive enumeration area model, the plan to use the model to generate a demand surface for the location-allocation models described in Chapter 6 was abandoned and, consequently, only a limited experimental version of the census tract model was tested. The variables used in this model are described in Table 4.6. Again an explanation of the relevant census terms may be found in Appendix 2. A summary of the

TABLE 4.3: Dependent and Independent Variables used in the Stepwise Multiple Regression Model based on Enumeration Area Data

Dependent Variable	VAR900 = COUNT divided by VAR005
Independent Variables	VAR901 = VAR264 divided by VAR005
	VAR902 = VAR143 divided by VAR005
	VAR903 = VAR235 divided by VAR005
	VAR904 = VAR194 divided by VAR005
	VAR905 = VAR193 divided by VAR005
	VAR906 = VAR187 divided by VAR005
	VAR907 = VAR123 divided by VAR005
	VAR908 = VAR205 divided by VAR005
	VAR909 = VAR230 divided by VAR005
	VAR910 = VAR232 divided by VAR005
	VAR912 = VAR007 divided by VAR005
	VAR913 = VAR010 divided by VAR005

TABLE 4.4: Summary of the Results of the Stepwise Regression Model described in Table 4.3*

Step	Variable Entered	Significance	Multiple R	R^2	R^2 Change	Simple R
1	VAR903	.000	.612	.375	.375	+.612
2	VAR907	.000	.631	.398	.024	+.070
3	VAR901	.018	.637	.406	.007	+.129
4	VAR902	.010	.644	.414	.009	+.005
5	VAR904	.030	.648	.420	.006	-.088
6	VAR906	.000	.664	.441	.021	-.064
7	VAR912	.209	.666	.443	.002	+.141
8	VAR910	.220	.667	.445	.002	-.114
9	VAR909	.124	.669	.448	.003	+.058
10	VAR913	.687	.670	.448	.000	+.082
11	VAR905	.919	.670	.448	.000	+.126

*Variable VAR908 was not entered owing to an insufficient F level

TABLE 4.5: Summary of the Results of the Stepwise Regression Model described in Table 4.3 with VAR903 excluded

Step	Variable Entered	Significance	Multiple R	R^2	R^2 Change	Simple R
1	VAR912	.002	.141	.020	.020	+.141
2	VAR905	.034	.171	.030	.010	+.126
3	VAR902	.011	.208	.043	.014	+.005
4	VAR901	.000	.265	.070	.027	+.129
5	VAR904	.013	.287	.082	.012	-.088
6	VAR906	.043	.301	.091	.008	-.064
7	VAR910	.564	.302	.091	.001	-.114
8	VAR913	.605	.303	.092	.001	+.082
9	VAR907	.717	.304	.092	.000	+.071
10	VAR909	.630	.304	.093	.000	+.058
11	VAR908	.741	.305	.093	.000	+.030

results of a stepwise regression carried out on these variables is shown in Table 4.7. The model appears to be very successful and achieved an explanation of over 68% of the variation in residential alarms when all four independent variables were included. However, in this run of the model residential alarms were expressed as an extensive variable and thus it may again be questioned whether the model is achieving an enlightening explanation if it merely says residential alarms increase with the number of houses or old houses in a census tract. The simple correlations with the average rent and average income figures are not suspect because the dependent variable is extensive, but they are also not very strong.

A second analysis was carried out in which the dependent variable was the number of residential alarms divided by the number of occupied dwellings. A list of all the variables in this second model is shown in Table 4.8. The results of the analysis are shown in Table 4.9. They are now inconclusive since explanation achieved by the model is not statistically significant at any step.

Cautionary Remarks in the Use of Explanatory Models

In the above analysis the stepwise regression models did not provide a large enough explanation of the variation in the dependent variable to permit them to be used to generate a demand surface. However, the models were not a complete failure and given a much larger data base of alarms and larger areal units than the enumeration areas originally used it may yet prove possible to develop an explanatory model. Interpreting the significance of such a model, however, would require some caution.

Firstly, it should be noted that the independent variables should

TABLE 4.6: Dependent and independent variables used in the first formulation of the stepwise regression model based on census tract data

Dependent Variable - RALARM = Number of residential alarms per cenus tract

Independent Variables - DATE = Total number of occupied dwellings constructed before 1946

HOUSES = Total number of occupied dwellings per census tract.

RENT = Average cash rent for tenant occupied dwellings per census tract

INCOME = Average income for males 15 years and over with income per census tract

TABLE 4.7: Summary of the results of the stepwise regression model described in Table 4.6

Step	Variable Entered	Significance	Multiple R	R^2	R^2 Change	Simple R
1	DATE	.000	.748	.560	.560	+.748
2	HOUSES	.000	.818	.669	.110	+.702
3	RENT	.256	.824	.678	.009	-.314
4	INCOME	.358	.827	.685	.006	-.280

TABLE 4.8: Dependent and independent variables used in the second formulation of the stepwise regression model based on census tract data

Dependent Variable - VAR001 = number of residential alarms per census tract divided by the total number of occupied dwellings

Independent Variables - VAR002 = total number of occupied dwellings constructed before 1946 per census tract divided by the total number of occupied dwellings

- RENT = average cash rent for tenant occupied dwellings per census tract

- INCOME = average income for males 15 years and over with income per census tract

TABLE 4.9: Summary of the results of the stepwise regression model described in Table 4.8

Step	Variable Entered	Significance	Multiple R	R^2	R^2 Change	Simple R
1	VAR002	.441	.110	.012	.012	+.110
2	RENT	.679	.125	.016	.004	-.029
3	INCOME	.881	.127	.017	.000	-.012

not all, necessarily, be subjected to the same significance levels for inclusion. Thus those variables for which there is strong theoretical evidence for their influence on the dependent variable should be allocated relatively easy significance levels for inclusion in the model. Those whose influence is somewhat more uncertain might be allocated substantially higher significance levels. Such an approach is advocated by Hausner (1974).

Secondly, it must be noted, as Goodchild (1974a) has pointed out, that in this type of model the dependent variable is in reality only a short-term, sampled estimate of the number of alarms that occur, on average, in the long term. Such short term samples are distributed as poisson variates (the theoretical basis for this statement and its influence on the solutions obtained from the location-allocation analyses are both discussed in Chapter 7). Consequently, it would be more precise to formulate the regression model in the following manner:

$$y = a_0 + a_1 x_1 + \ldots + a_i x_i + \varepsilon \qquad 4.2$$

$$y^* = y + \varepsilon^* = a_0 + a_1 x_1 + \ldots + a_i x_i + \varepsilon + \varepsilon^* \qquad 4.3$$

where y is the long term average number of fires
y^* is the observed number of fires
ε represents the structural error of the model
ε^* represents the statistical error of the model
a_0 is a constant
$a_1 \ldots a_i$ are a vector of coefficients
$x_1 \ldots x_i$ are the set of independent variables

Equation 4.2 represents the ideal situation. The long term average is found to be equal to a constant and a set of independent variables multiplied by their respective coefficients plus an error term. This error term is described by Goodchild (1974a) as <u>structural error</u>. However, since the long term average is not known it is estimated by using a sample value, y^*. This is shown in equation 4.3. Using y^* as the dependent variable introduces a second source of error into the model which Goodchild refers to as <u>statistical error</u>. The mean of y^* remains an unbiased estimate of the mean of y, the long term average. However, the variance of y^* is not an unbiased estimate of the variance of y because y^* also incorporates the statistical error of the poisson variate. The result of this is that the constants in equation 4.3 are not affected but the coefficient of multiple determination, R^2, and other statistics based on the variance are biased and the amount of bias is directly proportional to the size of the variance of the poisson variate. Since the degrees of freedom vary this can be demonstrated by expressing the variation in terms of sums of squares rather than variance measures:

$$R^2 = 1 - \frac{\text{unexplained variation}}{\text{Total Variation}} \qquad 4.4$$

$$= 1 - \frac{(\varepsilon + \varepsilon^*)^2}{(y^* - \bar{y})^2} \qquad 4.5$$

$$= 1 - \frac{\varepsilon^2 + (\varepsilon^*)^2}{(y - \bar{y})^2 + (\varepsilon^*)^2} \qquad 4.6$$

Equation 4.6 assumes that there is no covariance between ε and ε^* and between ε^* and $(y - \bar{y})$. For an infinite sample R^2 tends to be under-estimated and this under-estimation increases with an increase in the variance of the poisson variate. For a finite sample, though, R^2 may be either over or under-estimated.

A further difficulty which occurs when regression models are used is the problem of a spurious correlation. A correlation may thus be observed between variable A and variable B simply because they are both correlated to a third value, C. This problem has been alluded to by Goodchild (1976a; p.18-20). Thus, simply because there is a strong correlation between older dwellings and residential alarms does not necessarily mean that the older dwellings have a functional relationship with the number of alarms. The correlation may occur simply because both decline with increasing distance from the city centre. These problems might be resolved through the use of path analysis techniques (Flaman, 1975; Nie et al., 1975).

Two final problems occur due to the fact that the regression model is formulated using aggregated areal data either at the census tract or at the enumeration area level. These problems are also discussed by Goodchild (1976a;p. 27-29). The first problem is the size of the areal unit. If the unit is too small then there is a problem of data scarcity. The majority of units will not have any observations for the dependent variable. Alternatively, if the units are too large they may lose their homogeneity thus masking the correlation between dependent and independent variable. This is one advantage of using census tracts in such a model since one of the criteria for defining these areas is that they should be as homogeneous as possible in terms of economic status and living conditions. The second problem in using ecological correlations involves the danger of the so-called ecological fallacy which was discussed in a classic paper by Robinson (1950) and has been considered in subsequent papers by Menzel (1950), Duncan and Davis (1953) and by Goodman (1953; 1959) and also in papers by Deutsch (1969), Allardt (1969), Valkonen (1969) and Alker (1969) all of which appear in the volume edited by Dogan and Rokkan (1969). The problem is that it is extremely unlikely that the correlation of individual observations will correspond to the correlation of observations which have been aggregated over areal units such as census tracts. Robinson (1950, p. 356) points out, furthermore, that "whenever the within-areas individual correlation is not greater than the total individual correlation, and this is the usual circumstance" the ecological correlation will be numerically greater than the individual correlation. To understand why such discrepancies arise consider Table 4.10. Table 4.10 shows the number of residential alarms occurring in houses built before 1946 and from 1946 on. It also shows the number of houses in these two age categories which did not generate alarms. From such a table which shows internal frequencies as well as the marginal frequencies a fourfold-point correlation can be calculated (Duncan and Davis, 1953). Such a correlation is an individual correlation because in order to obtain the internal frequencies the data must be based on individual observations. In the situation where an ecological correlation is calculated only the marginal frequencies are available and since the table still has one degree of freedom, the internal frequencies are not fixed and may range between the limits shown in Table 4.11. In actual fact, if census tract level data are being used, marginal frequencies are obtained for each census tract and this considerably reduces the ranges for the internal frequencies shown in Table 4.11. If smaller areal units, such as enumeration areas, are used, the ranges will be even more curtailed and thus the possible values which the ecological correlation could feasibly take will approach the true value of the individual correlation more closely.

Conclusion

In concluding this chapter it may be stated that although the attempt to build an explanatory multiple regression model was not

TABLE 4.10: Hypothetical Data Set Necessary to Obtain Individual Correlation between Number of Residential Alarms and Age of Dwelling

	Dwellings Built Before 1946	Dwellings Built From 1946	Marginal Frequencies
Residential Alarms	40	10	50
No Residential Alarms	1960	3040	5000
Marginal Frequencies	2000	3050	5050

TABLE 4.11: Possible Ranges for Internal Frequencies for data in Table 4.10 when only Marginal Frequencies are known

	Dwellings Built Before 1946	Dwellings Built From 1946	Marginal Frequencies
Residential Alarms	0 - 50	0 - 50	50
No Residential Alarms	1950 - 2000	3000 - 3050	5000
Marginal Frequencies	2000	3050	5050

planner will not, in the initial analysis, wish to constrain the location of the fire stations. He will simply seek the optimal locations wherever they are. If, however, the problem was to establish which fire stations would respond to which alarms then the locations of all the fire stations would be fixed and the planner would be seeking the solution to the allocation part of the problem only. He would simply be attempting to determine the appropriate fire station response districts. Under other circumstances the planner may wish to locate another fire station in a town where some fire stations already exist. This may be seen as a hybrid problem in which it would be necessary to fix the location of the M-1 fire stations which already existed so that the optimal location of the Mth fire station could be determined with respect to the locations of the existing fire stations. All three of these variations on the location-allocation model are solved in Chapter 6.

Further variations of the Model

In addition, it should be noted that the location-allocation model described above may be varied in a number of ways not mentioned by Abler, Adams and Gould. In fact it is possible to distinguish at least eight further variations which may occur in formulating the model.

Variations in the Distribution of Points Demanding Service

The fourth variation in the model concerns the distribution of the N points to be served. This distribution may be even or uneven. If the distribution is even then the model represents a general

CHAPTER 5

Location - Allocation Models: A Review

In Chapter 3 a distance decay model was presented which explained over 74% of the variation in the distribution of alarms by census tract during 1973. This was described as a predictive model because the independent variable, distance from the centre of the distribution, could not be said to have a causal relationship with the occurrence of the alarms. Chapter 4 attempted to build a model in which the independent variables did have, to some extent, a causal relationship with the dependent variable. Unfortunately, this model failed to provide a high level of explanation. Consequently, it was decided to plan the locations of the fire stations on the basis of the actual distribution of 1973 alarms. This distribution is, of course, only a sample from a theoretical population and the possible errors which might result from sampling what is regarded as a poisson variate are discussed in Chapter 7 when the sensitivity of the proposed solutions to the fire station location problem is analysed.

Having decided to use the 1973 alarms as the best estimate of the demand surface the next step involved presenting the alarms in a form suitable for the location - allocation analysis described in Chapter 6. In order to understand the procedures used to generate the demand surface it is necessary to be completely familiar with the structure of the location - allocation model which was used.

General Form of the Location - Allocation Model

Throughout the 1960s and indeed right up until the present day both geographers and planners have been concerned with the use of location - allocation models for predicting, firstly, the optimal location of facilities and, secondly, the precise manner in which people or objects should be allocated to these facilities.

The most generalized formulation of the location - allocation problem is as follows:

Given (a) a set of N points which require servicing and whose demand may vary

and (b) a set of M facilities which provide services and whose capacity and number may vary

a set of locations is sought for the M facilities and a set of allocations for the N points to these facilities which optimize a predetermined objective function. Usually, this objective function is a distance, cost or time minimizing function.

At the present time, there is no exact algorithm which guarantees a rapid optimal solution for the location - allocation problem in its most general or unconstrained form where the objective is to minimize the aggregate travel within the system. Indeed, the only certain method of achieving such a solution is by complete enumeration of all possible solutions which is usually only feasible in trivial cases. It should, however, be noted that branch and bound techniques may be used to reduce the number of solutions considered. Ostresh (1973 b, p. 36) uses this method in his program MULTI but also notes that: ".... only trivially sized problems can be handled". Despite the fact that there is no rapidly obtainable, guaranteed, optimal solution for the problem in its most generalized form in which no constraints are imposed on any of the variables, in practical situations it is frequently possible to impose certain constraints on the model and so increase its mathematical tractability by making it more specific. Abler, Adams and Gould (1971) suggest that there are three ways in which these constraints are commonly applied.

The Effect of Placing Constraints on the Number of Facilities

Firstly, it is possible to constrain the number of facilities being located to a particular number. For example, the problem would be constrained in this manner if precisely two new fire stations had to be located in a city. If the number of facilities is constrained to only one then the problem degenerates to the classical industrial location problem posed by Weber (1929) in which there is one point providing a manufacturing service and N points (the market and raw material sources) which require servicing. The number of facilities would remain unconstrained in the problem if a planner was trying to ascertain the saving which would accrue from having, for example, a third new fire station as opposed to the two originally planned for.

The Effect of Constraining Facility Capacity

Secondly, in the location-allocation model the size or capacity of each of the M facilities may either be fixed or it may be allowed to vary. Thus in planning the location of fire stations it would be necessary to decide whether or not the fire stations were going to be required to answer only a constrained number of calls or whether they were going to be free to answer as many calls as, for example, occurred closest to them. The problem of obtaining an equitable workload for city fire stations is an important criterion for any realistic solution to the location-allocation problem. In some of the largest North American cities, such as New York, stations in the busiest sections of the city may indeed frequently have a demand for their services which exceeds their capacity to provide service. In smaller cities such as Denver, Colorado, the workload is lighter and capacity constraints are consequently less important. Hendrick, Plane et al. (1975) report that for Denver the stations were only busy approximately 5% of the time. In Chapter 6 similar estimates were made for London's fire stations. However, even in these smaller cities, a better solution to the location-allocation problem would be obtained if similar sized stations (for example, all one-bay stations) had equal service capacity constraints. This would help to ensure the desired equitable workload distribution for similarly sized stations. Unfortunately, there is a more subtle aspect to capacity constraint. This aspect is that a single station may be unable to satisfy the demand for service generated by a large fire. This aspect of the fire station planning problem was not considered in the present study but in the opinion of Fire Chief Jackson of Calgary it may be significant and its influence will be investigated in subsequent research in that city by the author.

The Effect of Constraining Facility Location

Thirdly, Abler, Adams and Gould (1971) point out that the locations of the M facilities in the model may be constrained to particular locations or alternatively, and more usually, they may be allowed to vary. If the problem is to find the optimal location for one or more new fire stations in a town which has no fire stations the planner will not, in the initial analysis, wish to constrain the location of the fire stations. He will simply seek the optimal locations wherever they are. If, however, the problem was to establish which fire stations would respond to which alarms then the locations of all the fire stations would be fixed and the planner would be seeking the solution to the allocation part of the problem only. He would simply be attempting to determine the appropriate fire station response districts. Under other circumstances the planner may wish to locate another fire station in a town where some fire stations already exist. This may be seen as a hybrid problem in which it would be necessary to fix the location of the M-1 fire stations which already existed so that the optimal location of the Mth fire station could be determined with respect to the locations of the existing fire stations. All three of these variations on the location-allocation model are solved in Chapter 6.

Further variations of the Model

In addition, it should be noted that the location-allocation model described above may be varied in a number of ways not mentioned by Abler, Adams and Gould. In fact it is possible to distinguish at least eight further variations which may occur in formulating the model.

Variations in the Distribution of Points Demanding Service

The fourth variation in the model concerns the distribution of the N points to be served. This distribution may be even or uneven. If the distribution is even then the model represents a general formulation of Christaller's more specific central place problem (Baskin, 1966). The central place problem may thus be formulated in the following manner: Given an even distribution of a base population of farmers, what are the optimal locations for a set of central places to serve that population? The solution to the problem is, of course, to locate the central places in a hexagonal lattice - just as Christaller suggested. If the distribution of the N points is uneven then the lowest cost solution, which minimizes the average distance of a point to a facility, will only be produced when the M facilities are allowed to vary in capacity. A solution in which each of the M facilities has an equal capacity may force points in sparsely populated areas to be further away from their nearest facility than they might have been if the facilities had an unconstrained capacity. Since, as was shown in Chapter 3, the demand for fire department service is not uniform across the city this would suggest that high capacity or two and three bay stations should be located in the downtown area where demand is high and low capacity or one bay stations should be located in the suburban periphery of the city where demand is low. Equal capacity stations might result in unacceptably long response times under certain conditions.

Variations in the Nature of the Demand Surface

A fifth variation in the model relates to the nature of the demand surface. As indicated above, the demand surface is usually considered to be punctiform and in these situations the model seeks to service the N points of demand. However, under some circumstances (usually when the N points are very numerous or when the nature of the demand is not known and has to be approximated by some continuous function) it may be necessary or preferable to have a continuous demand surface. Rush[illegible]n (1973) has provided an algorithm and a computer program, MAPTRANS, which yields a heuristic solution to the multiple facility location problem for a continuous demand surface. The surface is approximated by a trend surface function, for example:

$$Z = a + b_1 \left| \sin X \right| + b_2 \left| \sin Y \right| \qquad 5.1$$

Where the surface is complex but does not fluctuate too rapidly over short distances it may prove to be more accurate to approximate the demand surface by placing a fine grid over the area. Demand for service is then presumed to occur only at, for example, the centres of gravity of the N grid squares. The finer the grid and the more even the demand is *within* the squares the better will be the solution. Demand variations *between* squares are probably less relevant if the problem is formulated in this way with a punctiform demand surface than if Rushton's algorithm is used with a continuous demand surface. Thus Rushton (1973, pp. 120-121) notes that:

> Convergence [on an optimal solution] takes place ... for smooth demand density functions but can be of erratic quality for functions where large differences in demand density exist within the study area.

For this reason, in the present study, the 2,459 alarms which occurred in 1973 and which formed the demand surface for the location-allocation model were approximated by the centres of a mesh of polygons rather than by a trend surface equation such as the one obtained in Chapter 3. The actual mechanics of producing this demand surface are described below.

Variations in the Trafficability of the Model Surface

A sixth variation which may be introduced into the formulation of the model relates to the trafficability of the surface of the study area. The N points, which require servicing, and the M facilities, which provide the service, may be considered to be connected to a transportation network or, in theoretical terms, a graph. Obviously, this graph should not be disconnected or the problem may have no solution. Thus none of the points or the facilities may form isolated sub-graphs. However, the graph's degree of connectivity may vary between a lower limit in which it is simply a tree, and therefore only minimally connected, through to an upper limit in which the graph is fully, or maximally, connected and every point is thus directly connected to every facility. In between these two extremes the points and facilities may be embedded in a graph which forms a grid structure. This is the classic Manhattan block situation where distances between places can be evaluated using a Minkowski metric of 1.0 in the formula given below:

$$D_{ij} = (|(x_i - x_j)^R| + |(y_i - y_j)^R|)^{1/R} \qquad 5.2$$

where D_{ij} is the distance between points i and j

x and y are the locational coordinates

R is the Minkowski metric

The maximally connected graph represents the situation in which the surface has uniform trafficability and where the distance between point and facility may be evaluated using equation 5.2 with a Minkowski metric of 2.0, and it is this idealistic formulation of the model which is used in Christaller's central place theory. Rushton, Goodchild and Ostresh (1973, p. v) divide location-allocation problems into two classes. The first class are those problems which are formulated in a continuous space. In these problems distances between demand point and facility are evaluated as if there were a direct connection between the two. In the second class of problem demand points are considered to lie on a network which is not maximally connected. Hakimi (1964) has shown that the optimal locations for the facilities will always be at the nodes of this network in the p-median problems. Goodchild (1973) has provided a computer program for solving the continuous space problem. This program, LAP, is used in the present thesis in Chapter 7 for comparative purposes. It was felt, however, that a discrete space or network formulation of the location-allocation problem would provide a more realistic model of fire department activities and so the main analysis for the thesis was carried out using a discrete space program. This program was ALLOC5 (see Hillsman, 1974, for a discussion of ALLOC4, an earlier version of ALLOC5. Both programs are modified versions of ALLOC from Rushton and Kohler, 1973).

Variation in the Weight Assigned to Points Demanding Service

A seventh variation in the location-allocation model concerns the weight assigned to each of the N points. In some models it may be necessary to weight each of the demand points. For example, when the pattern of past fire alarms is used as a surrogate for the ideal demand surface in planning the location of new fire stations then the importance of an alarm (in influencing the fire station location) could be determined according to the assessed damage to property which was occasioned. Loss of life could be assessed at a very high dollar value so that the model would take into account such unfortunate occurrences. In this manner the weights assigned to each demand point would represent the losses occasioned by the alarm. Other weighting schemes might be used. In the present thesis weights were not employed in this way (though the effects of excluding non-emergency alarms from the analysis were examined) but this is obviously an area which would warrant further research.

Variation in the Order of Facility Assignment

An eighth variation which has been used in formulating location-allocation models concerns the order of assignment for new facilities. Scott (1971, pp. 143-154) suggests that the problem may be solved by either the myopic or the dynamic approach. To illustrate the differences between the two approaches consider the following example. Suppose a city should wish to install four new fire stations but because of budget restrictions it decides that installation must be spread over twenty years and that it will install one station at the end of each five year period. The problem then is: should the city install each of the fire stations in the optimal location at the relevant points in time (the myopic approach) or should it evaluate the optimal locations for the set of all four of the new fire stations and then locate the stations at these sites which are sub-optimal in the short-run but optimal in the long-term view (the dynamic approach)? The optimal sequencing in the dynamic approach may be evaluated by the complete enumeration of all possible sequences, or more efficiently by dynamic programming.

Variation in the Size of the Set of Feasible Facility Locations

A ninth variation in the model concerns the size of the point set from which the M facilities may be chosen. It is possible to treat this point set as infinite and thus allow the model to locate the fire station at any point within the city. In a more realistic formulation of the model it may be preferable to restrict the possible location of sites for fire stations if only because not all locations are feasible. Alternatively, the model may be formulated so that the fire station may be located anywhere and then once the optimal location is obtained the new fire station could be constructed at the nearest feasible location. On the other hand, the city's governing body may have suggested a short list of possible locations for the new fire station (especially, if it owns certain sites and is unwilling to expropriate others) and the model would then be used to select the best possible choice of the predetermined set.

Alternative Forms of the Objective Function

The form of the objective function provides yet another variation in the structure of the location-allocation model. It is appropriate here to cite a few of the more common objective functions. Frequently, the model is formulated so as to locate the facility at the point of minimum aggregate travel (MAT). This point minimizes the average travel time or distance between facility and user. Morrill (1974) describes the MAT point as the bivariate median and the location-allocation problem which seeks the locations of exactly p facilities which minimize average travel time between the facility providing the service and the demand point requiring the service as the p-median problem. A different objective function is used in what is commonly known as the p-centre problem. Here the objective is to minimize the maximum travel time between facility and demand point. It is interesting to note that as long as there are some demand points everywhere (i.e. the demand surface is continuous) the solution to the p-centre problem for an infinite surface of uniform trafficability and with facilities which are under no service constraints must be a hexagonal lattice of facilities as postulated by Christaller. Morrill suggests that it would be possible to obtain a close approximation to the solution of the p-centre problem by minimizing the cubed distances of the demand points from the facilities. Some location-allocation models seek to combine the objective functions of the p-median and p-centre problems. For example, such a model might seek to minimize average travel time so long as no demand point was greater than a specified critical distance from a facility. Halpern (1976) has been seeking analytical solutions to this class of problems. Morrill suggests a third objective function which might be appropriate for the model. This would seek to place the facility at the centre of gravity of the N demand points. Morrill points out that usually for only a small sacrifice in efficiency this location will minimize the variance in travel time between demand points and facility. With respect to the fire station problem this egalitarian solution is, unfortunately, not at all attractive in our non-egalitarian society. Such a solution would tend to move the facility away from the poor, who, in North America, are usually located at high densities close to the centre of the city, towards the rich, who are usually located at low densities on the city's periphery. Moreover, such rich people often have less need of public services such as fire stations since their modern, suburban houses are less susceptible to fire due to better wiring, improved construction and now, increasingly, the presence of smoke detectors. Finally, it should be noted that, as Munson (1975) has shown, the poor tend to suffer more severely from a fire than the more affluent who are protected by comprehensive insurance policies. These statements suggest, therefore, that, in the fire station problem at least, the objective function of the location-allocation model must take into account the nature of the distribution of the potential users of the service. Thus despite court decisions to the contrary in New York City (Walker, 1975 b) the objective function of the model is <u>not</u> value free.

Algorithm Variations

The location-allocation problem may be solved either by heuristic or exact algorithms. The heuristic algorithms usually have the advantage of computational speed and the disadvantage that they may terminate with sub-optimal solutions. Sub-optimal solutions arise if the heuristic becomes "trapped" in a position which is only locally, rather than globally, optimal. This problem may be partially overcome by initially increasing the increment used in the iterative steps of the heuristic or by changing the initial configuration for the set of M facilities. If either of these methods reduces the value of the objective function the original solution is shown to be sub-optimal. Scott (1971, pp. 7-57) provides a detailed discussion of a number of heuristic and exact algorithms which have been used. Heuristic algorithms are as varied as the ingenuity of the problem solver will allow. Indeed, Scott (1971, p. 39) notes that:

> Heuristic programming is less a rigidly defined mathematical procedure than a very general problem solving philosophy.

Because of this tremendous variety and because the two location-allocation models used in the present study, ALLOC5 and LAP, both use heuristic algorithms (which are described in Chapters 6 and 7, respectively) there will be no further discussion of heuristic procedures here. Exact algorithms suitable for the solution of location-allocation problems include: integer linear programming and also tree searching methods such as branch and bound algorithms, back-track programming algorithms and discrete dynamic programming. Scott (1971) gives a detailed discussion of each of these procedures including the advantages and drawbacks of each method and how their efficiency may be improved. However, his conclusion on the practical usefulness of these algorithms is essentially negative (Scott, 1971, pp. 36-37):

> .... the combinatorial explosiveness of many problems remains a forbidding obstacle to the application of exact solution methods. It is indeed doubtful if the branch and bound or back-track programming algorithms could handle any problem with much more than ninety or a hundred variables. Discrete dynamic programming algorithms are most especially sensitive to the number of states in any problem, and computational difficulties become very apparent where this number is in excess of about fifty. A very considerable improvement in the computational efficiency of all of these algorithms is necessary before really large problems can be handled with ease.

Massam (1975, pp. 63-70) has suggested an alternative classification of procedures for solving location-allocation problems. This classification includes the following six categories: (1) Mechanical;

(2) Geometrical; (3) Heuristic; (4) Numeric-analytical; (5) Simulation; and (6) Intuition.

Stochastic and Deterministic Alternatives for Allocation Rules

A final variation which may be introduced into the location-allocation model has been discussed by Goodchild (1974b). This variation concerns the degree to which the people being serviced have freedom of choice regarding the facility which services them. Goodchild envisages a spectrum of models ranging from those where the choice of service facility is completely voluntary through to those in which the people being serviced have no choice over the facility which will provide them with service. Fire station location-allocation models would seem to fall into the latter category while shopping centre models might be placed in the former group. However, under certain conditions fire station models could have allocation properties akin to those of the voluntary models to the extent that demand points might not always be best serviced by the station which was physically closest to them. Thus if spatio-temporal variations in response speeds are found to exist it might prove preferable to change the boundaries of response districts during the morning and evening rush hours as was tentatively suggested in Chapter 3. The probability of alarm occurrence in the affected space-time zones would then have to be taken into consideration in determining globally optimal locations for the stations. Furthermore, demand points cannot always expect to obtain service from the nearest station since the unit(s) from the appropriate station may be busy. However, low work loads, as reported in Chapter 6, and fire department covering or move-up procedures make this an unlikely occurrence in all but the very largest North American cities.

A Brief Description of Some Former Fire Station Location-Allocation Models

Colner and Gilsinn (1973) provide an excellent review of a series of fire station location-allocation models which have been formulated recently. They note that these models have several general characteristics. Firstly, they rely on response times rather than response distances as used in the standard grading schedules described in Chapter 2. These response times are usually generated by applying shortest path routines to the main routes in city street networks. Secondly, they evaluate a finite set of locations for the fire stations in terms of the stated objective function. These locations are assumed to be coincident with nodes in the street network. Finally, all of the models assume that demand is punctiform. Demand is assumed to occur at the centre of fire demand zones which are weighted according to the frequency of past alarm occurrences or according to the estimated severity of hazard within these zones. These weights may be employed directly in the objective function or they may be used implicitly as time constraints (the latter approach was used by Hendrick, Plane, et al., 1975, whose work was discussed in Chapter 2).

Colner and Gilsinn (1973) provide a list of assumptions which many previous location-allocation models have used. These assumptions will be listed briefly here since they emphasize the limitations of the various models.

Assumption 1: Each fire suppression unit is assigned to one station which has a fixed location at one of the network nodes. The unit is assumed to respond to all calls for service from this location. It is, therefore, assumed that it will not respond to alarms from the scene of an earlier alarm nor while returning to the station. This assumption while unrealistic would only be severe in the very largest North American cities, such as New York. In London, Ontario, and Denver, Colorado, for example, the low workloads per station justify the assumption (see Chapter 6 and Hendrick, Plane et al., 1973, respectively).

Assumption 2: The units are indistinguishable and equivalent. In reality, three different categories of unit might be defined. These would include: (1) fire suppression units such as pumpers; (2) fire rescue units such as ladder trucks; and (3) special support units which carry out a limited set of highly specialized functions. Thus in a sensitive analysis it might be appropriate to formulate three models, one to locate each of the three sets of units.

Assumption 3: The units are indivisible.

Assumption 4: A given fire demand point is served from the closest station. This is the usual practice of fire departments.

Assumption 5: Alarms or calls for service originate at a finite set of points which may be denoted as: f_i; $i = 1, 2, \ldots, n$, where n is the total number of demand points.

Assumption 6: Potential fire station locations are restricted to a finite set of points which are usually the set, or a subset, of the nodes of the street network. The set of feasible locations may be denoted: $E = \{e_j;\ j = 1, 2, \ldots, m$, where $m \leq n\}$

Assumption 7: The travel time $T_{ij} \geq 0$, required for a unit at location e_j to respond to an alarm at f_i, is known for all i and j.

Assumption 8: The expected number of alarms at a focal point, f_i, over a specified length of time, for example, a year, is known and may be denoted by W_i.

Assumption 9: A fire suppression unit is available whenever one is required. Again, this is a reasonable assumption when workload is low.

Assumption 10: Only one unit is required to respond to each alarm. This assumption tends to become increasingly unrealistic with increase in city size.

Many of these assumptions are basic to the location-allocation models which have been developed for fire station location. Certain models have required alternative assumptions and these will be discussed in due course.

Three distinct types of location-allocation model have been used. Firstly, there are the weighted time models. Secondly, there are the time constrained models, and, finally, there are the balanced workload models. These will now be discussed in turn.

Weighted Time Models

These models attempt to minimize disutility associated with the set of fire station locations. This disutility is measured by the followed equation:

$$DIS_{ij} = W_i T_{ij} \qquad 5.3$$

where DIS_{ij} is the disutility of serving node f_i from location e_j

W_i is a predetermined weighting function

T_{ij} is the time required for the servicing unit to travel from its location at e_j to point f_i

Basic Weighted Time Model

In the basic weighted time model there are n points demanding service and these are represented by $f_i : i = 1, 2, \ldots, n$. The model seeks to locate only one fire station and therefore assumption 4 is not necessary but assumptions 1 to 3 and 5 to 10 are required. The model may seem naive in that it only locates one station but it is in fact appropriate for small communities throughout North America. The model is given by the following equation:

$$\text{Model 1: Minimize } \sum_{i=1}^{n} W_i T_{ij} \qquad 5.4$$

where $1 \leq j \leq m$

m represents the number of possible locations for the station and the other terms are as previously defined

An obvious extension of Model 1 is a model which would allow the location of several fire stations at the same time. This extension, which may be called Model 2, would seek to locate M fire stations which would minimize total weighted travel time within the system. This model requires all ten assumptions stated above. The model may be described by the following equation:

$$\text{Model 2: Minimize} \quad \sum_{j=1}^{m} \sum_{i=1}^{n} W_{ij} \, T_{ij} \qquad 5.5$$

$$\text{Subject to:} \quad \sum_{i=1}^{n} W_{ij} = S_j \qquad 5.6$$

$$\sum_{j=1}^{m} W_{ij} = D_i \qquad 5.7$$

where S_j is the capacity of the j^{th} station (this constraint is only necessary where the capacity of the station is constrained)

D_i is the known demand of the i^{th} demand point

Such a model would be appropriate for cities which did not have excessively high alarm rates (such as Denver, Colorado, and London, Ontario, but <u>not</u> New York City) where assumptions 4 and 9 would be justified.

Availability Model

Carter, Chaiken and Ignall (1971) have formulated a model which relaxes assumption 9 requiring that the closest unit is always available. Their new model makes three further assumptions, however. These will be referred to as Assumptions 11, 12 and 13.

Assumption 11: The arrival of the alarms is a Poisson process.

Assumption 12: The mean service time is independent of the location of the alarm and the unit servicing the alarm.

Assumption 13: The study region, R, is divided into two districts A and B which are served by units 1 and 2 respectively. In addition, these units are dispatched according to the following rules: (i) the two units respond only to alarms within the study region; (ii) if a unit is available it will respond to all alarms within its own district; (iii) if a unit is available it will respond to an alarm in the other unit's district whenever that unit is unavailable; and (iv) when both units are unavailable, alarms will be served by units outside of the study region, R.

Given these assumptions Carter et al. (1971) showed that the focal points which should be included in district A in order to minimize the total expected travel time could be established from the following expression, which can be listed as Model 3.

$$\text{Model 3:} \quad A = \{f_i \, \varepsilon R \mid T_{i1} - T_{i2} \leq K\} \qquad 5.8$$

where T_{i1} is the distance between station 1 and focal point i

T_{i2} is the distance between station 2 and focal point i

R is the region

f_i are the focal points belonging to set R.

K is given by the following expression

$$K = \frac{\lambda n}{\lambda - \mu} \left(\sum_{i=1}^{n} W_i \right)^{-1} \left(\sum_{i=1}^{n} (T_{i1} - T_{i2}) W_i \right) \qquad 5.9$$

where λ is the mean arrival rate of the alarms,

μ is the mean service time.

The major shortcoming of this model is that it requires the set of locations for the stations to be already determined. In this respect the model is not a true location-allocation model but rather a districting algorithm which would have to be used in conjunction with a model such as the basic weighted time model.

Multiple Dispatch Model

The multiple dispatch model relaxes assumption 10 which stated that only one unit was required to answer each alarm. Instead the model replaces assumption 10 with the more realistic assumption 14.

Assumption 14: A second unit may be required on an alarm at focal point f_i. The probability of requiring a second unit on a given alarm at f_i is designated by q_i.

Given assumptions 1 to 9 and, in addition, assumption 14, then the total travel time for a given number of units can be minimized by stationing the units at the locations which satisfy the following expression:

$$\text{Model 4: Minimize} \sum_{i=1}^{n} W_i \{T_{ik_r} + q_i T_{ik_s} \mid e_{k_r}, e_{k_s} \in E_k, \; r \neq s\} \qquad 5.10$$

where $1 \leq k \leq \binom{m}{M}$

E_k is sub set k of M stations from m possible sites

$\binom{m}{M}$ is the binomial coefficient which yields the number of possible K subsets available

e_{k_r} is the r^{th} element in subset e_k

e_{k_s} is the s^{th} element in subset e_k

T_{ik_r} is the time from focal point i to the r^{th} element in subset e_k

T_{ik_s} is the time from the focal point i to the s^{th} element in subset e_s

W_i is the weight at focal point i

Model 4 could be made even more realistic by including probabilities that three or more units might be required to service an alarm.

Time Constrained Models

Time constrained models seek to ensure that no focal point lies more than a critical number of seconds from a fire station. In a sense they seek to determine a rational objective configuration using the philosophy which motivated the standards suggested by the insurance associations in the United States and Canada (see Chapter 2).

These models can be made operational by making assumption 15.

Assumption 15: There is a maximum time constraint for a response to an alarm at focal point f_i. This is designated as T_i. If this constraint is exceeded then a penalty is incurred. This penalty, G_i, is given by the following expression:

$$G(i, t) = \begin{cases} 0 \text{ if } t \leq T_i \\ \alpha \text{ if } t > T_i \end{cases} \qquad 5.11$$

where α is a large value.

The penalty function can now be attached to models 1, 2 and 4 in order to create time constrained (TC) versions of these models.

Model 1 (TC): Minimize $\sum_{i=1}^{n} W_i T_{ij} + G(i, T_{ij})$ 5.12

Model 2 (TC): Minimize $\sum_{j=1}^{M} \sum_{i=1}^{n} W_{ij} T_{ij} + G(i, T_{ij})$ 5.13

Model 4 (TC): Minimize $\sum_{i=1}^{n} W_i \{T_{ik_r} + q_i T_{ik_s} + G \quad i, T_{ik_r}$

$|e_{k_r}, e_{k_s} \in E_k, r \neq s\}$ 5.14

In Model 4 (TC) the constraints could be extended to the second, third and fourth due units, and any additional ones which were felt to be significant.

Hendrick, Plane et al. (1975) used time constrained models in which there were four different constraints - their value depending upon the seriousness of the hazard identified at the focal point (see Chapter 2 for a complete discussion). Toregas et al. (1971) formulated a model which attempted to determine the locations of the minimum number of stations necessary to ensure that each focal point was located within a pre-specified service time.

Balanced Workload Models

All the models described so far have assumed that, whenever possible, focal points would be serviced by the nearest station. This is assumption 4. Balanced workload models replace this with Assumption 16.

Assumption 16: Each fire suppression unit is assigned the same total workload and the workload at a given focal point, f_i, is assumed to be directly proportional to the weight, W_i.

Any model requiring assumption 16 would lead to service areas of different sizes wherever there was an uneven distribution of weights, W_i, and where the stations were not allowed to vary in size. Balanced workload models would tend to be less efficient in areas where alarm rates are low.

The model may be formulated as follows:

Model 5: Minimize: $$\sum_{j=1}^{m} \sum_{i=1}^{n} T_{ij} W_i Y_{ij} X_j \qquad 5.15$$

Subject to: $$\sum_{j-1}^{m} Y_{ij} X_j = 1; \; i = 1, 2, \ldots, n \qquad 5.16$$

$$\sum_{j=1}^{m} X_j \leq M \qquad 5.17$$

$$\sum_{i=1}^{n} W_i Y_{ij} X_j \leq {}^{1}/_{M} \sum_{i=1}^{n} W_i;$$

$$j = 1, 2, .. m, \qquad 5.18$$

where $X_j = 1$ if a unit is located at j and 0 otherwise

W_i is the weight associated with the workload at focal point f_i

T_{ij} is the shortest time between focal point f_i and the unit located at e_j

Y_{ij} is the fraction of the workload at focal point f_i assigned to the unit at e_j

Constraint 5.16 simply states that the fractions of workload allocated must not exceed the total workload. Constraint 5.17 states that the model must not locate more than the M stations that the researcher wants to locate. Finally, constraint 5.18 ensures that the weight or workload for each station is equal for all M stations.

The above discussion sought to outline the general conceptual structure of the location-allocation model and then presented the mathematical formulation of a number of location-allocation models which have been used in the planning of fire stations. The remaining portion of this chapter will discuss the procedure used in the present study to generate the demand surface of focal points which has been a common feature of all the location-allocation models described above.

Generation of the Demand Surface of Focal Points

In the present study there were a number of different ways in which a spatial series representing the long term, stationary demand for fire department service might have been modelled. Ideally, every one of the original alarms might have been used but no available computer program could handle such a large set of focal points. Consequently, a series of attempts were made to fit statistical models to the 1973 demand surface. In Chapter 3 it was noted that the distance decay function provided the most parsimonious model. In Chapter 4 an explanatory multiple regression model was used but the results were disappointing. The distance decay function, therefore, remained the best statistical model. However, because it was in such an experimental stage and because it had not been tested for other time periods in the City of London nor for other cities it was felt that it would be best not to use this surface in the location-allocation models. As a result, it was decided that the observed demand surface should be re-described in terms of 150 fire demand zones which was the largest number of demand zones which the computer program could handle. Each demand zone was to be represented by a focal point. Since fire trucks travel along major routes within a city it was felt that it would be appropriate to define these 150 focal points as the major road intersections in the city. The focal points were also chosen so as to ensure that they provided a good coverage of the whole city and so that the best, highest density coverage was provided in areas of high demand. These focal points are shown in Figure 5.1.

The weight assigned to each focal point was simply the number of alarms occurring within the fire demand zone around the point. This fire demand zone was defined as comprising all the space, and therefore all the alarms closer to the given focal point than to any other focal point. Such a space or zone is known as a Thiessen polygon or Dirichlet region. Thiessen (1911) introduced these polygons into the geographical literature when he suggested that these space-filling polygons could be used to determine the precipitation averages over an area. This is correct if one can assume that:

> ... the amount of rain recorded at any station should represent the amount for only that region enclosed by a line midway between the station under consideration and surrounding stations ...
>
> Thiessen (1911, p. 1083), quoted in Rhynsburger (1973, p. 135).

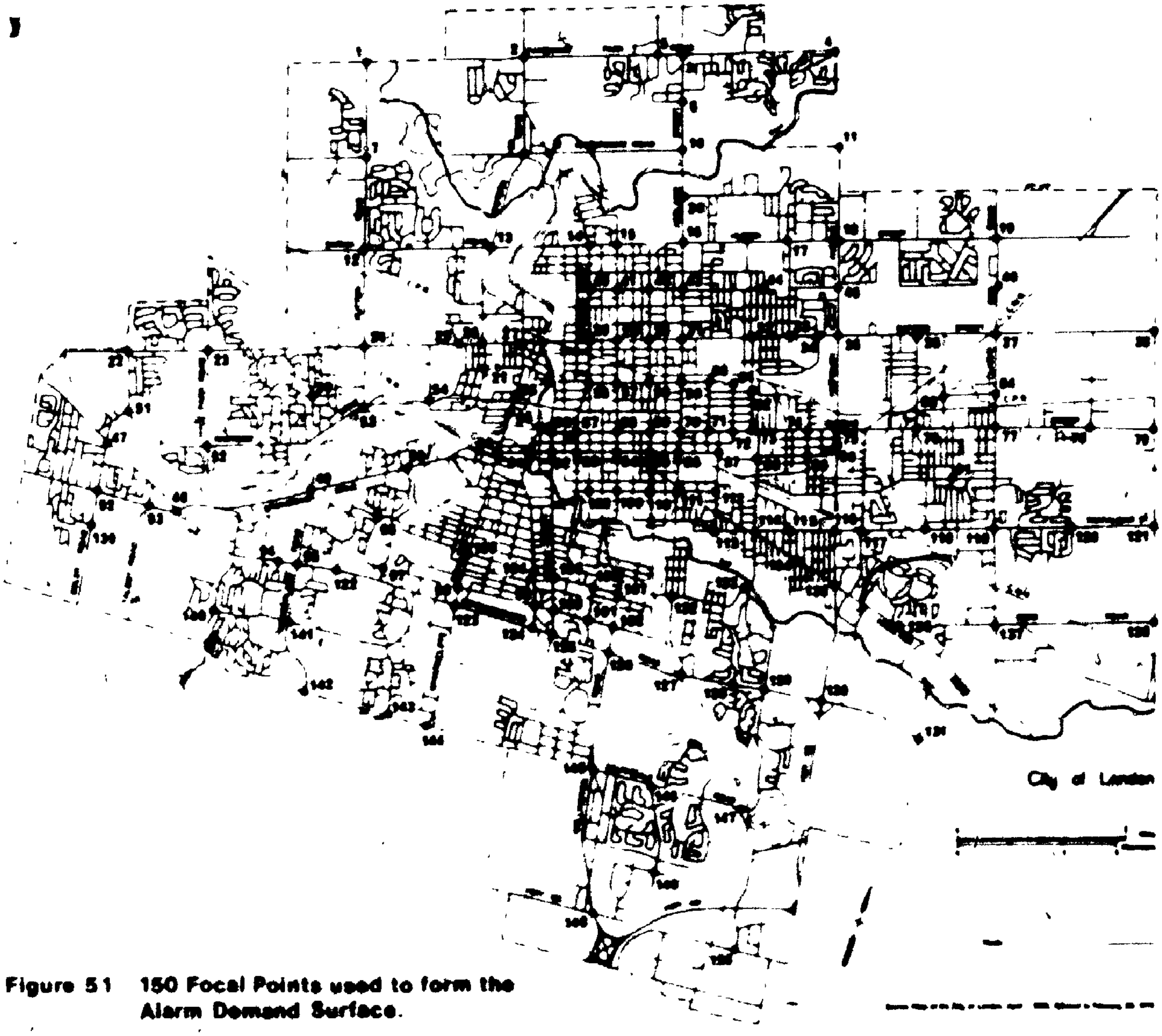


Figure 51 150 Focal Points used to form the Alarm Demand Surface.

The method can, in fact, be improved on by removing the assumption that the rainfall is spatially invariant over each polygon area. This improvement, the inclined plane method, was originally described by Whitney (1929) and involves the use of the dual of the Thiessen polygons, commonly known as the Delaunay triangles. These triangles are formed by joining the neighbouring polygon centres. Isohyets are then drawn across the plane in the form of straight lines as shown in Figure 5.2. In comparing the two methods, Thiessen's and that shown in Figure 5.2, Whitney (1929, p. 463) states:

> The objection to the Thiessen method seems to be that we know that rainfall is not distributed uniformly over certain areas as the method assumes. We also know that average rainfall on an area is not perfectly described in terms of triangular planes, but we have more difficulty in proving how the rainfall distribution varies from this last assumption.

Ritchie (personal communication) is carrying out research to define a function which will interpolate over the entire triangular net with first derivative continuity.

In the present study the Thiessen polygon method was used. The polygons were small and the error in assuming that demand was uniform within a polygon would not be great. The direction of the error and its likely effect can, however, be noted. Since the number of alarms tends to decrease as one moves away from the city centre the number of alarms in the half of the polygon closest to the city centre will tend to be under-estimated by the assumption of uniform density over the polygon. The number of alarms in the half of the polygon furthest from the city centre will similarly be over-estimated.

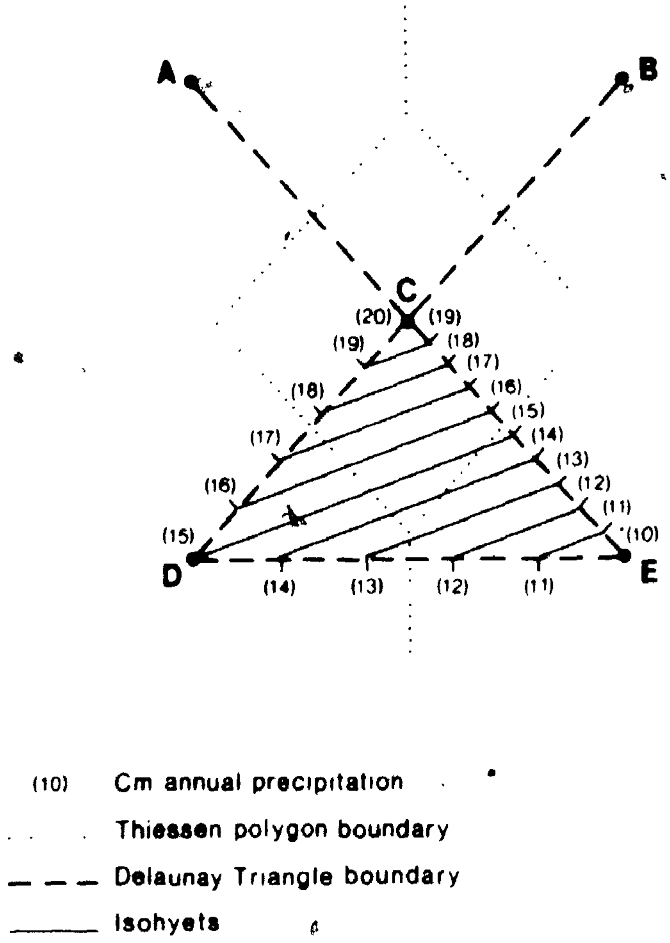


Figure 5.2 The Inclined Plane Method for Providing Rainfall Estimates.

Thus the location-allocation model will tend to locate stations in slightly more decentralized positions than would otherwise have been the case. Whether the effects are significant or not is a problem that will have to be left to future research.

Algorithms for Constructing Thiessen Polygons

Rhynsburger (1973) describes a series of algorithms for constructing Thiessen polygons. The early methods described by Horton (1917, 1923) and by Kopec (1963) relied on a geometrical construction, by hand, of the polygons. This method was tedious and time consuming and mistakes were easily made.

Recently a number of computer algorithms have been described for drawing the polygons. Perhaps the least imaginative involves overlaying the study area with a fine grid of points. For each of the grid points the algorithm determines the closest observation or focal point and the grid point is then assigned to the polygon around the nearest focal point. Those grid points equidistant from two or more focal points define the edges or vertices of Thiessen polygons.

A better algorithm was described by Gambini (an account may be found in Tobler, 1970). This algorithm increments along the perpendicular bisectors of the lines joining all n (n - 1) / 2 pairs of focal points, where n is the number of focal points. If during the incrementing process a point is found which is equidistant from the two generating focal points and further from all other points then a polygon edge has been found. Unfortunately, the incrementing routine in this algorithm is slow and tedious. Shelton (1971) improved the efficiency of a similar algorithm by incorporating a routine for eliminating from consideration those points which were clearly not geographical neighbours (geographical neighbours are points whose polygons have a common edge or vertex in the case of full and half neighbours, respectively).

Rhynsburger (1973) describes what is perhaps the best non-probabilistic computer algorithm presently available for determining polygons. Basically, Rhynsburger's algorithm involves taking the nearest point to a given focal point. The midpoint of the line joining the two points is then found and this is known to lie on a polygon edge between the two points due to Theorem 1, for which Rhynsburger provides the proof.

> Theorem 1: The nearest centre to a given centre is always a Thiessen neighbour, and the midpoint of the line joining the two is always contained within the polygon edge between them. This applies as well when two or more centres are equally near.

The remaining portion of the algorithm depends on two further theorems which Rhynsburger also proves.

> Theorem 2: Given one point known to be within a polygon edge, all endpoints of this edge can be found.

> Theorem 3: Given a polygon edge and one of its endpoints, the adjacent edge can be found.

Rhynsburger's algorithm also makes use of some ingenious modifications of the usual coordinate geometry formulas in order to increase the efficiency of the algorithm (the algorithm is available in a computer program which may be obtained from the Geography Program Exchange at Michigan State University).

Finally, a probabilistic algorithm has been described by Goodchild (1976b). This algorithm employs the fact that if a polygon vertex lies between nodes i, j and k then there will be no fourth node l within the circle which passes through i, j and k and which is centred on the vertex. The algorithm also limits its search to a set of i, j and k points which lie on the circumference of a circle with a radius which is no greater than CR. CR then is a critical radius. With a larger value of CR the researcher can be more confident of not missing any vertex. If the probability that no vertex has been missed is given by α then α can be related to CR by the following formulae (Goodchild, 1976b, p.3):

$$\alpha = \left[1 - e^{-\pi\lambda (CR)^2} \right]^{2n} \qquad 5.19$$

and

$$CR = \left[\frac{1}{\pi\lambda} \log \left(1 - \alpha^{1/2n}\right) \right]^{1/2} \qquad 5.20$$

where n is the number of points

λ is the density of points per unit area

Goodchild's algorithm employs the following ten steps:

(i) Select a node i

(ii) Select a node j greater than i.

(iii) Reject node j if the smallest circle with i and j on its circumference has a radius greater than CR.

(iv) Select a node k greater than i and j.

(v) Reject node k if the circle having i, j and k on its circumference has a radius greater than CR.

(vi) Select a node l greater than i, j and k.

(vii) Reject node l if it lies within the circle having i, j and k on its circumference.

(viii) Go to 6 if more 1's remain

(ix) If all 1's are rejected a vertex exists for nodes i, j and k

(x) Go to (iv), (ii) and (i) until all i, j and k are exhausted.

The algorithm was originally programmed by Goodchild as a separate routine but has now been incorporated as a subroutine within the PLUSX computer package (Goodchild, 1976c). In order to operate the routine the user simply has to define the locations of the original set of points and the value of α, the probability of not missing a vertex. The routine then draws the Thiessen polygons as shown in Figure 5.3. The PLUSX package was also used to determine how many of the original alarms were in each of the Thiessen polygons, and this information was then attached to the SPSS data file described in Chapter 4.

Thus, the true long run data surface was now represented by a series of 150 nodes, or major road intersections, each weighted by all those alarms which, in 1973, occurred closer to that node than to any other node. It was this surface that was used as the raw data for the location-allocation models described in Chapter 6.

Conclusion

Chapter 5 sought to describe the major variations in the structure of the location-allocation model. A series of models representing the subset of these variations which were appropriate to the fire station location-allocation problem were then described.

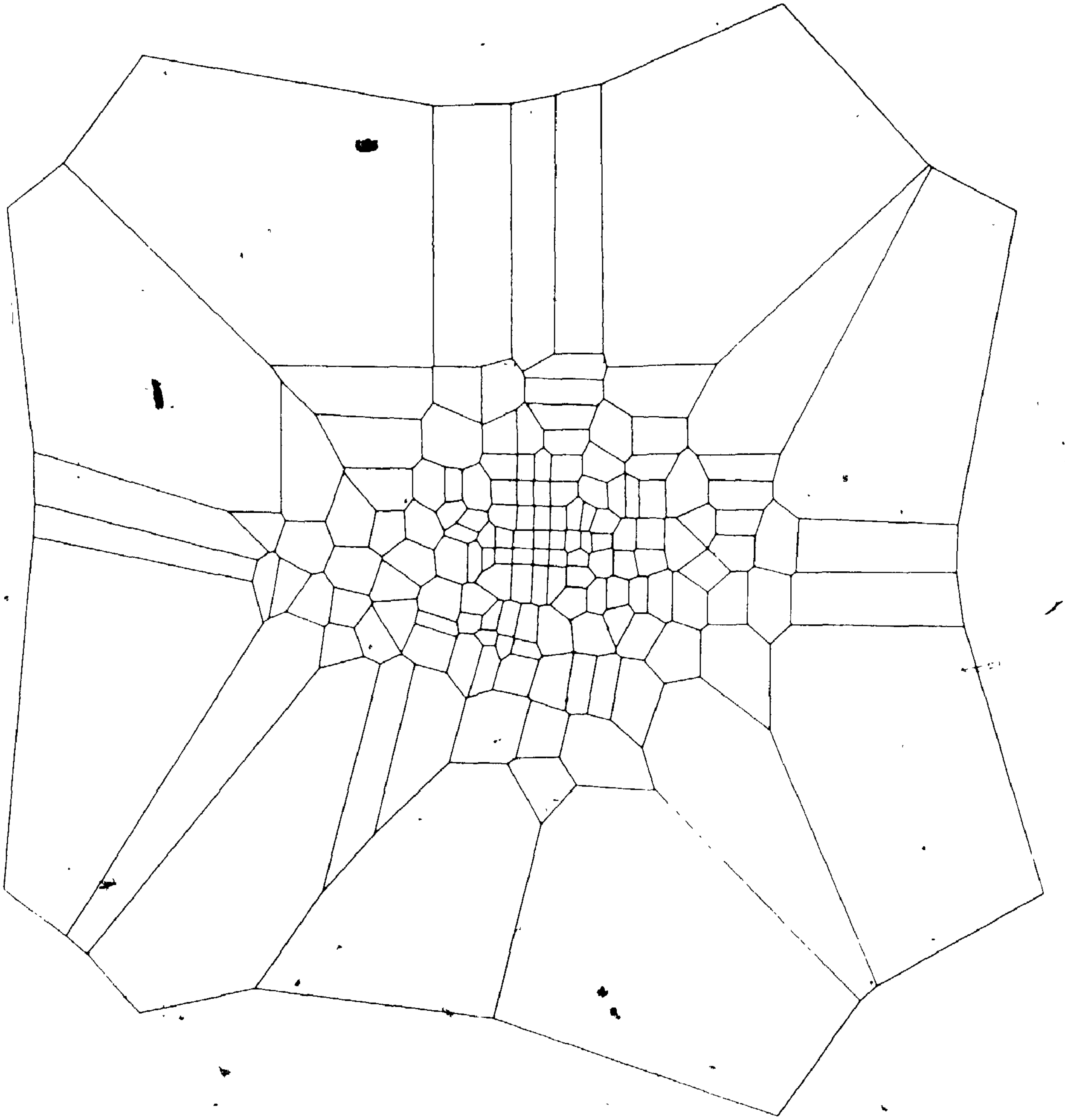


Figure 5.3 The 150 Thiessen Polygons Used to Form the Demand Surface for the Location-Allocation Analysis

Most of these models required the generation of a demand surface comprised of a series of weighted focal points centred within a series of fire demand zones. Consequently, the final section of this chapter described the procedures used in the present study to provide a model demand surface.

CHAPTER 6

Location-Allocation Analysis for the London, Ontario, Fire Stations

In this chapter the validity of using a static location-allocation model as opposed to a dynamic simulation model is discussed. After that the advantages of a discrete space formulation of the model are described along with the mode of operation of the ALLOC5 computer program. A necessary data input to this program is the shortest path matrix between all focal points and the procedures for obtaining this matrix are mentioned next. The rest of the chapter is devoted to a discussion of a series of investigations using the ALLOC5 location-allocation model. These analyses include a simple allocation model for obtaining fire department response districts, a model for determining the optimum location of nine fire stations and a model for determining the relative merits of the locations of the existing Fire Station 3 and Fire Station 6, both of which are of interest since the former was recently moved and the latter might be moved as part of future re-location strategies (Fire Chief Ray Morley, personal communication). Finally, two further models investigate the problem of locating a tenth fire station in London, which is already being discussed by the Fire Department, and the effect of introducing maximum distance constraints on a location-allocation model which seeks to minimize the average distance between demand point and fire station.

The Validity of a Static Model

As Hendrick, Plane et al. (1975) have emphasized the validity of a static location-allocation model depends largely on the validity of the assumption that a fire suppression unit is always available from the nearest location. If this assumption is not valid then it is preferable to use a simulation model which will simulate the arrival of alarms and the dispatch of fire suppression units. Such a model would be able to acknowledge the arrival of concurrent and almost concurrent alarms in a single fire response district and could dispatch the second closest fire suppression unit to the second alarm. The use of such simulation models is most appropriate in the very largest North American cities, such as New York, where alarm rates are now very high. This is described in a series of publications by Carter and her associates from the New York City Rand Institute (see Carter, 1974; Carter, Chaiken and Ignall, 1974; Carter, Ignall and Walker, 1975; and also Carter and Rolph, 1973, 1975).

It is now appropriate to examine the validity of the assumption that a fire suppression unit is always available for the case of London, Ontario. To do this the SPSS data file containing the data on the 1973 fire alarms (as described in Chapter 2) was accessed from the computer. A series of SPSS COMPUTE statements were then used to calculate the time each station was 'busy' supplying fire department services. These estimates were obtained by multiplying the company time spent at an alarm by the station(s) responding to that alarm. Such a procedure would tend to over-estimate the time each station had no fire suppression units available for the following two reasons. Firstly, some of the larger stations might send only part of their resources to an alarm especially if they were not the first due response. Secondly, if a unit is not the first due response it would not be servicing the alarm for the full time. Thus it might be called in later or sent back earlier.

The CONDESCRIPTIVE program produced the total number of minutes that each of the nine fire stations was busy during 1973. This was then divided by the number of minutes in a year and a fraction obtained which represented the proportion of the year that the station was busy. Finally, this fraction was multiplied by 100 to give the percentage of the total time that each station was busy. These figures are shown in Table 6.1. The fact that the busiest station, Fire Station 1, was only busy answering alarms just over 5% of the time does much to justify the assumption that a unit is always available. Thus the probability that Fire Station 1 would have to answer a second alarm while it was engaged in servicing the first alarm is simply the probability that the first alarm will occur times the probability that the second alarm will occur.

This is given as:

$$p\ (1) = .0502 \tag{6.1}$$

$$p\ (2) = .0502 \tag{6.2}$$

$$\begin{aligned} p\ (1 \text{ and } 2) &= (.0502)\ (.0502) \\ &= .00252 \end{aligned} \tag{6.3}$$

where p(1) is the probability of the first alarm

p(2) is the probability of the second alarm

In other words for only one quarter of one percent of the time will Fire Station 1 not be available to answer the alarms which require its services. It should be noted, however, that since the density of alarms varies throughout the day (see Chapter 3) the situation may at some points be considerably better and at some points considerably worse than the above analysis would suggest.

To ascertain how bad the situation might become the CONDESCRIP-

TABLE 6.1: Workloads for Fire Stations in London, Ontario, During 1973

	Percentage of the Year Busy
Fire Station 1	5.02%
Fire Station 2	4.10%
Fire Station 3	3.10%
Fire Station 4	2.71%
Fire Station 5	2.77%
Fire Station 6	1.27%
Fire Station 7	2.77%
Fire Station 8	2.01%
Fire Station 9	1.96%

TABLE 6.2: Workloads for Fire Stations in London, Ontario, for the Period 1600 to 2100 hours During 1973

	Percentage of the Year Busy
Fire Station 1	6.83%
Fire Station 2	5.10%
Fire Station 3	5.06%
Fire Station 4	3.95%
Fire Station 5	3.39%
Fire Station 6	2.11%
Fire Station 7	3.65%
Fire Station 8	3.10%
Fire Station 9	2.97%

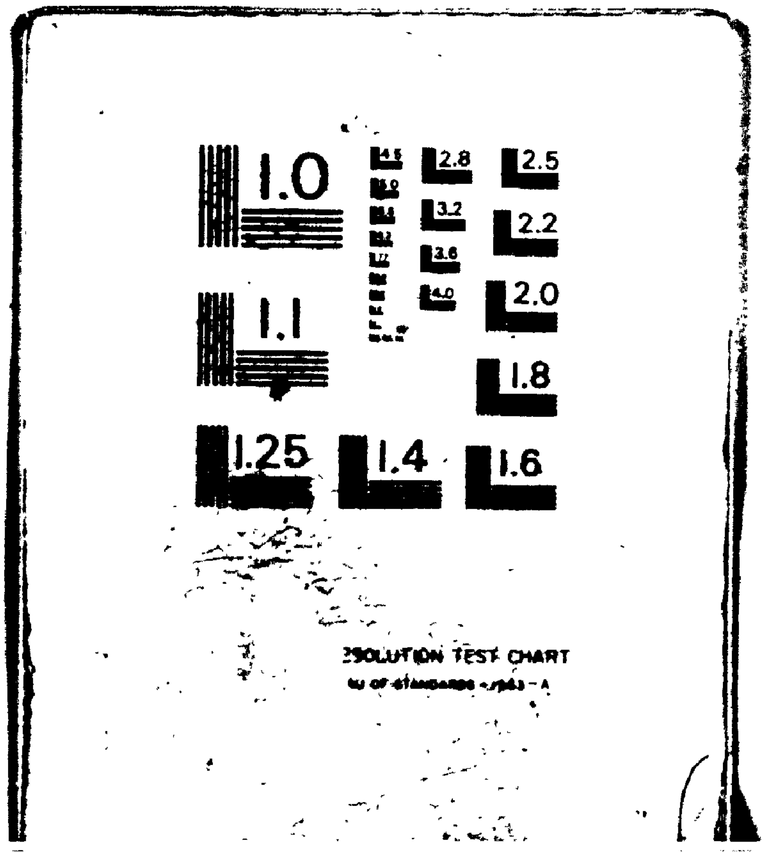
TIVE program was re-run in order to calculate how busy each station was during the busiest five hours of each day. This period was defined as lasting from 1600 hours to 2100 hours on the basis of the results obtained from Chapter 3. The results are shown in Table 6-2. Each station is only slightly more busy during this period. Station 1 is now busy almost 7% of the time which would mean that the probability of a second alarm coming while it was answering a former alarm would now be just less than half of one percent.

It is felt that this analysis of the station workloads justifies the use of a static location-allocation model rather than a dynamic simulation model such as the one developed by the New York City Rand Institute.

The Advantages of a Discrete Space Model

Having decided that the location-allocation model was not inappropriate the next step in the analysis involved determining the best formulation of the location-allocation model. Two alternatives presented themselves. The model could be formulated as a continuous space or as a discrete space model. It was decided that the most appropriate formulation would be the discrete space version since this would allow the model to recognise such linear barriers to movement as the railway tracks and the Thames River and such spatial barriers as parks, cemeteries, Wolseley Barracks and large industrial areas all of which would inhibit the movement of fire suppression units within London. The most sophisticated discrete space computer program for solving location-allocation problems available to the author was ALLOC5 and the structure of this program is discussed in the next section.

3


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
ESOLUTION TEST CHART
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The Structure of the ALLOC5 Computer Program

As was noted in Chapter 5 ALLOC5 is a slightly modified version of ALLOC4. These modifications were introduced by Hillsman in June, 1974. The original program, ALLOC4, was written by Hillsman and is documented in Hillsman (1974).

The program contains three algorithms for solving the p-median location-allocation problem which seeks to minimize the total travel time or distance between facilities and demand points. These are the Maranzana, the Teitz and Bart and the Rushton-Hillsman algorithms, respectively. These algorithms will now be briefly described. Complete discussions may be found in the original and the additional references which are cited.

The Maranzana Algorithm. This was introduced by Maranzana in 1964. Maranzana defines the problem to be solved in the following manner (Maranzana, 1964, p. 262):

> We are given: a set P of n points $p_1, \ldots, p_n$; a set of associated weights $W_1, \ldots, W_n$; a non-negative, n-dimensional, symmetric distance matrix d_{ij} and we are required to find: m sources, $p_{x1}, \ldots, p_{xm}$, an associated partition of P into m subsets of sinks, $P_{x1}, \ldots, P_{xm}$, served respectively by the m sources so that
>
> $$\sum_{i=1}^{m} \sum_{p_j \in P_{xi}} D_{xi,j} W_j \qquad (1)$$
>
> is a minimum where $D_{i,j}$ is the minimum path length from p_i to p_j. Transport cost is proportional

to the summation (1). Solution by means of direct enumeration is obviously impractical for the typical problem.

Maranzana's algorithm incorporates two steps. The first step involves determining the shortest path between any two points in the network and the second step involves determining the "centre of gravity of a set of weighted nodes" on a network. For the first step he uses an algorithm due to Bellman (1958). This will not be discussed since as will be noted the ALLOC5 program requires a shortest path matrix as part of its raw data. The second part of the algorithm, which is included in ALLOC5, involves defining the "centre of gravity". The "centre of gravity" for a subset, Q, of the total set of points, P, is defined as:

$$\sum_{p_k \varepsilon Q} D_{j,k} W_k \leq \sum_{p_k \varepsilon Q} D_{i,k} W_k \text{ for all } i \qquad 6.4$$

Thus, the optimal location of a single source is at the "centre of gravity" of the set.

Verbally stated the second portion of Maranzana's algorithm begins with an arbitrary selection of the m sources from the p points. The p points are then divided into subsets to be served by these sources. This is achieved by allocating each point to its nearest source. Next the "centre of gravity" for each subset associated with a source is defined and the source is re-located at the "centre of gravity". The points are then re-allocated to the nearest of these new sources and the process is repeated until the source points do not change. It should be noted that Bellman's "centre of gravity" is in fact the point of minimum aggregate travel (MAT point). The centre of gravity is more commonly defined as the point which minimizes distance squared and this point rarely coincides with the MAT point.

The Teitz and Bart Algorithm. The operation of this algorithm is described very succinctly by Revelle, Marks and Liebman (1970, p. 706) which is quoted in the discussion by Rushton and Kohler (1973, p. 166):

> A node which is currently not a center is substituted for each of the nodes which is currently in the set of centers. The node to be removed from the set of centers is the one which upon replacement by the chosen non-center yields the greatest decrease in the total weighted distance. A second non-center is then chosen for successive substitution, and the process is repeated. The process is continued until no node replacement yields a decrease in the objective . . .

Rushton and Kohler (1973, pp. 170-171) note that generally the Teitz and Bart algorithm tends to be superior to the Maranzana algorithm:

> In 75 runs from random starts, for fifty demand points and ten supply points, Teitz and Bart in every case found the same low of 1,561,823. Maranzana had variable results on this problem ranging from a high of 2,454,046 to a low of 1,609,825. That is Maranzana never performed as well in 75 trials as Teitz and Bart.

ALLOC5 not only solves the p-median problem but it may also be used to solve the p-median problem with maximum distance constraints. The latter problem is solved by replacing infeasible distances in the shortest path matrix with very large numbers and so effectively prohibiting their inclusion in the solution. A discussion of this particular problem is contained in Toregas and Revelle (1972). An alternative algorithm is presented by Khumawala (1973) and this is compared to the Teitz and Bart algorithm in Hillsman and Rushton (1975). Hillsman and Rushton indicate that their version of Teitz and Bart algorithm tends to outperform Khumawala's 1973 algorithm. Khumawala (1975) presents a new algorithm which in some instances outperforms the modified Teitz and Bart algorithm. But Khumawala agrees with Hillsman and Rushton's

(1975, p. 88) statement that:

> Generalizing on the basis of an analysis of only one data set could well be questioned, and we would be the first to urge that it should remain an open question as to which of the two algorithms examined here performs best. Because both are highly efficient in the use of computer time and core storage and because cases are found in which one outperforms the other, it is most productive to regard them as complementary. Most interesting is the study of their relative performances in specific cases to derive insights into the particular circumstances in this type of location problem that cause local minima entrapment.

The p-median problem with maximum distance constraints is solved below for the London fire station problem.

The Rushton-Hillsman Algorithm. This algorithm has two phases. The first phase involves replacing the most expendable centre in the configuration until no further improvement in the objective function is possible. The second phase uses what Hillsman (1974) describes as the "localized vertex substitution algorithm". In this procedure each centre is replaced but only by those nodes which lie within its service region. The algorithm will switch between phase one and phase two until no further improvement occurs in the solution.

Other Aspects of the Structure of ALLOC5

As data input the ALLOC5 program requires a shortest path matrix for the set of focal points. The procedure for obtaining such a matrix is discussed below. The program also allows the focal points to be weighted. In most of the location-allocation models described below these weights represented all the alarms which occurred in the Thiessen polygon surrounding each focal point. In some of the runs the false alarms were ignored and in some only the emergency alarms were used. The objective was to determine whether these changes in the weighting procedures would affect the solution.

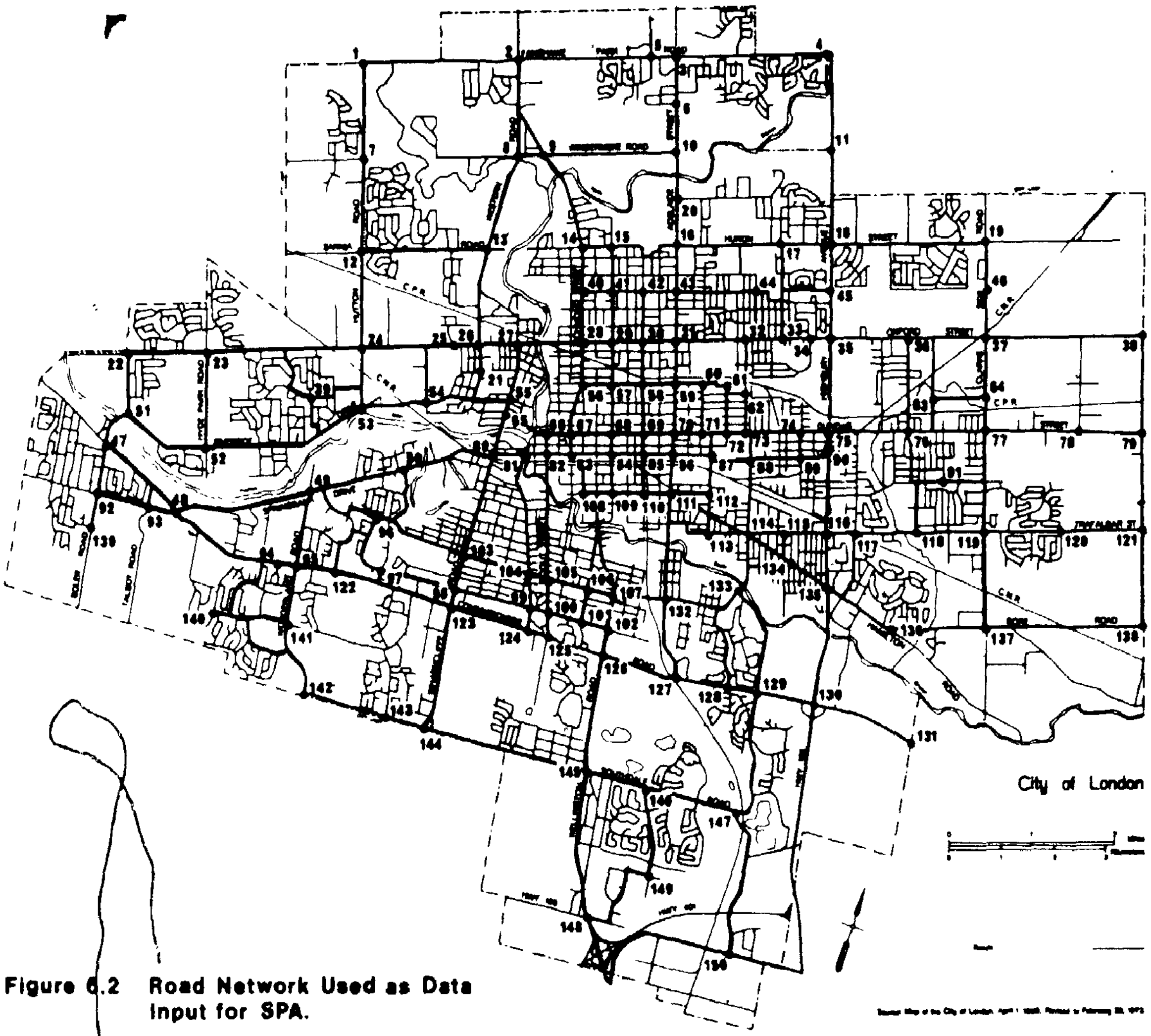
The Generation of the Shortest Path Matrix

In order to run ALLOC5 the shortest path matrix between the 150 nodes shown in Figure 5-1 had to be obtained. To do this the computer program SPA was used (see Ostresh, 1973c). As a shortest path routine SPA had many advantages. Firstly, it was large enough to handle the present problem. It is currently dimensioned to handle problems with up to 500 nodes and 1000 links. Secondly, it has an option for producing punched output and finally, this output is in a format which can be read, without modification, by ALLOC5. Ostresh (1973c) states that the algorithm used in SPA was originally discovered independently by Dijkstra (1959) and by Whiting and Hillier (1960) and was subsequently modified by Rushton and Ostresh (1971) and further modified by Ostresh (1973a).

The shortest path distances (figures in 50 feet units) for the first three nodes in the network are shown in Figure 6.1. The actual road network used in the shortest path analysis is shown in Figure 6.2. It might be argued that it would have been better to use a shortest time matrix as the raw data for the location-allocation model. This is true. However, obtaining accurate times for fire trucks travelling along the arcs of the specified network (possibly at different times of day and under different traffic conditions) was beyond the financial limits of this study. It was also felt that it would have been presumptious to have used the relationship between response time and distance discovered in Chapter 3 without further testing the validity of this relationship. Moreover, since the postulated relationship was linear it would not affect the solution which was obtained (see Chapter

```
   1     0   148   298   443   275   341    86   235   241   367   533   169   289
 334   360   438   538   585   735   409   390   480   405   255   344   367   399
 419   445   474   474   542   575   600   619   693   767   917   346   373   400
 430   431   509   598   775   568   661   692   599   533   468   309   372   451
 457   483   512   512   539   565   589   773   820   462   506   504   526   555
 555   582   606   623   678   702   776   850   940   999   499   527   523   521
 543   573   573   610   652   700   719   836   613   663   773   759   669   699
 625   655   604   667   676   595   625   634   637   647   563   536   566   592
 605   569   607   641   682   707   767   832   905   983   744   642   676   686
 699   756   766   762   803   903   682   659   655   698   768   861  1011   642
 872   807   871   791   754   803   861   881   946   938  1017
   2   148     0   150   295   127   193   234    87    93   219   385   295   175
 186   212   290   390   437   587   261   286   600   525   375   286   263   285
 271   297   326   326   394   427   452   471   545   619   769   466   225   252
 282   283   361   450   627   688   711   578   485   653   581   422   359   337
 309   335   364   364   391   417   441   625   672   348   380   356   378   407
 407   434   458   475   530   554   628   702   792   851   385   413   397   373
 395   425   425   462   504   552   571   688   733   738   663   645   555   585
 511   541   538   519   528   481   511   508   489   499   415   388   418   444
 457   421   459   493   534   559   619   684   757   835   630   528   562   560
 551   608   618   614   655   755   534   511   507   550   620   713   863   762
 762   693   757   677   640   655   713   733   798   790   869
   3   298   150     0   145    23    43   384   236   212    86   235   444   324
 274   248   170   270   317   467   128   435   749   674   524   435   412   378
 315   288   285   255   323   356   381   400   474   548   698   615   270   243
 243   212   290   360   507   803   710   577   484   797   709   550   487   406
 353   326   323   294   320   346   370   554   601   395   351   327   289   320
 336   363   377   394   444   468   543   617   707   766   384   356   334   310
 272   302   328   341   374   422   451   538   787   737   662   644   554   565
 491   420   403   369   378   461   396   378   339   349   265   238   268   294
 307   271   309   343   384   409   469   534   607   685   619   508   441   425
 401   458   468   464   505   605   384   361   357   400   470   563   713   816
 761   602   737   657   620   505   563   583   648   640   719
```

Figure 6.1 Shortest Path Distances for the First Three Focal Points Shown in Figure 5.1



Source: Map of the City of London, April 1 [illegible], Revised to February 28, [illegible]

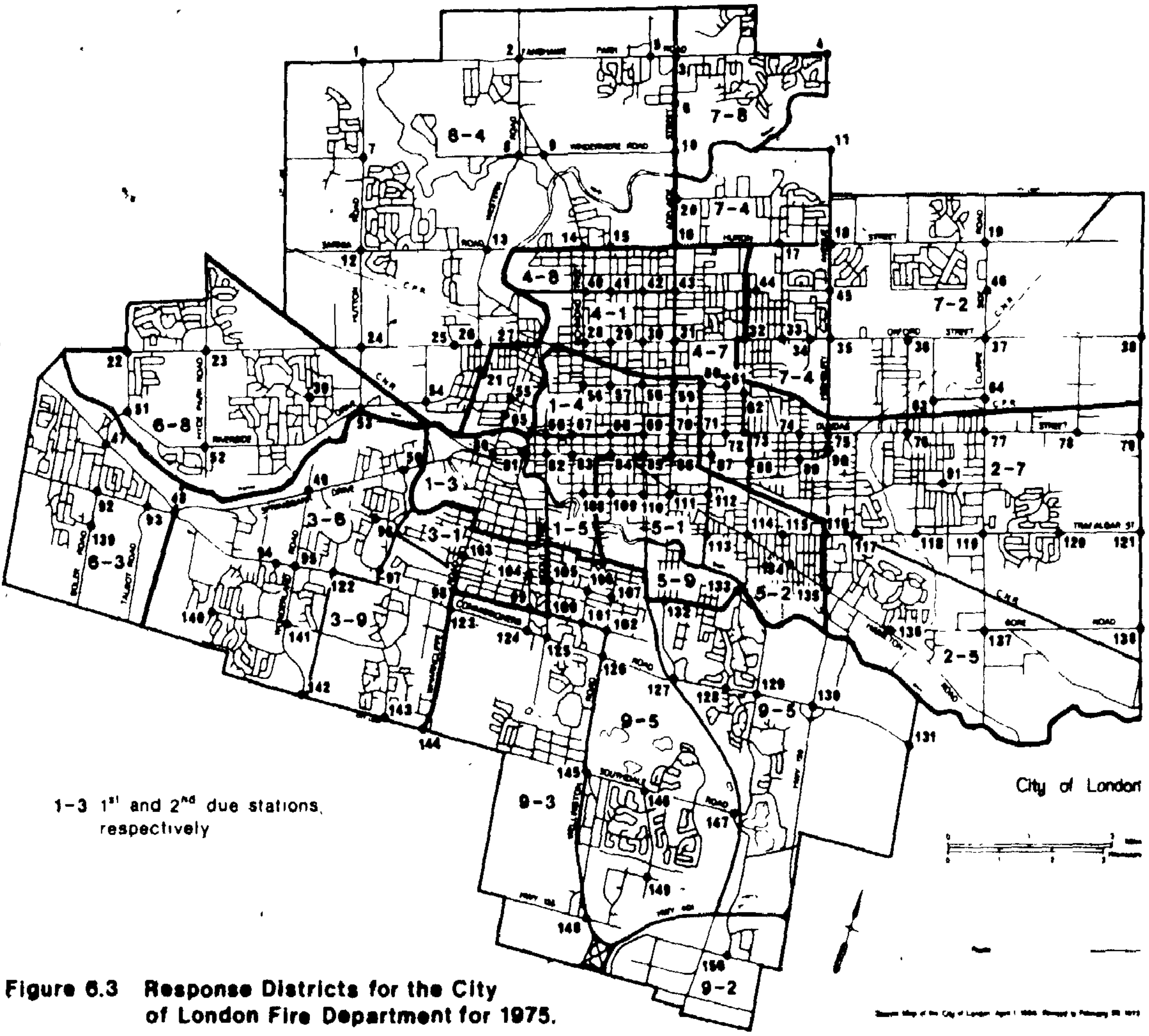
Figure 6.2 Road Network Used as Data Input for SPA.

7 for a discussion of this point). Variation in the relationship between distance and response time either through time or over space might have a significant effect upon the solution obtained from a location-allocation model. Variation in the relationship over time would affect the allocations made and might therefore cause changes in the first due and second due fire department response districts. Spatial variations in the relationship might well affect the actual location of the fire stations. Thus if trucks travel more slowly in the centre of the city than they do in the periphery of the city (as was tentatively suggested in Chapter 3 and also by Hendrick, Plane et al., 1975) then this would suggest that the density of stations in the core of the city should be higher than in the periphery of the city – even higher than that warranted by the heavier demand in the central core.

Obviously, the precise nature of the relationship between response time and distance must be investigated for all time-space variations in subsequent, better-funded research.

Allocation Studies and Fire Department Response Districts

The fire department response districts in use in London, Ontario, during 1975 (that is after the re-location of Fire Station 3 from Bruce St. to Wonderland and Commissioners Road) are shown in Figure 6.3. In order to compare these with what might be described as an optimal set of response districts the ALLOC5 program was run with the nine fire stations fixed at focal points which were the closest to their original 1976 locations. The weights used for the focal points were all the alarms which occurred closer to them than to any other focal point (that is within their Thiessen polygon). Since the location of 15 alarms could not be established the total weight came to 2444. The location of



1-3 1st and 2nd due stations, respectively

Figure 6.3 Response Districts for the City of London Fire Department for 1975.

the fire stations were fixed at focal points 8, 30, 45, 47, 84, 88, 95, 111, and 145 which were the closest points to their original locations. Running ALLOC5 in this manner gave the first due response districts.

In order to determine the second due response districts the program was re-run nine further times. Each time one of the nine stations was removed and the new allocation for the eight remaining stations was obtained. The eight remaining stations would thus retain their original allocations and some would obtain portions of the response district which had formerly been allocated to the station which was now removed from the analysis. These portions would represent part of the second due response districts of the relevant stations. Figure 6.4 shows the results of this analysis.

Comparisons between Figure 6.3 (the actual map of response districts) and Figure 6.4 (the proposed, optimum allocation given 1975 fire station locations) are hard to make. The real response districts tend to be somewhat simpler and follow established road, river and rail boundaries almost invarably whereas the proposed districts are more complex and may therefore be less acceptable from an operational point of view. Perhaps the biggest difference between the two maps is found in the first due response district for Fire Station 2. This covers an extremely large area on the map resulting from the analysis as opposed to the actual extent of the response district. In Figure 6.4 Fire Station 2 has acquired portions of the first due response districts of both Fire Station 5 and Fire Station 9. Had Fire Station 2 been located just a little further north, however, Fire Station 5 would have been closer to focal point 114 and therefore to all those that lie to the south and east of 114 along Hamilton Road (focal points 134, 135, 136)

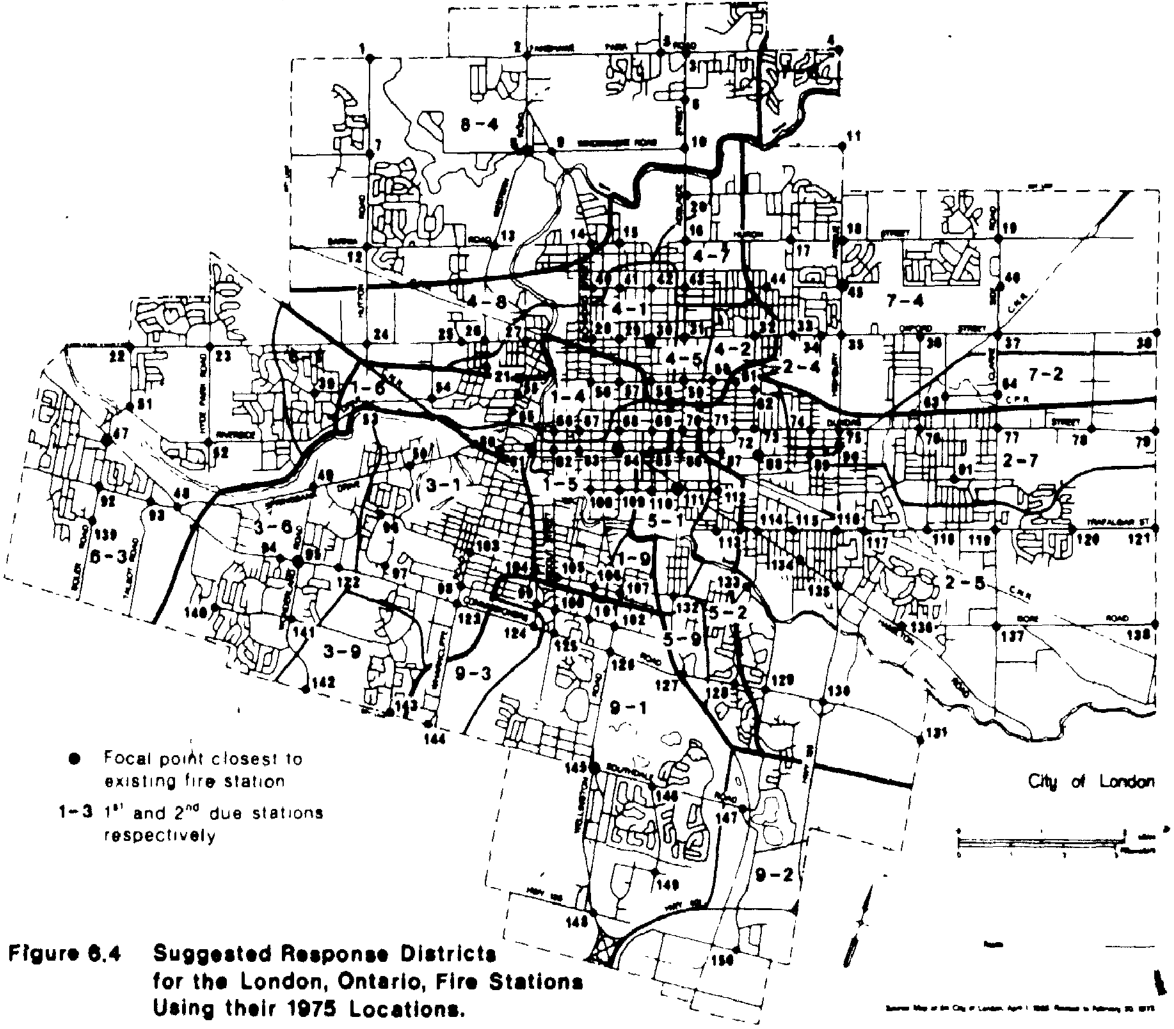


Figure 6.4 Suggested Response Districts for the London, Ontario, Fire Stations Using their 1975 Locations.

and to the south of Hamilton Road (that is focal points 129, 130, 131 and 133) and to the points on Gore Road (137, 138). In essence then it would make little differences to the objective function of minimizing total travel time within the system if all those focal points were contained in the first due response district of Fire Station 5.

The fact that Fire Station 9 appears to be over-extended in the eastern portion of its first due response area in Figure 6.3 and that Fire Station 2 appears similarly over-extended in the south eastern portion of its first due area in Figure 6.4 suggests the possible need for a new, tenth fire station in this area. This point will be mentioned again, below, when the topic of the location of the tenth station is discussed in more detail.

Another interesting aspect of this analysis is the first due weight for each station. Given the response districts shown in Figure 6.4 the first due weights represent all the 1973 alarms for which each station would be first due. The weights for this recommended allocation are shown in Table 6.3. Obviously, the balanced workload goal has not been achieved. This is less desirable, however, in a situation where the size of stations varies from the small one bay stations such as Fire Station 4 to the larger stations such as Fire Station 1 which has three bays (see Chapter 1 for a full description of each fire station's capacity). Station 2 appears to be overworked and again this reinforces the conclusion that a new station in this region is sorely needed. Stations 3, 8 and 9 appear to be underworked in this hypothetical allocation. In 1973 these locations were rather futuristic choices. At that point it might have been argued that all three stations could have been located closer to the centre of the city (as indeed Station 3 was)

TABLE 6.3: First Due Weights for the Suggested Allocation Shown in Figure 6.4

Fire Station Number	First Due Weight Using 1973 Demand Surface
1	535
2	474
3	182
4	325
5	198
6	132
7	231
8	173
9	194

so as to relieve some of the workload of Stations 1 and 4 and also 2 and 5, respectively. However, the present locations of Stations 3, 8 and 9 do reduce excessively long runs to the periphery of the city. Furthermore, the areas served by all three stations have experienced extensive growth in residential building over the last few years and so their location corresponds more to a dynamic solution of the location-allocation problem than to a myopic solution (see Chapter 5 for a discussion of these alternatives).

Finally, it can be observed from Table 6.3 that in this hypothetical 'optimal' allocation Fire Station 6 has the lowest first-due workload. This again confirms the suggestion of Fire Chief Ray Morley (personal communication) that Fire Station 6 might well be moved north of the river and further into the centre of the city. Another reason for this suggestion is that given Station 6's present site there is little possibility that its capacity can be increased. The topic of whether to move Station 6 or leave it where it is is considered again, in detail below.

The Optimal Locations and Allocations for Nine Fire Stations in London

The objective of this analysis was to determine the nine best locations and allocations for fire stations in London. The exercise is rather academic since there is no likelihood that all nine stations could be moved to these sites. However, this analysis does allow the researcher to determine how close to the optimum the present locations are and, therefore, which of the stations are most suboptimal in their location.

The objective function for this analysis was again that of the **p-median** problem where the aim is to minimize the total weighted distance between focal points and service facilities. Three weights were used. In the first analysis all the 1973 alarms were used. In the second analysis the false alarms were removed and in the final run only the emergency alarms were used. Arguments can be made for using any of these weighting schemes. There is no real need to arrive at the scene of a false alarm or a non-emergency alarm with the alacrity with which one must answer an emergency alarm. However, unless a sophisticated adaptive response policy can be formulated all alarms must be treated in the same way and all must be responded to as possible emergencies.

In the first analysis using all the alarms as weights the nine Fire Stations were originally located at those focal points closest to their actual 1976 locations. These were focal points 84, 88, 95, 30, 111, 47, 8, and 145 for the stations from 1 to 9, respectively. For this initial situation the program ALLOC5 computed the most expendable centre (that is the centre which would increase the objective function by the smallest amount if it were dropped without replacement) to be focal point 111 (Fire Station 5). This must be a comforting result for Fire Chief Morley since he has observed (personal communication) that Fire Station 5 does have structural problems and that it might well be closed if a new larger station could be built in the southeast of the city. Other 'efficiency' statistics for the original locations using all 1973 alarms as the weights are shown in Table 6.4. The maximum distance travelled is between Fire Station 2 (at focal point 88) and focal point 138 on the extreme eastern boundary of the city. This distance is 469 units of 50 feet which is almost 4½ miles. Again, this is further evidence for the need for a new station in the southeast in order to reduce these excessively long runs. According to the regress-

TABLE 6.4: Optimum Locations for Nine Fire Stations Using all 1973 Alarms as the Demand Surface

Efficiency Statistics for Original 1976 Fire Station Locations

Most Expendable Centre is at 111

Maximum Distance Travelled is 469 units* from Focal Point 138 to the Centre at 88

Total Weighted Distance is 264493 weighted units

Average Distance to Nearest Centre is 108 units

Efficiency Statistics for Optimum Locations

Most Expendable Centre is at 98

Maximum Distance Travelled is 361 units from Focal Point 138 to the Centre at 116

Total Weighted Distance is 225743 weighted units

Average Distance to Nearest Centre is 92 units

Percent Decrease in Weighted Distance (the objective function) between the original and final locations is 14.65

Station Number	1	2	3	4	5	6	7	8	9
Original Centre Locations	84	88	95	30	111	47	45	8	9
Final Centre Locations	83	116	98	16	86	47	36	13	146

---

*units are 50 feet

ion equation 3.19 which was used to relate response time to distance travelled, a run of this length would take over 8 minutes, which is an unacceptably long response time.

The efficiency statistics for the final optimum solution using all the alarms show an improvement in every measure (see Table 6.4). The maximum distance travelled has been reduced by about a mile even though no distance constraints were included in the problem. The average distance between centre and focal point is now less than a mile and the total weighted distance (the objective function) is now nearly 15% lower than it was at the start of the analysis when the stations were at their original 1976 locations. In the final situation Station 1 shows little change (moves from focal point 84 to 83) while Station 2 is moved considerably further to the southeast (from 88 to 116) again confirming the comments made above about the coverage in this part of the town. Station 3 is moved slightly to the east (from 95 to 98) and Station 4 slightly to the north (from 30 to 16) and this latter adjustment was also anticipated by the London Fire Chief who has recognized the increasing demand for fire department service in the Huron-Adelaide area and to the north. Station 5 is actually moved in (from 111 to 86) to compensate for Station 2's move out. Station 6 remains where it is which is surprising considering the comments made about 6 above and below. However, the importance of Station 6's location has been increased by moving Station 3 east. If Station 3 is considered fixed then Station 6's location becomes sub-optimal as shall be seen below. Station 7 is moved out to the east and slightly south (from 45 to 36). This is partly a function of Station 4 being moved north and slightly east and partly a function of a genuine need for better coverage in this industrial area and again, at the risk of being repetitive, this need has been discerned by the Fire Chief. Station 8 moves slightly south from point 8 to point 13 probably because of the low demand to the north of 8. Finally, Station 9 is moved slightly east to improve the coverage in the southeast of the city. The suggested optimum set of locations and allocations (first due response areas) is shown in Figure 6.5.

This analysis was then repeated without using the false alarms as part of the focal point weights. The most significant change in the suggested optimum locations for the nine stations was that Station 8 now moved even further south to focal point 26. This was because the location of Station 8 was not now constrained by the large number of false alarms generated by the University of Western Ontario and its associated residences (see Chapter 3 for a discussion of the distribution of false alarms).

Finally, the analysis for the best nine locations for fire stations was repeated for a third time using only the emergency alarms as weights. The results are shown in Table 6.5 and Figure 6.6. The major change between the results of this analysis and that shown in Table 6.4 and Figure 6.5 is that Fire Station 6 which was originally located at focal point 47 and which was not moved in the first analysis is now moved to focal point 77 in order to satisfy the demand for fire department service in the eastern portion of the city. Thus using all the alarms as weights in the model tends to suggest that the location of Fire Station 6 is sound. However, using only emergency alarms emphasizes the fact that Fire Station 6 is located too far to the west to function efficiently. Both these results were anticipated by the Fire Chief.

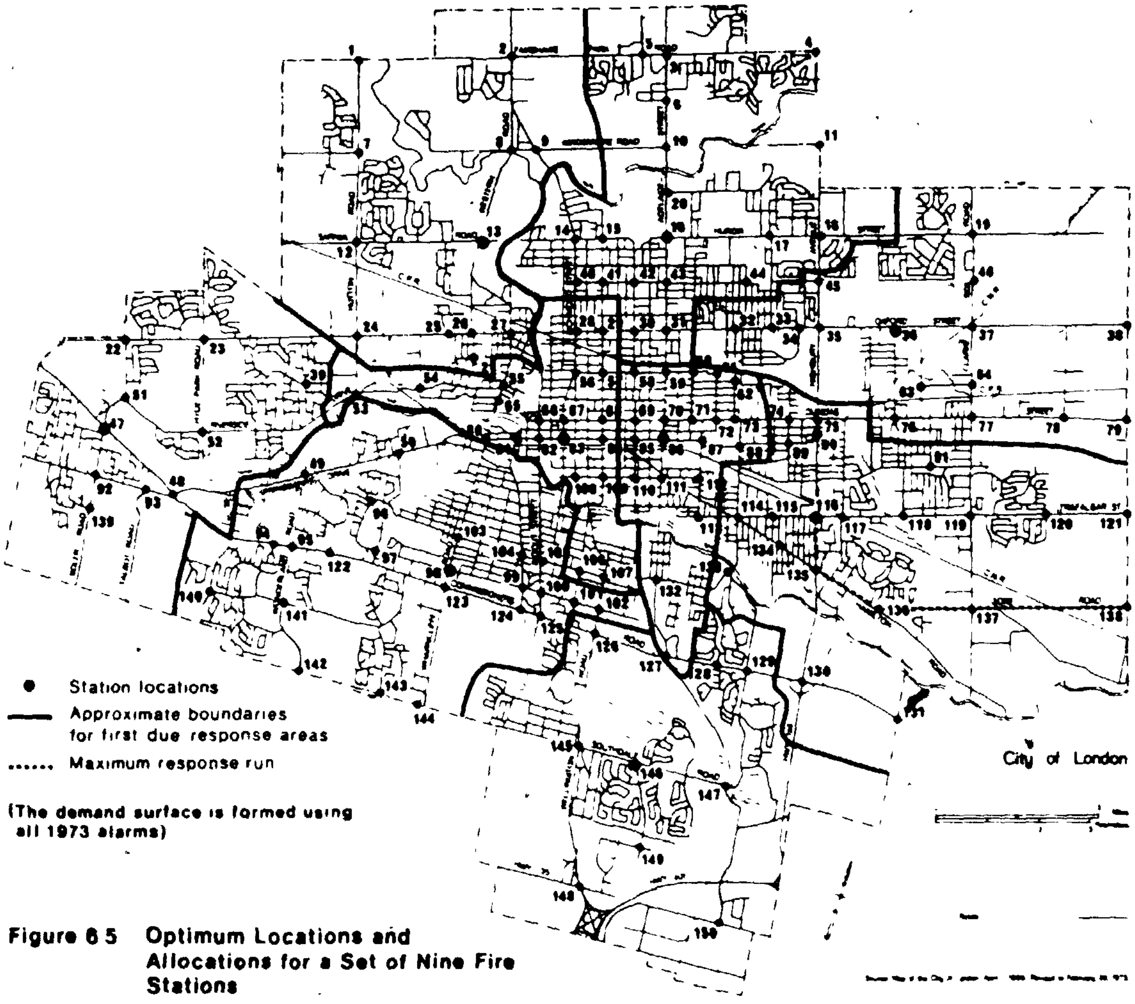


Figure 6.5 Optimum Locations and Allocations for a Set of Nine Fire Stations

TABLE 6.5: **Optimum** Locations for Nine Fire Stations Using Only the 1973 Emergency Alarms as the Demand Surface

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Emergency Statistics for the Original 1976 Fire Station Locations

Most Expendable Centre is at 47

Maximum Distance Travelled is 469 units* from Focal Point 138 to the Centre at 88

Total Weighted Distance is 43282

Average Distance to Nearest Centre is 111 units

Efficiency Statistics for Optimum Locations

Most Expendable Centre is at 70

Maximum Distance Travelled is 321 units from Focal Point 138 to the Centre at 77

Total Weighted Distance is 32941 weighted units

Average Distance to Nearest Centre is 84 units

Percent Decrease in Weighted Distance (the objective function) between the original and final locations is 23.89

Station Number	1	2	3	4	5	6	7	8	9
Original Centre Locations	84	88	95	30	111	47	45	8	145
Final Centre Locations	83	114	95	16	70	77	35	26	146

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*units are 50 feet

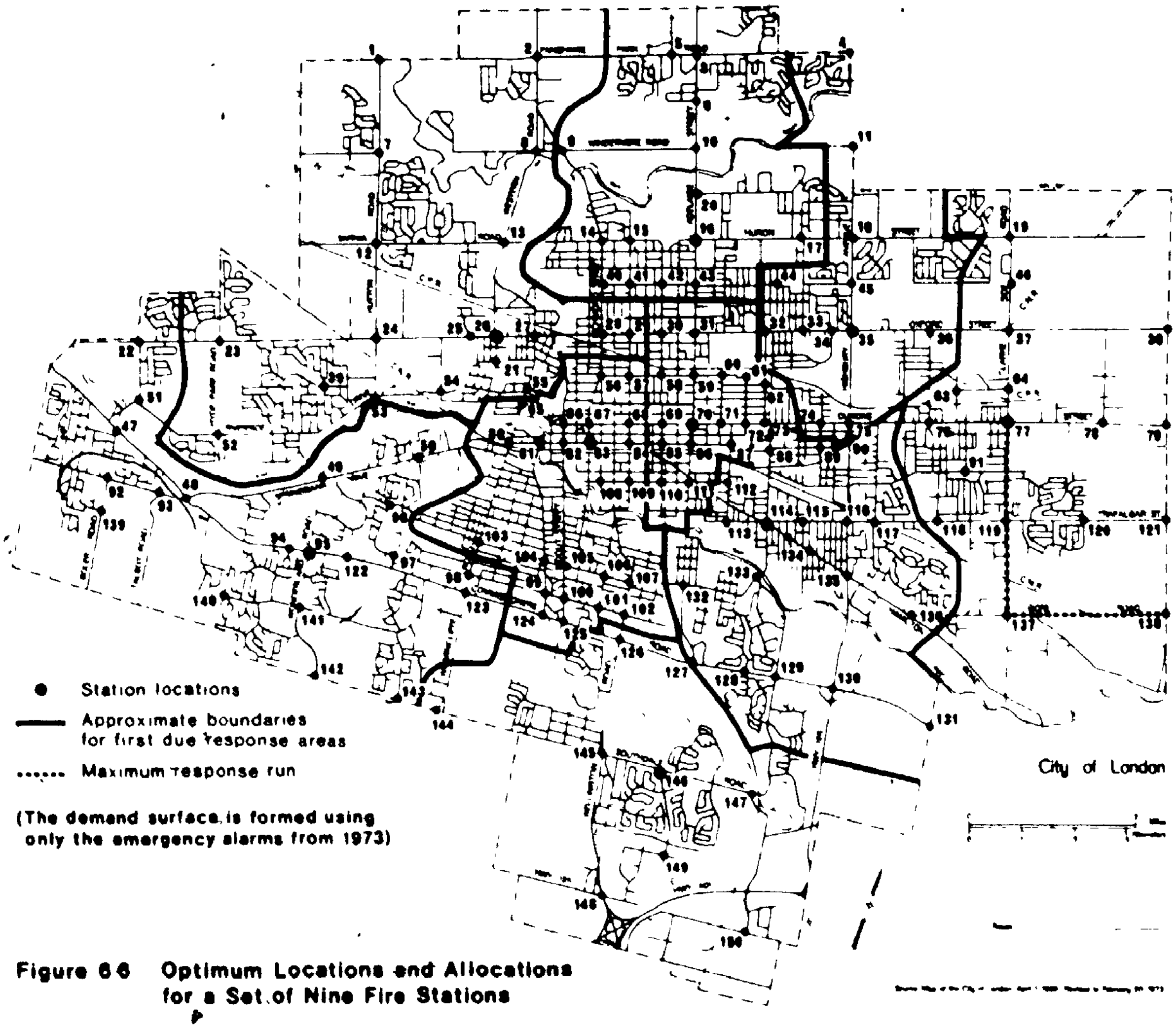

Figure 6.6 Optimum Locations and Allocations for a Set of Nine Fire Stations

The present analysis therefore provides the evidence to support his intuitive understanding of the problem.

Further Analysis of the Location of Fire Station 6

Since Fire Station 6 was being considered for possible re-location it was felt that it would be worthwhile to analyse the location of this Station in isolation from all the others. Consequently, the ALLOC5 program was re-run using all the 1973 alarms as weights and with all the Fire Stations, except 6, constrained to the focal points closest to their 1976 locations. Thus only Fire Station 6 was allowed to move from its original location to a more efficient site. The result was that Fire Station 6 moved from focal point 47 to focal point 119 on the other side of the city. This only reduced the objective function by a little over 2% but it did reduce the longest run by almost four-fifths of a mile. Simply put the analysis has revealed that it would be better to close down Fire Station 6 completely and replace it with a new station in the southeast of the city. The question of locating a tenth fire station and also relocating Fire Station 6 (the problem which was being considered by the London Fire Department at the time of writing) is discussed below.

Analysis of the Location of Fire Station 3

The London Fire Department recently moved Fire Station 3 from its location on Bruce Street to a new location on the southwestern corner of the Wonderland and Commissioners Road intersection (see Chapter 1). It appeared from the author's discussions with some of the firemen stationed at the new number 3 location that they felt that they were not as busy as they used to be when they were located on Bruce Street.

The allocation analysis used to determine optimum fire response districts which was described above also suggested that the first due responsibilities of the new Fire Station 3 were not as heavy as might have been expected (however, it is only fair to add that this station's second due responsibilities are quite significant). A priori it appears that the new location of Fire Station 3 is not exceptionally good given the 1973 demand surface. However, given the rapid residential growth in this portion of the city and the possible, future industrial growth that would be generated by a new 402 Highway link to the southwest of London the location appears much more rational.

It is impossible to determine how good the location will be in five years time since the demand pattern at that point is unknown. It is feasible, though, to ascertain the extent to which the new location was sub-optimal in terms of the 1973 demand surface. To carry out this analysis the ALLOC5 program was run using the 1973 alarms as the weights for the focal points. All the Stations were constrained to their 1976 locations except Fire Station 3 which was allowed to move to its optimal location. In the first run the Maranzana algorithm was used first, followed by the Rushton-Hillsman algorithm. In the final solution to the problem Station 3 was only moved from focal point 95 to 98. The efficiency statistics for this problem are shown in Table 6.6. It was felt, however, that this solution might only be locally optimal and so the analysis was re-run using the Teitz and Bart algorithm. In this case, where only one centre is mobile, the Teitz and Bart algorithm, which examines all possible substitutions for the one mobile centre must by definition be optimal (Rushton, personal communication). (It is not immediately obvious why the Rushton-Hillsman algorithm as programmed in ALLOC5 is not also optimal. Phase 1 of the Rushton-Hillsman examines

TABLE 6.6: Optimum Location of Fire Station 3 with other Stations Constrained to their 1976 Locations

(The demand surface is formed using all 1973 alarms, and the Maranzana and Hillsman-Rushton algorithms are used to solve the problem)

Efficiency Stations for the Original 1976 Fire Station Locations

Most Expendable Centre is at 111

Maximum Distance Travelled is 469 units* from Focal Point 138 to the centre at 88

Total Weighted Distance is 264493 weighted units

Average Distance to Nearest Centre is 108 units

Efficiency Statistics for Optimum Location of Fire Station 3

Most Expendable Centre is at 111

Maximum Distance Travelled 469 units from Focal Point 138 to the centre at 88

Total Weighted Distance is 261534 weighted units

Average Distance to Nearest Centre is 107 units

Average Decrease in Weighted Distance (the objective function) between original and final locations is 1.11

Station Number	1	2	3	4	5	6	7	8	9
Original Centre Locations	84	88	95	30	111	47	45	8	145
Final Centre Locations	84	88	98	30	111	47	45	8	145

---

*units are 50 feet

all possible alternatives to the most expendable centre. However, it will find the optimum solution only if the most expendable centre happens to be the only mobile one.) Table 6.7 shows that the optimal solution is a distinct improvement on the result of the Maranzana and Rushton-Hillsman heuristics. Now Fire Station 3 moves out of the local minimum on the objective function's surface over to focal point 119 in the southeast where the need for a new station has already been mentioned. This new location, in fact, offers only a slight improvement in the objective function but it also has the fortuitous advantage of reducing the maximum distance travelled by about a mile. The need for a new station in the southeast is discussed specifically in the next section. The preceding analysis tends to suggest that although Fire Station 3 may not be in the best location, at present, should a new station be built in the east or southeast then Fire Station 3's location will prove to be an increasingly good choice.

Suggestions for a Tenth Fire Station in London

Perhaps one of the most practical problems that the methodology presented here can be used for is to determine the location of a new fire station. In order to carry out this analysis the ALLOC5 program was run with the nine Fire Stations constrained to the focal points which were closest to their 1976 locations. A tenth fire station was located at focal point 1 and was allowed to move to its optimum location, as found by the Teitz and Bart algorithm. The results are shown in Table 6.8. Figure 6.7 shows the locations of the ten Fire Stations and their first due response districts.

As has been mentioned above, the London Fire Department is not only planning to build a tenth fire station but it is also discussing

TABLE 6.7: Optimum Location of Fire Station 3 with Other Stations Constrained to their 1976 Locations

(The demand surface is formed using all 1973 alarms and the Teitz and Bart algorithm is used to solve the problem)

Efficiency Statistics for the Original 1976 Fire Station Locations

Most Expendable Centre is at 111

Maximum Distance Travelled is 469 units* from Focal Point 138 to the Centre at 88

Total Weighted Distance is 264493 weighted units

Average Distance to Nearest Centre is 108 units

Efficiency Statistics for Optimum Location of Fire Station 3

Most Expandable Centre is 111

Maximum Distance Travelled is 361 units from Focal Point 131 to the Centre at 88

Total Weighted Distance is 260641 Weighted units

Average Distance to Nearest Centre is 107 units

Percent Decrease in Weighted Distance (the objective function) between the original and final locations is 1.46

Station Number	1	2	3	4	5	6	7	8	9
Original Centre Locations	84	88	95	30	111	47	45	8	145
Final Centre Locations	84	88	119	30	111	47	45	8	145

---

*units are 50 feet

TABLE 6.8: Optimum Location of a Tenth Fire Station with the other Nine Stations Constrained to their 1976 Locations

(The demand surface is formed using all 1973 alarms)

Efficiency Statistics for the Original 1976 Fire Station Locations Plus a Tenth Station Located at Focal Point 1

Most Expendable Centre is at 1

Maximum Distance Travelled is 469 units* from Focal Point 138 to the Centre at 88

Total Weighted Distance is 259344 weighted units

Average Distance to Nearest Centre is 106 units

Efficiency Statistics with the Tenth Station Located at its Optimum Site

Most Expendable Centre is at 111

Maximum Distance Travelled is 361 units from Focal Point 131 to the Centre at 88

Total Weighted Distance is 236749 weighted units

Average Distance to Nearest Centre is 97 units

Percent Decrease in Weighted Distance (the objective function) between the original and final locations is 8.71

Station Number	1	2	3	4	5	6	7	8	9	10
Original Centre Locations	84	88	95	30	111	47	45	8	145	1
Final Centre Locations	84	88	95	30	111	47	45	8	145	119

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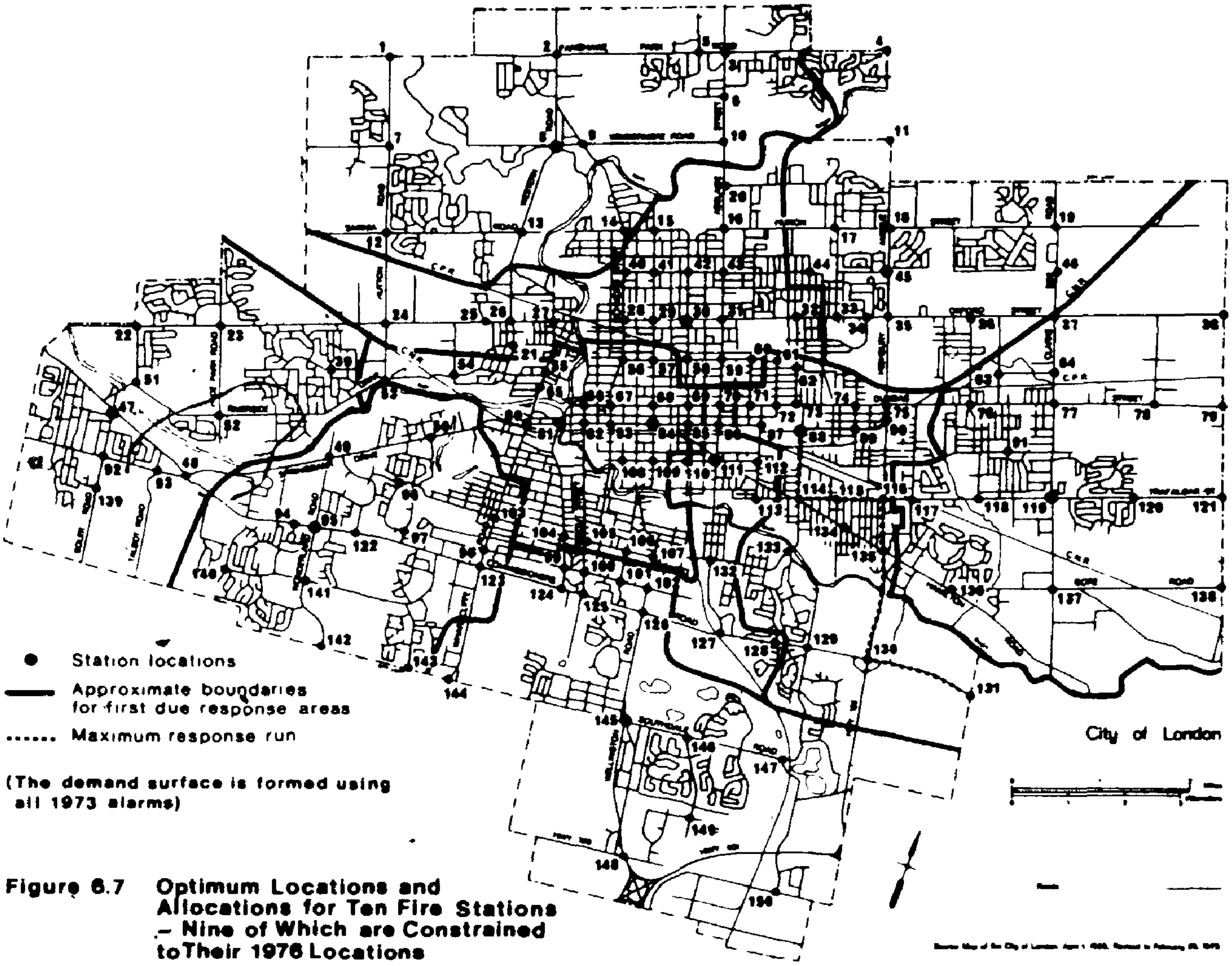
*units are 50 feet



● Station locations

━━ Approximate boundaries for first due response areas

...... Maximum response run

(The demand surface is formed using all 1973 alarms)

Figure 6.7 Optimum Locations and Allocations for Ten Fire Stations – Nine of Which are Constrained to Their 1976 Locations the possibility of finding a more suitable location for Fire Station 6. A new location would allow a larger station to be built (the fact that, at present, Fire Station 6 is located in the same building as the Byron library prohibits expansion) and the communities north of the Thames in the western part of the city might be given better service without significantly reducing the service to the Byron residents (especially since the new Fire Station 3 is now much closer to the Byron area).

The ALLOC5 program was run again with ten Fire Stations. The nine existing Fire Stations were all constrained to the 1976 locations <u>except</u> for Station 6 which was free to move to any optimum point. The tenth Fire Station was located at focal point 119 since this had been found to be the optimum location in the previous analysis when Station 6 had been constrained to its original location. Fire Station 10 was also free to move to any new optimum that might be found. Even using the Teitz and Bart algorithm no better locations could be found for Fire Stations 6 and 10. This would suggest that Fire Station 6 was 'in the right place' but Chief Morley pointed out to the author that this result was what he too would expect if he considered <u>all</u> the 1973 alarms as important as had been done in this analysis. He suggested that the situation might be very different if only the emergency alarms were used since many of the alarms in the area were minor. Grass fires, brush fires and garbage fires along with a number of false alarms were all quite common. To evaluate the Fire Chief's hypothesis the analysis was re-run using only the emergency alarms from 1973 as the weights for the focal points. The only change in the results was that Station 6 now moved north of the Thames and then east to focal point 55. The efficiency statistics for this solution are shown in Table 6.9 and

TABLE 6.9 : Optimum Location of Fire Stations 6 and 10 with the other Eight Stations Constrained to their 1976 Location

(The demand surface is formed using only the emergency alarms from 1973)

Efficiency Statistics for the Original 1976 Fire Station Locations plus a Tenth Station Located at Focal Point 119

Most Expendable Centre is at 47

Maximum Distance Travelled is 291 units* from Focal Point 7 to the Centre at 8

Total Weighted Distance is 37892 weighted units

Average Distance to Nearest Centre is 97 units

Efficiency Statistics with Fire Station 6 and 10 moved to their Optimum Sites

Most Expendable Centre is at 84

Maximum Distance Travelled is 311 units from Focal Point 22 to the Centre at 95

Total Weighted Distance is 35628 weighted units

Average Distance to Nearest Centre is 91 units

Percent Decrease in Weighted Distance (the objective function) between the original and final locations is 5.97

Station Number	1	2	3	4	5	6	7	8	9	10
Original Centre Locations	84	88	95	30	111	47	45	8	145	119
Final Centre Locations	84	88	95	30	111	55	45	8	145	119

---

*units are 50 feet

the locations and allocations in Figure 6.8. The results of the analysis confirmed the Fire Chief's suspicions. However, a few words of caution are necessary when interpreting these results. In 1973 London suffered what came to be known as the Oxford Park Disaster. The gas explosions which caused the disaster resulted in numerous emergency alarms in the region just to the north of focal point 55 and undoubtedly it is these alarms that have helped to pull Fire Station 6 so far towards the centre of the city. It may also be noted from Table 6.9 that the longest run now occurs just to the north of the Byron area. Consequently, it can be concluded that Fire Station 6 should be moved in towards the city centre but not to the extent suggested by the above analysis.*

The Effect of Maximum Distance Constraints

One final analysis was carried out in order to determine the degree to which distance constraints would affect the optimum locations for the nine fire stations described in Table 6.4 and Figure 6.5. The maximum distance from a focal point to a centre in this solution is given as 361 units. Using equation 3.19 this represents a response time of just under seven minutes which is not very acceptable. As a result this analysis was re-run using a series of distance constraints ranging from a high of 350 units to a low of 240. The lowest distance constraint which resulted in a feasible solution was 260 units. When the program

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*Footnote: Since the analysis for this study was completed it has been announced that Fire Station 6 will be relocated at focal point 24 - the junction of Hutton Road and Oxford Street. In addition Hutton Road and Wonderland Road will be linked by a new bridge over the Thames. Construction on the new Fire Station will begin towards the end of 1977 while the new bridge will be opened in the fall of 1978.

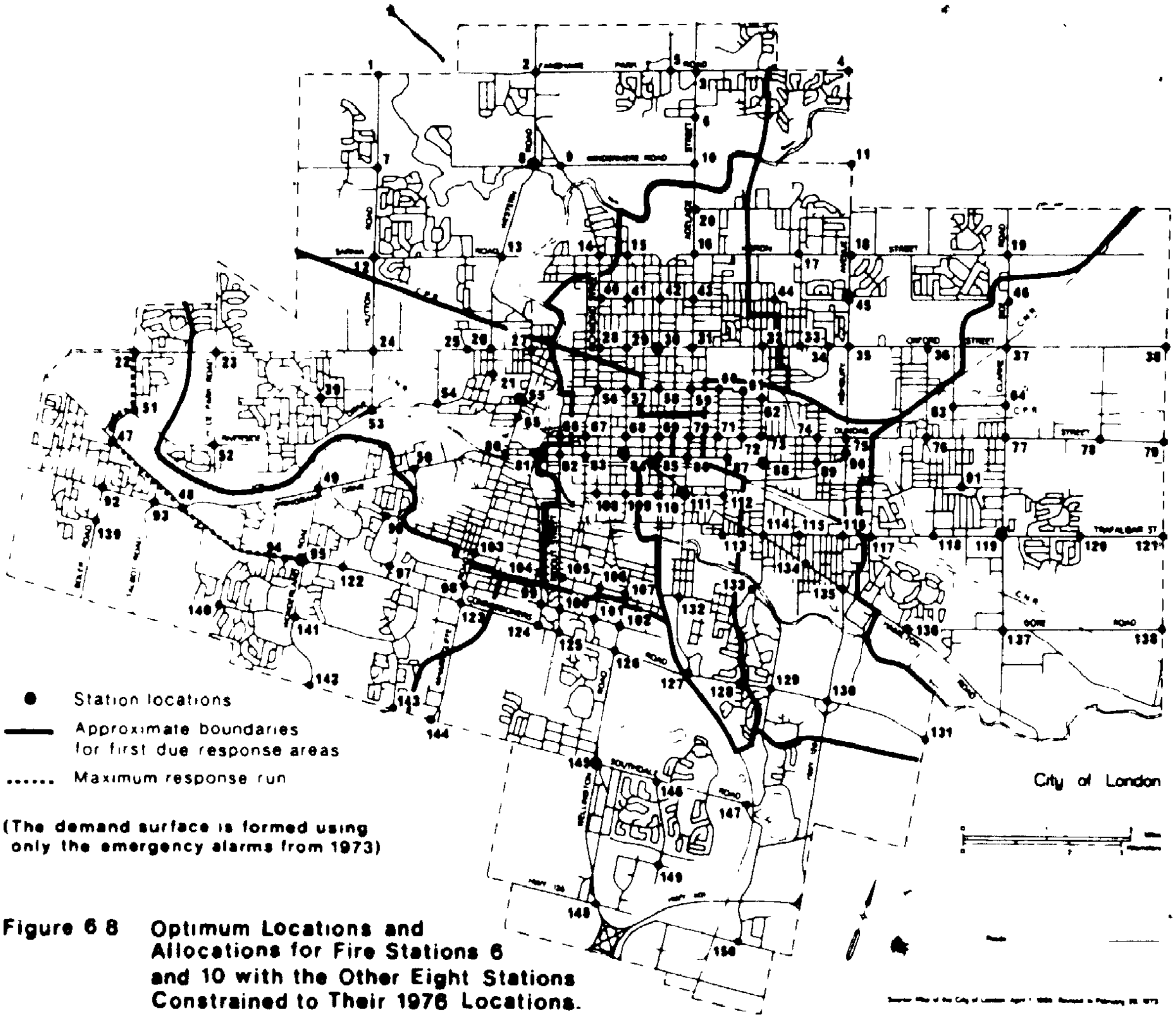

Figure 6 8 Optimum Locations and Allocations for Fire Stations 6 and 10 with the Other Eight Stations Constrained to Their 1976 Locations.

was run using a constraint of 240 units no solution could be found. 260 units represents a constraint of having no focal point more than 2.46 miles from a fire station. The results of the analysis using a distance constraint of 260 units are shown in Table 6.10 and in Figure 6.9. The fact that Stations are now located at focal points 83, 95, 18, 9 and 146 would suggest that Fire Stations 1, 3, 7, 8 and 9 are all well located with respect to the criterion of trying to minimize the maximum response distance. Interestingly enough apart from Station 1 these are all the newer Fire Stations (see Chapter 1).

Conclusions

This chapter began with a defence of the usefulness of the static location-allocation model for solving some of the strategic and tactical problems faced by modern fire departments. The discrete space model was shown to be more realistic for these types of problems than the continuous space model. Consequently, the computer program ALLOC5 was used to help analyse a variety of situations of both academic and practical interest to the London Fire Department. Chapter 7 discusses the sensitivity of these solutions to a variety of the model's implicit and explicit assumptions.

TABLE 6.10: Optimum Locations for Nine Fire Stations Using a Distance Constraint of 260 Units* and All the 1973 Alarms as the Demand Surface

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Efficiency Statistics for the Starting Locations (These are the optimum locations without distance constraints - see Table 6.4)

Most Expendable Centre is at 98

Maximum Distance Travelled is 361 units from Focal Point 138 to the Centre at 116

Total Weighted Distance is 225743 weighted units

Average Distance to Nearest Centre is 92 units

Efficiency Statistics for Optimum Locations with a Distance Constraint of 260 units

Most Expendable Centre is at 70

Maximum Distance Travelled is 258 units from Focal Point 51 to the Centre at 95

Total Weighted Distance is 245889 weighted units

Average Distance to Nearest Centre is 101 units

Percent Increase in Weighted Distance (the objective function) between the original and final locations is 8.92

Station Number	1	2	3	4	5	6	7	8	9
Original Centre Locations	83	116	98	14	86	47	36	13	146
Final Centre Locations	83	116	95	70	78	24	18	9	146

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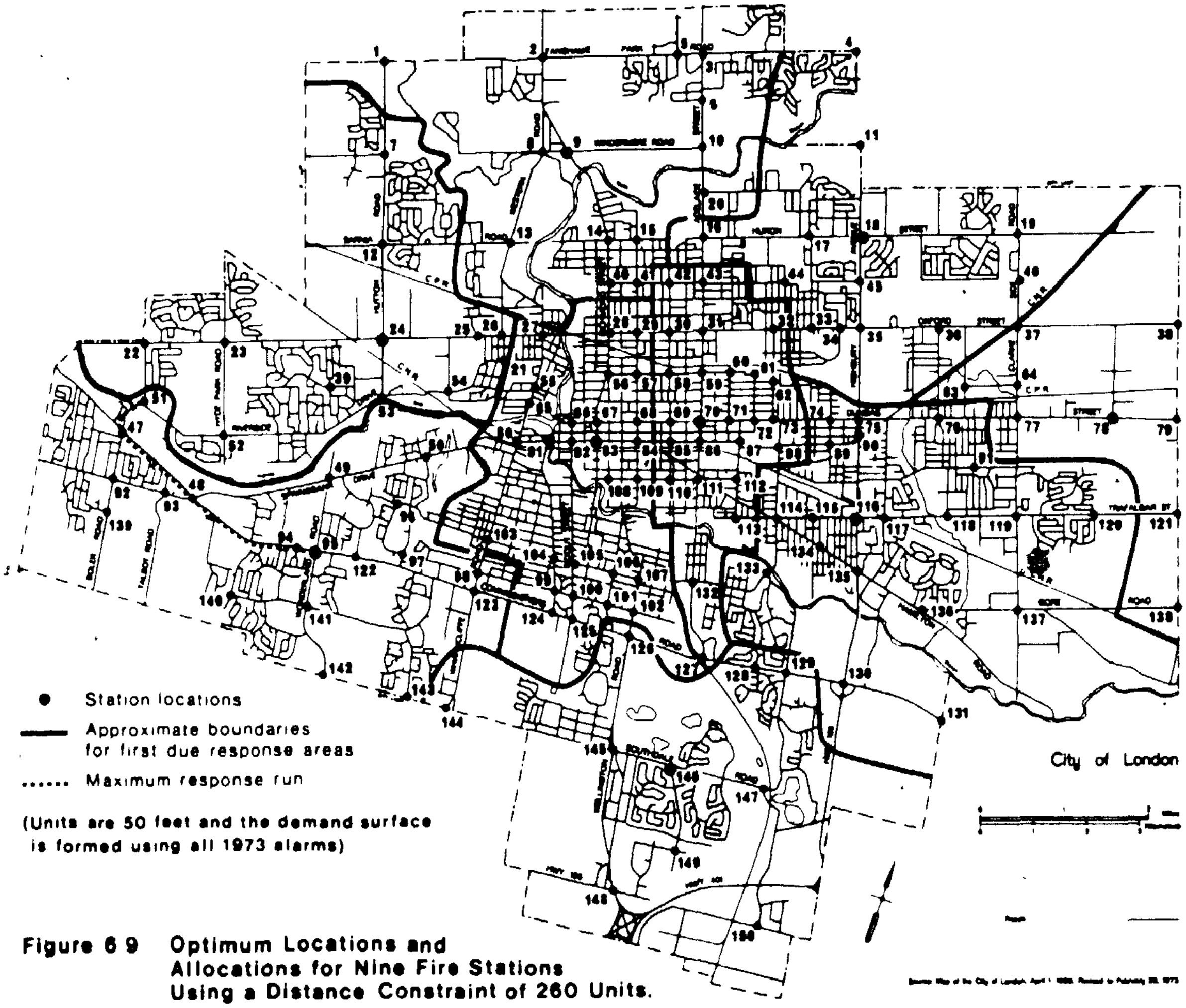
*units are 50 feet



(Units are 50 feet and the demand surface is formed using all 1973 alarms)

Figure 6.9 Optimum Locations and Allocations for Nine Fire Stations Using a Distance Constraint of 260 Units.

CHAPTER 7

Solution Sensitivity in Location-Allocation Analysis

Ideally, it would be useful to prove two statements regarding the sensitivity of location-allocation models. The first of these statements would be that the model was insensitive to all the assumptions which were made in the course of the analysis. The second statement would be that the model was not so insensitive that the optimum solution (or one very close to it) could be easily guessed by an informed observer. In the present chapter the robustness of the model to various assumptions is examined. Subsequently, the results of certain analyses discussed in Chapter 6 are compared to random solutions and solutions produced by geography students who were informed as to the nature of the alarm distribution. Finally, the effect of mis-locating one centre is examined.

An Examination of the Robustness of the Location-Allocation Model to Various Assumptions

In carrying out the location-allocation analysis described in Chapter 6 a number of assumptions were implied in the models used. The most obvious of these assumptions is that the demand surface was estimated without significant error. Significant error can be defined as error which would result in a change in the locations of the stations. It was also assumed that the size of the Thiessen polygons was small enough to catch the various undulations in the demand surface. The disutility of not servicing an alarm was assumed to be linear with distance and the models also assumed that any changes in the demand surface which occurred over time would not influence the results of the analysis during the immediate future. Finally, it is worthwhile determining the effect of using a continuous space model as opposed to the more sophisticated discrete space model employed in Chapter 6.

The effects of these assumptions are now discussed separately.

Sensitivity of the Location-Allocation Model to Data Errors

The data used to estimate demand for fire department service in the location-allocation models were those alarms which occurred during 1973. The number of alarms which may occur in an interval of time and space may be considered to have a random or poisson distribution if it is assumed that the density of the process is constant. (This statement was confirmed by the Rand Institute's research on New York City and by the author's research on London.) Lacking additional information it is most reasonable to assume that the number of alarms which were observed for 1973 represented, in each case, the mean value of the poisson distribution which they were part of. If these observed values are considered to be part of a theoretical distribution it becomes necessary to investigate whether the results of the analysis would have been affected if the researcher had observed some other value of the poisson distribution. The question is whether the location-allocation model is so sensitive that it would be seriously impaired by using different members of these distributions.

In order to resolve these problems twenty poisson deviates were generated for each of the 150 weights used to form the all alarm demand surface described in Chapter 6. These poisson deviates were generated from poisson distributions with means equal to the original weights. Thus twenty new demand surfaces were generated all of which might feasibly have been observed. Another twenty more surfaces were created by using the number of emergency alarms observed in each polygon as the mean of the poisson distribution. This further set of surfaces represented a group of surfaces that might have been observed instead of the surface of emergency alarms described in Chapter 6.

The ALLOC5 program was then used to locate nine fire stations using each of the poisson surfaces as the weights for the 150 focal points. The results based on the poisson deviates generated from all the alarms are shown in Table 7.1 and the results based on the poisson deviates generated using the emergency alarms only are shown in Table 7.2. Table 7.1 emphasizes the remarkable stability of the model when a large data set is used. In most instances the same focal point or one adjacent to it is chosen as the location for the fire station. Table 7.2 shows though that the model is much less stable when considerably smaller data sets are used. The fire station locations vary much more although generally they are all located in approximately the same regions. Table 7.3 shows the total weights for each of the surfaces and also the standard deviations for these weights. The standard deviations are also expressed as a percentage of the original weights and this shows the poisson deviate surfaces based on the emergency alarms to be more than twice as variable as those based on all the alarms. The situation is, in fact, much worse than this table suggests since a poisson deviate is generated for <u>each</u> of the 150 demand regions. Thus, in the case of the "all alarm" surface the mean for each region is, on average, just over 16 alarms but for the emergency alarm surface the mean is only just over two and a half alarms and therefore poisson deviates based on the latter surface tend to have a significantly greater effect.

The conclusion which can be drawn from this analysis is that considerable confidence can be placed on the locations which were obin 7.2:

$$W' = W\ (1 - N(0,\sigma) \qquad 7.1$$

$$W' = W\ \log\ (N(0,\sigma) \qquad 7.2$$

where W' is the modified weight

W is the original weight

$N(0,\sigma)$ is a vector of errors having a normal distribution, a mean of zero and a standard deviation of σ

Goodchild's second comment was that in this type of study it is difficult to relate the standard deviation to any "real" or physical aspect of the problem.

Sensitivity of the Location-Allocation model to grid size

It might also be asked whether the 150 fire demand regions represent a sufficiently sensitive recording grid to capture all the main features of the demand surface. If 150 regions are enough then the suggested locations for the fire stations should not change to any great degree if more regions were used.

Closely, allied to the problem of grid size is the problem of using a single point to estimate all the demand within each polygon. Thus the finer the mesh of the grid or the smaller the polygons the less error will be incurred by this approximation. In the present study no test of the effect of different grid sizes was carried out since the ALLOC5 computer program could not operate with more than 150 demand points. However, in defence of the model used in the thesis it is worthwhile noting Nordbeck and Rystedt's (1972, pp. 221-226) discussion of these points. They were able to investigate these problems in more detail since NORLOC is a continuous space location-allocation program which can accept a larger number of demand points as input data. They

TABLE 7-2. Suggested Optimum Locations of Nine Fire Stations Using Various Demand Surface Based on the Total Number of Emergency Alarms Received During 1973

	OL	AEAS	PDS 1	PDS 2	PDS 3	PDS 4	PDS 5	PDS 6	PDS 7	PDS 8	PDS 9	PDS 10	PDS 11	PDS 12	PDS 13	PDS 14	PDS 15	PDS 16	PDS 17	PDS 18	PDS 19	PDS 20
Station 1	84	83	70	67	83	83	68	83	82	82	82	103	67	83	82	67	83	82	83	83	67	67
Station 2	88	114	77	88	135	116	77	88	70	88	116	116	116	116	114	116	114	116	114	116	114	116
Station 3	95	95	122	98	122	95	98	95	95	95	95	95	49	95	141	95	95	141	49	95	95	122
Station 4	30	16	16	43	43	16	16	16	16	16	16	28	16	43	42	16	43	16	16	16	16	43
Station 5	111	70	115	132	70	132	114	111	114	111	111	111	70	70	70	70	70	70	70	70	70	70
Station 6	47	77	67	119	77	36	92	117	119	77	28	77	132	119	77	77	119	77	119	119	119	132
Station 7	45	35	33	18	35	70	35	36	36	18	36	35	36	36	35	35	19	34	36	36	45	36
Station 8	8	26	26	12	26	26	26	25	24	26	12	24	12	26	25	25	25	25	25	26	26	12
Station 9	145	14[illegible]	127	149	132	149	149	147	146	146	146	147	146	147	132	126	132	147	147	146	147	147

Legend: OL = Original Locations

AEAS = Locations Using Actual Emergency Alarm Surface

PDS 1 ... PDS 20 = Locations Using Poisson Deviate Surfaces based on Emergency Alarms Numbers 1 to 20

TABLE 7.3: Weights of Poisson Deviate Surfaces

	Total Weights for "All Alarm" Surfaces	Total Weights for Emergency Alarm Surfaces
1973 Surface	2444	390
PDS 1	2452	390
PDS 2	2454	366
PDS 3	2330	372
PDS 4	2362	402
PDS 5	2364	363
PDS 6	2372	384
PDS 7	2397	417
PDS 8	2502	420
PDS 9	2389	379
PDS 10	2359	375
PDS 11	2417	386
PDS 12	2434	414
PDS 13	2411	370
PDS 14	2429	383
PDS 15	2433	376
PDS 16	2467	390
PDS 17	2370	382
PDS 18	2435	391
PDS 19	2407	396
PDS 20	2482	38[illegible]
Standard deviation	45.64	16.25
Standard deviation as percentage of original weight	1.86%	4.17%

tained in Chapter 6 from those models using all the 1973 alarms as their focal point weights. Much less confidence can be placed on the models which used only the emergency alarms as weights. Consequently, it may be suggested that if only emergency alarms are to be used then a longer time series is necessary in order to ensure that the results are stable.

A useful discussion of the effect of observation error on the results of a location-allocation analysis is given by Nordbeck and Rystedt (1972, pp. 217-221). They suggest that, in some situations, observation errors can be considered to be normally distributed over the surface of the map and can also be considered to have a mean of zero. An earlier study (Gould, Nordbeck and Rystedt, 1971) made these assumptions in order to investigate the sensitivity of a location-allocation model which sought to locate five facilities in Tanzania. In this analysis a square grid map of 200 cells was placed over the area. The population for each grid cell was then recorded and the five facilities were located optimally using the program NORLOC. In order to check the stability of the model a series of normally distributed random numbers with a mean of zero and a standard deviation of 0.05 were generated and stored in a matrix having the same dimensions as the square grid map. Each of the random numbers in this matrix was then multiplied by the corresponding elements in the population map to give a new matrix which was referred to as the error matrix and which contained errors of the desired size. The values in the error matrix were then subtracted from the values in the original population to give a new matrix of population figures in which each of the elements was distorted by the desired error. The new population grid of distorted values was then used as data input for the NORLOC location-allocation computer program.

Distorted population grids were created in this manner using random numbers with a standard deviation of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50. Only when the standard deviation reached the value 0.35 was any instability produced in the model. At that point two of the five facilities moved one grid cell west. After that the new set of locations exhibited a stability of their own. The analysis was terminated when the standard error of the random numbers reached 0.50 since at this point the errors were so large that in some of the cells negative populations were being produced. Nordbeck and Rystedt (1972, p. 219) conclude their discussion of this paper with the following comment:

> One can sum up these investigations by saying that the location model is insensitive to reasonable errors in the square net map used as input data, always assuming that the errors are normally distributed. The model gives the same or nearly the same solution to the location problem without any noticeable influence being exerted by errors in the input data.

To provide further confidence in these remarks Nordbeck and Rystedt carried out a similar analysis for seven facilities in southern Sweden using the same methodology as was used in the Tanzania study. The new sets of data once again produced very little change in the locations of the facilities. This, therefore, provided further evidence of the robustness of the model.

Goodchild (personal communication) has made two observations regarding the work of Gould, Nordbeck and Rystedt. Firstly, he points out that the use of a log-normal distribution to modify the original weights would overcome the problem of negative populations when standard deviations of more than 0.50 were used. The old modifying equation is given as equation 7.1 while Goodchild's suggestion is shown in 7.2:

$$W' = W\ (1 - N(0,\sigma) \qquad 7.1$$

$$W' = W\ \log\ (N(0,\sigma) \qquad 7.2$$

where W' is the modified weight

W is the original weight

$N(0,\sigma)$ is a vector of errors having a normal distribution, a mean of zero and a standard deviation of σ

Goodchild's second comment was that in this type of study it is difficult to relate the standard deviation to any "real" or physical aspect of the problem.

Sensitivity of the Location-Allocation model to grid size

It might also be asked whether the 150 fire demand regions represent a sufficiently sensitive recording grid to capture all the main features of the demand surface. If 150 regions are enough then the suggested locations for the fire stations should not change to any great degree if more regions were used.

Closely, allied to the problem of grid size is the problem of using a single point to estimate all the demand within each polygon. Thus the finer the mesh of the grid or the smaller the polygons the less error will be incurred by this approximation. In the present study no test of the effect of different grid sizes was carried out since the ALLOC5 computer program could not operate with more than 150 demand points. However, in defence of the model used in the thesis it is worthwhile noting Nordbeck and Rystedt's (1972, pp. 221-226) discussion of these points. They were able to investigate these problems in more detail since NORLOC is a continuous space location-allocation program which can accept a larger number of demand points as input data. They found that for a location-allocation study in Kronoberg County, Sweden, the locations of the facilities were quite stable for models using grid cells 1, 2, 4 and 8 kilometres square (Nordbeck and Rystedt refer to these values as the "equidistance"). However, when an equidistance of 16 kilometres was used the map was made up of only about 50 squares and the solution became unstable. Nordbeck and Rystedt (1972, p. 224) conclude therefore with the following statement:

> The results from the sensitivity analysis indicate that the solutions obtained are only affected to a small extent by moderate variations in the size of grid square used. The model can be said to be stable in this respect.

These same two authors also investigated the effect of estimating the population of each grid cell on the demand map using what they described as "real estate" data and "parish" data. Real estate data represents accurate population data at the real estate (i.e. building or land parcel) level. With this data people can be accurately assigned to their correct grid cell. With parish data the researcher simply knows the number of people residing in each parish (or some other administrative unit). Thus the whole population of the parish or unit is usually assumed to have just one set of coordinates. In the case of data from parishes this might be the coordinates of the parish church. As a result the population of each parish is never split between more than one grid cell. It is simply assumed to fall completely within the grid cell which contains the critical set of coordinates. Nordbeck and Rystedt found that location-allocation models based on the two different types of data tended to yield the same set of locations for the facilities. However, they did not investigate the effect of approximating the population of a grid cell at the centre of the grid. If the population is not uniformly distributed across the cell then presumably this must make some difference but whether it is a significant difference which will affect the outcome of the analysis is another matter. In the present study each alarm was correctly assigned to the right polygon and so in that respect the model may be considered to be based on "real estate" data. However, the distribution of the alarms within each polygon was known not to be uniform and was, generally, of a higher density in that half of the polygon which lay closest to the city centre. The probable effect of this was that each of the models tended to produce a set of final locations which may have been slightly more decentralized than would otherwise have been the case. However, since most of the models did not incorporate any distance constraints, any inaccuracies might have the desirable effect of ensuring a more equitable coverage in areas of low demand.

Sensitivity of the Location-Allocation Model to the Implied Cost Function

Nordbeck and Rystedt (1972) also investigated this aspect of the stability of the location-allocation model. They point out that the cost of transportation over distance can be represented by the following equation:

$$\mathrm{COST}\ (D) = A + C\ (D^{B}) \tag{7.3}$$

where COST (D) is cost at distance D

A represents a fixed loading cost

C is a coefficient and B an exponent which determine how cost increases for each additional increment in D

Where B in equation 7.3 is unity then the relationship between cost and distance is linear, and where B is greater than one then cost rises at an increasing rate with distance and where it is less then cost rises at a decreasing rate with distance.

Each of these parameters may also be given an interpretation in the case of the fire station location problem. The 'cost' term might be replaced by an 'expected damage' or 'percentage destroyed' dependent variable. 'Distance' could represent distance between a fire and a fire station or if preferred the variable 'time taken to travel from fire station to the site of the alarm' could be used to replace distance. The 'fixed loading cost' would be replaced by 'company turn-out time'. C and B would be the coefficient and exponent which would relate the rate of burning or destruction of the property to the distance travelled or truck travel time.

The <u>implied</u> cost or disutility function used in the location-allocation models described in Chapter 6 may also be written in the same form as equation 7.3. However, in the implied model the parameter A is equal to zero and C and B are both equal to one. In essence, this means that the implied cost function does not take into consideration the constant effect of company turn-out time and furthermore it assumes that the relationship between disutility and distance is linear with no scale factor. It is necessary, therefore, to determine the effect of these assumptions on the location-allocation model. If it is assumed that turnout time is spatially invariant then excluding it from the implied cost function will have no effect on the results of the location-allocation model.

If the scale factor, C, and the exponent, B, are included in the model the objective function for the location-allocation model may be written:

$$\text{Minimize } Z = \sum_{j=1}^{M} \sum_{i=1}^{N} W_{ij} C d_{ij}^{B} \qquad 7.4$$

where the model seeks to locate M facilities and allocate N demand points requiring service

d_{ij} is the distance between the ith demand point and the jth facility

W_{ij} is the unknown weight allocation from the ith demand point to the jth facility.

The above model includes all aspects of the cost function described in equation 7.3 apart from the fixed turn-out time which has already been discarded as irrelevant to the location-allocation problem. With the model expressed in the form of equation 7.4 it can be seen that the scale factor C, is also an unnecessary distraction provided that it is given a value larger than zero. It is unnecessary to consider C because it can be placed before the summation signs in equation 7.4 to give equation 7.5:

$$\text{Minimize } Z = C \sum_{j=1}^{M} \sum_{j=1}^{N} W_{ij} \quad d_{ij}^{\ B} \qquad 7.5$$

Equation 7.5 is identical to equation 7.4 and it shows that the scale factor can be used to determine the solution cost <u>after</u> the analysis has been completed and does not, therefore, need to enter into the solution of the problem when it has a value greater than zero. In order to keep the analysis simple, and in the absence of other information, C was implied to have a value of 1.0 in the problems discussed in Chapter 6. A value of zero for C would imply that the model was insensitive to distance considerations and this is clearly not the case in the fire station problem.

The influence of the exponent B is much more interesting since it controls how sensitive the model is to distance. If B is equal to zero then distance has no influence on the model and all locations are equally attractive. If B is less than 1.0 the cost function is described as concave, if it is equal to 1.0 it is linear and if it is greater than 1.0 it is described as convex. Nordbeck and Rystedt (1972) investigated the effect of using various B values which ranged from 0.6 to 1.6. They noted that the model was relatively insensitive to variations in B. In the situation where they attempted to locate 12 facilities the model did alternate between two different solutions owing to the existence of a local optimum which was very nearly as good as the global optimum. Another conclusion which Nordbeck and Rystedt reached was that as the value of B was increased the facilities tended to move closer and closer to the geometric centres of their respective unlands or trade areas or response districts. This result might have been expected in the light of Morrill's (1974) work (which was mentioned in Chapter 5) where he noted that location-allocation models which seek to minimize distance squared will locate facilities at the centre of gravity of their regions rather than at the point of minimum aggregate travel. Locating at the centre of gravity is equivalent to using a B value of 2.0.

It may be concluded that the location-allocation model is relatively insensitive to <u>small</u> variations in the exponent B. However, using a value of 2.0 instead of 1.0 may result in significant inaccuracies if there is a wide discrepancy between the location of the centre of gravity and the point of minimum aggregate travel, respectively. A discussion of the differences between the centre of gravity and the point of minimum aggregate travel may be found in a number of works including Court (1964), Porter (1964) and Neft (1966).

Nordbeck and Rystedt (1972) also investigate the effect of using a logistic cost function in the location-allocation model. As a transportation cost function this may occur if two transportation modes are used. The function is shaped like a lazy S and indicates a slow increase in cost with increase in distance, initially. This is followed by a rapid increase in cost and, finally, there is a return to a slower rate of increase. This function might be particularly appropriate for the fire station problem. Thus it would be reasonable to expect that the progress of a fire will initially be slow. This would be followed by a period of rapid burning in which much of the structure and contents would be consumed and finally there would be a third period where any subsequent damage would only occur very slowly. Equation 7.3 can be modified to take into consideration a logistic cost function (Nordbeck and Rystedt, 1972, p. 39):

$$\text{COST}(D) = A + C \cdot \text{sign}(D-E) \cdot (\text{abs}(D-E))^B + CE^B \qquad 7.6$$

where E is the value lying at the centre of the interval in which the largest increase occurs.

sign (D-E) is simply the sign of the difference between D and E.

abs (D-E) is the absolute value of the difference between D and E.

A, B, C and D are as for equation 7.3.

Nordbeck and Rystedt used both a linear and a logistic cost function to locate seven facilities in southern Sweden and found little difference between the results of the two analyses. Ideally, it would be desirable to use logistic cost functions if these really related increase in response distance to increase in damage caused. However, in practice, a large number of different functions would have to be estimated for different types of fires and alarms and different building structures. Consequently, until data is available to calibrate these functions comfort can be drawn from Nordbeck and Rystedt's conclusion that the location-allocation gives a stable solution regardless of whether a logistic or linear cost function is used.

Sensitivity of the Location-Allocation Model to Changes in the Focal Point Weights

In the analysis described in Chapter 6 three types of weights were investigated. These were, respectively, all the 1973 alarms, the 1973 alarms minus the false alarms, and the 1973 emergency alarms. Certain instabilities in the model were noted due to the fact that many of the alarms in the central-western portion of the city were non-emergency alarms. This meant that when only emergency alarms were used as the weights Fire Station 6's present location became considerably less attractive. Thus this location-allocation model appears to be relatively unstable when different types of alarms are used as weights.

The model's stability regarding changes in the weights which could occur through time might also be questioned. Nordbeck and Rystedt (1972, pp. 248-261) investigated the stability of location-allocation models for the whole of Sweden using the 1855, 1917 and 1965 populations. They found that only where they sought to locate a large number of facilities (23 facilities were located in one example) and only where there were local minima close to the global minimum did the solution become unstable. However, it must also be noted that most of the population changes between 1855 and 1965 in Sweden occurred within regions rather than between regions and as a result the correlation between the 1855 and 1917 population map was 0.85, between the 1917 and 1965 map it was 0.90 and between 1855 and 1965 it was still 0.68. Within region changes which are characterised by high correlation coefficients such as these are unlikely to affect the solution of a location-allocation model.

It should be noted, though, that even with a correlation of 0.68 there is still a high degree of uncertainty regarding the precise distribution of the 1965 population. This uncertainty is given as the square root of $1-r^2$ which in this case is .75. This means that a researcher is still 75% as uncertain about the 1965 population after knowing the 1855 population as he would be with no knowledge at all.

The changes in the alarm demand surface for London, Ontario, are likely to involve both the within region type which does not promote model instability and the between region type which may lead to an unstable solution. If each of the 150 polygons described in Chapter 5 is considered to represent a region then the within-region changes may occur due to a general upward trend in the number of alarms occurring each year. The total annual number of alarms for the period 1972-1975 has shown such an upward trend: 1972 - 2,095 alarms; 1973 - 2,459 alarms; 1974 - 2,733 alarms; 1975 - 2,792 alarms. The between-region changes in number of alarms could occur due to major urban renewal projects which have recently been completed in London's downtown core. Although the large buildings which have been built represent larger hazards they will, in all likelihood, generate far fewer demands for fire department service than the old restaurants and hotels which preceded them. New subdivisions, new apartment buildings and any annexation to the city will also create new demands for fire department service where none previously existed. However, until an accurate explanatory regression model of the type described in Chapter 4 can be built, the likely effect of these changes on the demand pattern cannot be predicted and, until the changing demand pattern is predicted, the effects of these changes on solution stability cannot be investigated.

Sensitivity of the Location-Allocation Model to the Use of a Continuous as Opposed to a Discrete Space Formulation

Nordbeck and Rystedt (1972) also discussed whether the continuous space formulation was necessarily inferior to the more accurate discrete space formulation of the location-allocation model. This is an important topic because discrete space models require far more information and are thus more costly to set up. They are also more costly to solve in terms of computer time and, generally, discrete space programs cannot solve such large problems as continuous space programs (for a discussion of the limits of a continuous space and a discrete space program see Goodchild 1973, and Rushton and Kohler, 1973, respectively). Nordbeck and Rystedt use a continuous space program, NORLOC, to locate five high schools in Lund, Sweden. The problem is then re-solved using the actual main road distances in the city. The suggested optimum locations for the schools are very similar in both solutions. Nordbeck and Rystedt (1972, pp. 246-247) conclude their analysis with the following comment:

> If all five schools are taken together it is impossible to say which of the two sets of locations is best. The difference between them is unimportant and the two sets of locations can for practical purposes be treated as one. The use of distance measured via a road network does not give any clear advantage over the use of straight line distance. Against this must be set the fact that use of distance measured via a network incurs computer processing costs 10 to 15 times greater than those incurred when straight line distances are used. Further costs are also incurred in preparing the description of the road network and its transfer to computer readable form. The increased costs for the use of the more complicated model are not compensated for by increased precision in the results obtained.

Obviously, the discrete space approach is going to realise its greatest advantage when there are significant barriers to travel within the study area. Nordbeck and Rystedt do not mention the existence of any barriers to movement in their study area and none is shown on the map of the main roads in Lund which they provide. The discrete space approach is also more realistic for the fire station problem where the trucks always follow certain main routes to the general location of the alarm. Finally, it should be noted that the fire trucks are far less manoeuverable than many smaller vehicles and thus the continuous space model becomes even less appropriate.

In order to determine whether there was any significant difference between the two formulations of the model in the present study a continuous space model was used to determine the optimum locations for nine fire stations in London. The demand surface was formulated using all the 1973 alarms and the problem was solved using the continuous space location-allocation program LAP (Goodchild, 1973). The program produced nine sets of coordinates for the suggested locations of the nine fire stations. In order to compare this solution with that obtained using the ALLOC5 program the nine stations were each moved to their nearest focal point (which involved only very minor adjustments) and then the solution was evaluated using the ALLOC5 program. The results are shown in Table 7.4 and the pattern of locations and allocations are shown in Figure 7.1 (this may be compared to Figure 6.5 which shows the pattern of locations and allocations which was obtained using the ALLOC5 program). Although there appears to be little difference between the two solutions (two locations are the same and at least two more are very close) when the solutions are evaluated the ALLOC5 results are shown to be more than 14 percent lower than the "cost" of the present locations while the LAP solution saves less than 8 percent.

Thus substantial savings are achieved by using the more detailed

TABLE 7.4: Suggested Optimum Locations for Nine Fire Stations using a Continuous Space Program (LAP) and all the 1973 Alarms as the Demand Surface

Fire Station Number	1	2	3	4	5	6	7	8	9
Original Location	84	88	95	30	111	47	45	8	145
Final Location (LAP)	84	117	80	30	111	48	45	13	146
Final Location (ALLOC5)	83	116	98	16	86	47	36	13	146

Original Total Weighted Distance is 264493 weighted units*

Final Total Weighted Distance (LAP) is 243875 weighted units

Final Total Weighted Distance (ALLOC5) is 225743 weighted units

Percent Decrease in Total Weighted Distance (LAP) is 7.80%

Percent Decrease in Total Weighted Distance (ALLOC5) is 14.65%

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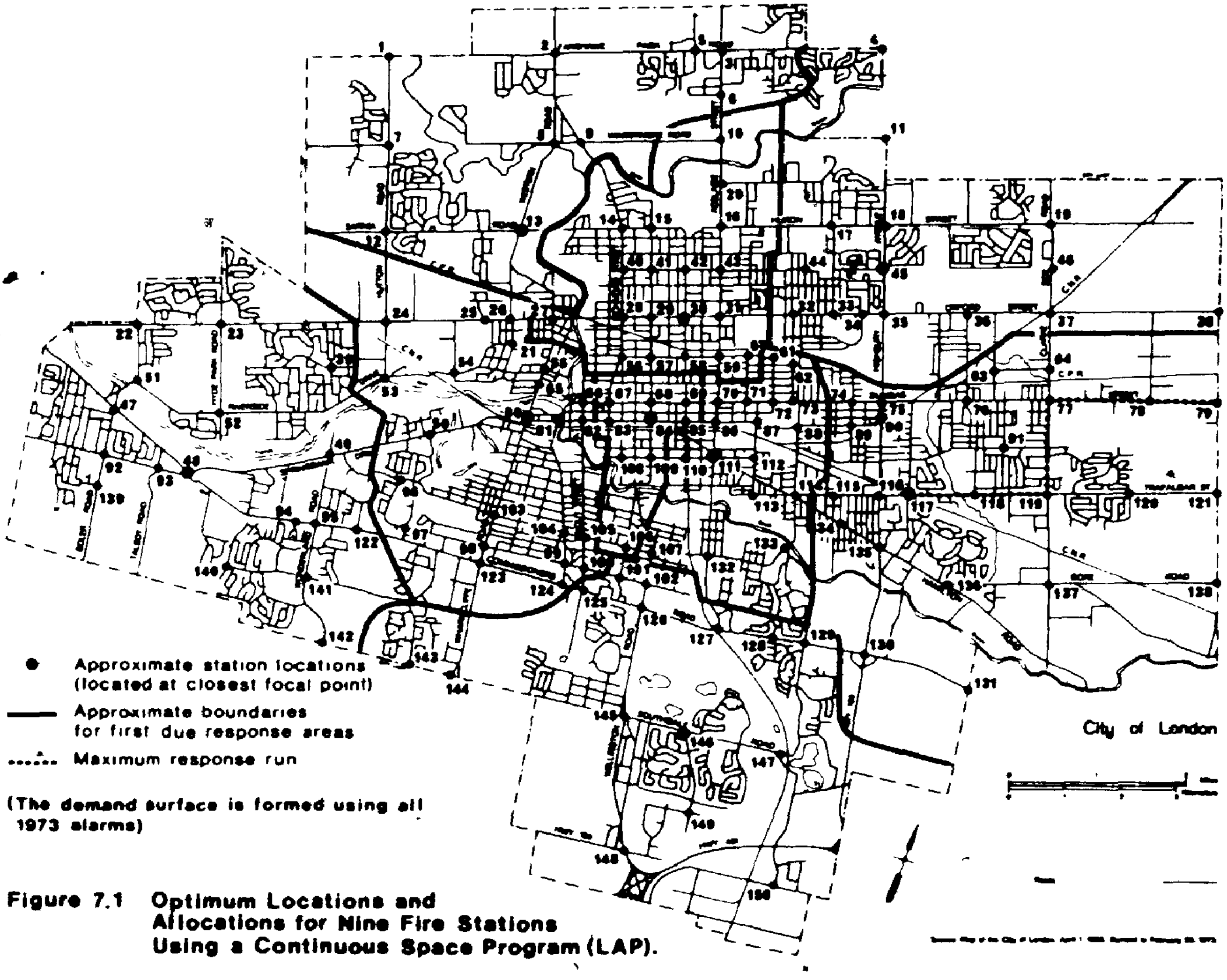
*units are 50 feet



(The demand surface is formed using all 1973 alarms)

Figure 7.1 Optimum Locations and Allocations for Nine Fire Stations Using a Continuous Space Program (LAP).

model and this contradicts Nordbeck and Rystedt's findings. However, only in the case of Fire Station 6 is it obvious that a physical feature (the River Thames) has acted as a real barrier to fire station location. Thus in the ALLOC5 solution Fire Station 6 is located much closer to the bridge than in the LAP solution. Consequently, it must be conceded that the judicious use of barriers in the LAP model may have improved the LAP solution.

An Examination of the Efficiency of Alternative, Non-Optimal Solutions to the Location-Allocation Model

In this section a series of non-optimal solutions to the problem of locating nine fire stations to serve the demand surface formulated by using all the 1973 alarms is investigated. These non-optimal solutions include a series of random solutions, a series of solutions suggested by a class of university geography students and finally a series of solutions in which one node is located sub-optimally.

The Efficiency of Random Solutions to the Location-Allocation Model

In order to determine the efficiency of random solutions to the location-allocation problem a series of sets of random numbers were used to locate the nine fire stations. These solutions were then evaluated using the ALLOC5 program. The ALLOC5 program obtained an optimal allocation of the 150 demand points to these random locations and then evaluated the "Total Weighted Distance" and the longest run for each solution. Twenty random solutions were examined in this manner and the results are shown in Table 7.5. These solutions range from a high of being 102% more expensive than the optimal total weighted distance in the case of solution two to a low of being only 23% more expensive in the case of solution 19. Solutions 2 and 19 also have the longest and

TABLE 7.5: A Comparison of Twenty Random Solutions to the Optimal Solution for the Location of Nine Fire Stations Using all the 1973 Alarms as the Demand Surface

The total weighted distance for each solution and the longest run are expressed as a percentage of the optimal solution obtained without distance constraints

	Total Weighted Distance as Percentage of Optimal	Longest Run as Percentage of Optimal
Solution 1	138	111
Solution 2	202	181
Solution 3	159	132
Solution 4	156	164
Solution 5	172	148
Solution 6	156	148
Solution 7	141	133
Solution 8	166	143
Solution 9	139	128
Solution 10	161	145
Solution 11	132	132
Solution 12	156	132
Solution 13	144	144
Solution 14	151	133
Solution 15	136	129
Solution 16	148	148
Solution 17	134	130
Solution 18	129	131
Solution 19	123	107
Solution 20	135	132

shortest maximum runs which are 81% and 7% more expensive, respectively. This analysis shows that it is, in fact, quite unlikely that a random solution will be much more than 100% more expensive than the optimal solution obtained without distance constraints and this is because the distribution of focal points makes it improbable that a random solution will be produced in which all the fire stations are clustered together in a small spatial area. Thus the geometry of the city and of the focal points precludes such a poor result for these random solutions. This analysis is also useful as a standard for comparing the success of the intuitive solutions which are discussed in the next section.

The Efficiency of Intuitive Solutions to the Location-Allocation Model

Schneider (1971, p. 99) has made the following statement with respect to the results of an experiment which he carried out with a class of seventeen graduate urban planning students:

> The results of this experiment show that a relatively inexperienced, but intelligent, person can rather quickly solve a fairly simple location problem nearly as well as one of the better computer techniques now available. However, we cannot conclude from this simple experiment that this will also be true for larger, more complex, and more realistic problems. Although the amount of computer time required will increase non-linearly with the size of the problem, the amount of an analyst's time would probably increase even faster as larger problems are posed.

Schneider's experiment consisted of asking his class of urban planning students to locate five ambulance dispatch centres in a hypothetical city. The city was square and was served by a square grid of residential streets on which the average travel speed was twenty miles per hour. An irregular arterial street system was superimposed over this and on these streets the average speed was forty miles per hour. The junctions of the streets formed the 77 possible locations for the dispatch centres. The students were also provided with information on the distribution of accidents which represented the demand surface for which the ambulances were to provide service. The objective function was to minimize total travel time subject to the constraint that no ambulance trip would be longer than ten minutes. The students were required to determine both the best locations of the ambulances and also the best allocations of their services to the accident distribution.

The computer was then used to generate 10,000 sets of five random numbers each of which was evaluated as a possible solution to the problem. These 10,000 solutions, however, represent only a 0.05 percent sample of the 19,757,815 possible solutions to the problem. The best of the evaluated computer solutions had a total travel time of 24,869 minutes and a longest trip of 7.3 while the best student solution had a total travel time of 24,881 minutes and a longest trip of 9.0 minutes. When the student solution was modified to produce an optimal allocation the total travel time dropped to 24,581 minutes which was better than the best computer solution. However, whether one of the more than 19½ million remaining solutions is still better cannot be determined.

Finally, it is worthwhile noting that the cost of evaluating the solution was about $40.00 and took about 8.5 minutes on a CDC 6400 computer.

It is now possible to compare Schneider's experiment with a similar study which was undertaken for the present research problem. In this experiment a class of 48 university geography students were asked to locate nine fire stations in the City of London, Ontario. They were provided with a map of the city (which they were not familiar with) and a three dimensional block diagram of the 1973 all alarm demand surface (Figure 3.5). They were not required to determine the response districts for their stations which were, in fact, resolved using the ALLOC5 program. The results of this analysis are shown in Table 7.6. In terms of total weighted distance the best solution is only 8% more expensive than the optimal solution which was solved without distance constraints. The students were not questioned about their rationale for choosing their set of locations (in his study Schneider did conduct such an inquiry) but it appears that they may have been more concerned about achieving a more equitable distribution. Thus solution number 31 achieved a very low value for its longest run. It was actually, fractionally shorter than that achieved by the unconstrained optimal solution. However, the total weighted distance for this solution was more than 9% higher than that achieved by the unconstrained optimal solution. It should also be pointed out that when a distance constraint of 350 was placed on the model the total weighted distance of the optimal computer solution increased less than 0.1% but the longest run was decreased by over 11%. The results of using various other distance constraints on the model were reported in Chapter 6.

When these results are compared to those reached by Schneider (1971) a number of conclusions may be drawn. Firstly, it would appear that he did not avail himself of "one of the better computer techniques now available". Simply, evaluating a sample of random solutions is a crude and expensive methodology for approximating the optimal solution. Obtaining the optimum solutions for 9 centres and 150 focal points usually required less than 50 seconds on a CDC Cyber 73 and the cost of these solutions was less than $4.00. It is interesting to note that the number of possible solutions to this problem is more than six orders

TABLE 7.6: A Comparison of 48 Intuitive Solutions to the Optimal Solution for the Location of Nine Fire Stations Using all the 1973 Alarms as the Demand Surface

The total weighted distance for each solution and the longest run are expressed as a percentage of the optimal solution.

	Total Weighted Distance As Percentage of Optimal	Longest Run As Percentage of Optimal
Solution 1	144	153
Solution 2	129	132
Solution 3	112	109
Solution 4	117	121
Solution 5	114	104
Solution 6	129	107
Solution 7	113	119
Solution 8	111	106
Solution 9	122	106
Solution 10	112	109
Solution 11	120	119
Solution 12	113	130
Solution 13	129	130
Solution 14	129	121
Solution 15	113	107
Solution 16	111	106
Solution 17	149	132
Solution 18	126	139
Solution 19	119	127
Solution 20	116	125

cont'd

TABLE 7.6 cont'd

	Total Weighted Distance as Percentage of Optimal	Longest Run As Percentage of Optimal
Solution 21	108	106
Solution 22	121	113
Solution 23	127	129
Solution 24	122	128
Solution 25	119	114
Solution 26	130	148
Solution 27	119	120
Solution 28	122	110
Solution 29	129	125
Solution 30	123	113
Solution 31	109	100
Solution 32	126	113
Solution 33	117	106
Solution 34	121	104
Solution 35	120	102
Solution 36	111	106
Solution 37	125	134
Solution 38	116	109
Solution 39	138	153
Solution 40	118	125
Solution 41	114	101
Solution 42	120	137

cont'd

TABLE 7.6 cont'd

	Total Weighted Distance As Percentage of Optimal	Longest Run As Percentage of Optimal
Solution 43	134	126
Solution 44	117	106
Solution 45	114	112
Solution 46	116	118
Solution 47	121	115
Solution 48	114	106

of magnitude greater than in Schneider's problem.

Secondly, it should be pointed out that a "good" solution is not good enough when the problem involves emergency facility location. The cost of obtaining the best solution seems insignificant when it is compared to the cost of operating with the second best solution or just a good solution. Indeed one of the main aims of this thesis is to develop methodology which will give fire departments the ability to obtain the best solution (for a given objective function) quickly and cheaply.

Finally, this computer assisted methodology is preferable to an intuitive methodology because it allows the Fire Chief to determine a unique solution (again for a given objective function) using an explicit and rational methodology. Such a solution should be far more acceptable and less equivocal to the city government and interested citizen groups.

The Sensitivity of the Optimal Solution to a Single Incorrectly Located Station

In this section the sensitivity of the model to one incorrectly located station is investigated. This investigation involved using the optimal solution (without distance constraints) for the set of nine fire stations. One of these nine optimal locations was focal point 13. The analysis consisted of moving the station at focal point 13 to adjacent focal points and then re-evaluating the cost of the new solution using an optimal allocation of focal points to the new set of locations. This analysis was carried out simply to determine the change in total weighted distance which would occur if one station was located incorrectly. No analysis was made of the change in the longest run since this was not relevant to this particular investigation and would have confused the issue.

Table 7.7 shows what happens when the station which was located at focal point 13 is moved to one of the surrounding focal points while the other stations are held at what were their optimal locations. The response districts are, however, rearranged so that the focal points are allocated optimally for the new solution. The station is re-located, in turn, at those focal points which lie closest to the old station. The distance figures in Table 7.7 were converted to tenths of a mile by multiplying the distances by 50 and dividing the result by 528. These new distances were then regressed against the increase in cost using the SPSS program SCATTERGRAM. The results are shown in Figure 7.2. The correlation coefficient for this relationship was +0.920 and the regression equation is shown below:

$$Y = 99.065 + 0.344\ (X) \tag{7.7}$$

where Y is the total weighted distance as a percentage of the optimal

X is the distance in tenths of a mile from focal point 13.

The regression states that for each mile of error in locating the fire station which should be located at focal point 13 the objective function will increase by a little more than 3.4%. However, since the intercept of the regression line with the Y axis is only just over 99%, and not 100%, the objective function would only increase by about 2.5% for the first mile of error. The regression analysis was repeated for two subsets of the original data. The first subset represented the situation where the station was re-located at one of the 'inner' seven focal points. These were focal points closer to the centre of the city than focal point 13 and included focal points 21, 25, 26, 27, 54, 55, and 65. This regression produced a correlation coefficient of +0.987 and the following regression equation:

TABLE 7.7: Evaluation of Incorrectly Locating a Single Fire Station in a Set of Nine Fire Stations

In this analysis the demand surface comprised all the 1973 alarms. The optimal solution involved no distance constraints.

Station at Focal Point 13 Relocated at:	New Total Weighted Distance as Percentage of Optimal	Distance to Focal Point 13 of New Station
1	108.41	289*
2	106.09	175
5	110.15	302
7	105.90	203
8	103,42	88
9	104.39	112
12	103.20	120
21	102.16	111
24	104.00	200
25	101.36	111
26	100.86	88
27	102.33	125
39	107.88	291
53	106.46	247
54	104.93	184
55	104.89	173
65	105.48	184

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*units are 50 feet

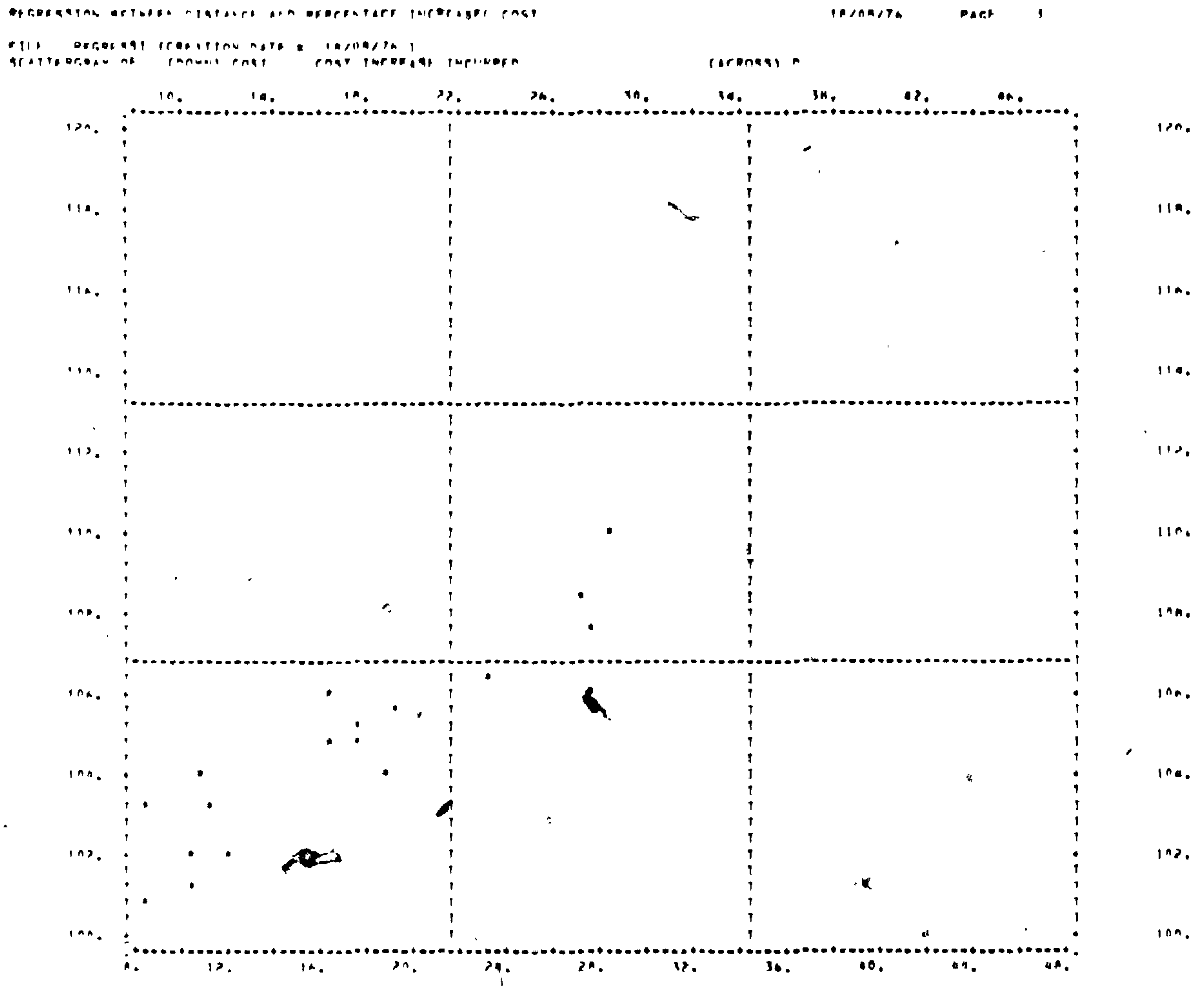

Figure 7.2 Regression Analysis for the Data Shown in Table 7.7 (see also Equation 7.7 on the text)

$$Y = 96.584 + 0.497 (X) \qquad 7.8$$

where the terms are as above.

The second subset contained the 'outer' ten focal points and these were those points lying closer to the periphery of the city than focal point 13 and included focal points 1, 2, 5, 7, 8, 9, 12, 24, 39, and 53. This regression produced a correlation coefficient of +0.905 and the following equation:

$$Y = 100.629 + .279 (X) \qquad 7.9$$

where the terms are as before.

These regressions suggest that a small deviation from the optimal location towards the periphery of the city is less costly than a small deviation towards the centre of the city. Conversely, a large deviation towards the core of the city is less costly than a large deviation towards the periphery. These results are shown in Table 7.8.

This analysis provides the researcher with some idea of how costly it would be to locate incorrectly the station which should be at focal point 13. It appears also that the precise nature of the mistake is important. Thus the cost changes depend upon the direction of the mistake - i.e. whether it is towards the city core or towards the periphery. It is reasonable to suppose that the cost would also change if another station in a different part of the city was analysed. Presumably, it is more important to locate a station accurately in a high demand area than in a low demand area. However, a detailed analysis of this aspect will have to be left to future research. Similarly, the effects of incorrectly locating two or more stations at the same time will have to be left to later studies. It is reasonable to speculate that these effects will be complex since the costs of two or more

TABLE 7.8: Increase in Total Weighted Distance Expressed as Percentage of Optimal for Deviations from the Optimal Location at Focal Point 13

Number of Miles of Deviation	Deviations Toward Periphery	Deviations Toward City Centre
0	96.584	100.629
1	101.553	103.422
2	106.521	106.215
3	111.489	109.008

incorrect decisions may compound each other or may, possibly, cancel each other out.

Finally, it must be mentioned that the sensitivity analysis described above portrayed the increase in the cost of the solution as a percentage of the <u>total</u> cost of the model. It is just as realistic, though, to portray the increase in cost as a percentage of the total weighted distance for focal point 13's former response district. If this is done for the situation when the fire station is located at focal point 1 then the cost of providing service to this region increases to 39064 weighted units when formerly it was only 20083 weighted units. The new figure is 194.51% of the old. This new expression of the cost represents the actual cost to the <u>local</u> community of a poor location and this emphasizes the need for a rational locational methodology as opposed to Schneider's informed guesses.

Conclusion

The purpose of this chapter was two-fold. Firstly, it sought to show that the assumptions of the methodology presented in this thesis do not represent a serious impediment to the practical application of the model. The main weakness was shown to lie in the size of the sample of emergency alarms.

Secondly, the chapter emphasized the advantages of the computer assisted methodology over the significantly less precise, intuitive methodology described by Schneider.

CHAPTER 8

Conclusions and Suggestions for Further Research

Introduction

In this final chapter the main contributions of the present research are summarized. A subsequent section discusses a series of suggestions for 'follow-up' studies in London, Ontario, and a number of recommendations for the London Fire Department which would help expedite such studies. Finally, there is a short discussion of several aspects of the fire station location problem which warrant further research.

Major Contributions of the Present Research

The investigations of the temporal and spatial distribution of the alarms represent significant contributions. In Chapter 3 the temporal distribution of alarms in London was shown to exhibit a daily cycle and was also found to have a remarkably similar pattern to the temporal distribution of alarms in two American cities, New York and Tacoma. Such daily cycles were shown to be important in cities with high alarm rates where an adaptive response policy might be instituted during the busiest portions of the day when resources were overworked.

The study of the spatial distribution of alarms in London, also discussed in Chapter 3, is perhaps more interesting because this aspect of the research has been ignored by other workers. The predictive model, which used a distance decay function, was very successful in accounting for the variation in the spatial distribution of alarms. This model obviously warrants further testing. It should be used to predict the spatial distribution of alarms for different time periods for London and also for different cities. Should the model prove to yield the same high levels of explanation for these different situations changes in the parameters of the model will yield interesting insights into the differences between the various surfaces.

The analysis of response times also showed temporal and spatial variations but these results like the results from other research were not conclusive. However, since most firemen feel intuitively that these variations do exist, this area will warrant further research. This is especially so if fire departments are going to be able to justify expenditures on 'Opticom' systems for changing traffic lights (mentioned in Chapter 3). The cost of fitting these devices to the traffic lights at just over 150 intersections in London and to all the city's fire trucks is expected to be just over $400,000.

The typology of location-allocation models described in Chapter 5 was also felt to be an important contribution. This typology emphasizes the wide applicability of the location-allocation model to many problems which are currently being studied in geography. The typology also helps to highlight those aspects of the present study which may prove useful for applying location-allocation models in other sectors of the space-economy.

In Chapter 6 a series of location-allocation problems were solved for the City of London. These are problems which the Fire Department is currently facing. A critic might feel that these studies did no more than confirm the suspicions of the Fire Chief, Ray Morley. However, it is the opinion of the author that this in itself was no mean achievement for the Fire Chief has a detailed comprehension of the intricate nature of the problem which he has gained from years of experience. Studies such as this can provide the executive officers of city fire departments with the quantitative evidence to justify their intuitive solutions of the problem. In addition, there is always the possibility that a location-allocation study will reveal some aspect of the problem which had previously been overlooked.

Suggestions for 'Follow-up' Studies in London, Ontario and Recommendations for the Fire Department which would aid the Execution of Such Studies

It is perhaps most useful to begin with the recommendations which would aid future studies of this type to be undertaken. Ideally, a city fire department should carry out a study of this type annually. Now that the methodology is established the only impediment to the realization of this objective is the tedious data collection which would be necessary and which was described, at length, in Chapter 2. It is here suggested that all the data collected for this study and described in Chapter 2 (and any data which subsequent studies deem to be useful) should be recorded on machine readable forms as the alarms occur during the year. At the end of the year the data can be rapidly read into the computer and the analysis proceeded with. Most of the data is already collected by the Fire Department and recorded on non-machine readable forms and thus the cost of developing the new data collection system would amount to little more than the design of the new form and their purchase. One piece of information which is not already collected but which is essential to such studies is the location of each alarm in terms of some coordinate system. Recording this immediately after each alarm occurs would require very little effort. The census tract and enumeration area in which each alarm occurred could also be recorded at the time of the alarm or could be obtained later through the use of a 'point in polygon' routine.

Such procedures as these would allow a series of follow-up studies which could determine if there were any significant between-region changes in the alarm demand surface over the years. It would also allow a larger data set of emergency alarms to be built up. As was noted in Chapter 6 the poisson deviate surfaces based on the emergency alarms did not produce very stable solutions and so this would prove a useful subsequent study.

The analysis should also be repeated in order to locate different types of fire-fighting apparatus. Thus once the locations of the stations have been determined the model might be re-run in order to determine which stations should receive the aerial fire-fighting units. The demand surface for this analysis, using the methodology described in the present research, might be comprised of all those recent alarms which required the services of an aerial unit.

Follow-up studies in London, Ontario, might also concern themselves with the location of an eleventh fire station. Such a station will be required by the early 1980s and planning for its location should begin immediately.

Finally, two slightly different studies might also be carried out in London. Firstly, a simulation model (patterned after the Rand Institute's model - see references in Chapter 6) might be used to generate data and allocate fire fighting equipment to the simulated alarms. This would demonstrate the degree to which the static models which are described in Chapter 6 were relevant. The appropriateness of the static models can be judged by the number of times the nearest fire fighting unit is not available to serve one of the simulated alarms.

Secondly, as was suggested in Chapter 2, a cluster or factorial analysis might be carried out on a series of measures of an alarm's importance. These measures might include estimated damage in dollars, number of lives lost, number of stations answering, number of fire-fighters involved, total length of time spent at the scene of the alarm and, lastly, the number of fire-fighters multiplied by the total length of time. The cluster or factorial analysis would reveal how much interdependence there was between these variables. Thus it could be established which variables were yielding duplicate and therefore redundant information and which were providing additional information concerning the alarm's importance.

Aspects of the Fire Station Location Problem which Warrant Further Research

Without doubt one of the most disappointing aspects of the present study was the failure of the multiple regression model described in Chapter 4. Despite the drawbacks of the methodology of regression analysis, which were previously mentioned, this would appear to be, potentially, the most accurate method of predicting alarm occurrence. Furthermore, with the institution of far more detailed building codes in Ontario in the near future the accuracy of such models might be greatly increased. Model construction would also be facilitated if the insurance companies would release their data on building characteristics and past fire incidences. It is unfortunate that such information is so jealously guarded since the release of this type of data would prove very useful in the tactical and strategic planning of fire department activities and the reduction of risk to property and life.

The sensitivity analysis discussed in Chapter 7 is also only a beginning. More detailed work is required on the problem of grid size and whether it is worth building ever larger ALLOC-type models. For larger Canadian cities such as Toronto and Montreal this may indeed be necessary. The relative merits of discrete and continuous space formulations of the model must also be looked at in more detail. For example, it should be determined how a continuous space model which has a <u>larger</u> number of demand points <u>and</u> also incorporates barriers will fare against a discrete space model which has fewer demand points.

The effects of incorrectly locating one station in various parts of the city should be more fully researched - as should the effects of incorrectly locating two, three and more stations.

Additional research, both at the empirical and at the analytical level, needs to be carried out on the effects of combining the p-median and the p-centre problems. Halpern's 'cent-dian' (mentioned in Chapter 2) is obviously a point worth looking for. This is especially true when it is realised that in London the length of the maximum run for the solution to the problem of locating nine stations optimally can be greatly reduced by imposing a mild distance constraint <u>without</u> affecting the total weighted distance by more than the smallest amount (this was mentioned in Chapter 7). This also relates to Barr and Smillie's (1972) point that a slightly sub-optimal solution may have other characteristics which make it eminently more desirable. Moreover, this raises the question of whether first due response time is the most desirable objective. Chief Jackson of the Calgary Fire Department (as mentioned in Chapter 2) feels that it may be more important to get an unspecified number of men to the scene of a fire within a certain time. Thus he feels that it is better to get an <u>effective</u> fire-fighting force to the scene of the fire a little more slowly than to get an <u>ineffective</u> force there as quickly as possible. Determining just what is an effective force is one of the goals of a study presently being carried out in Calgary by the author and Halpern. It should also be pointed out that if it is assumed that first due response time is the only important objective then there would be little need for two and three bay stations. Since most Fire Chiefs would agree there was a need for such stations it can be safely assumed that the objective function isolated in this study is not the only one which should be considered in future research. Such future research must consider the relative merits of alternative objective functions. It should also investigate the relative merits of the methodologies advocated by PTI, DUO, NYCRI (all of which were described in Chapter 2) <u>and</u> the methodology described in this research. In all likelihood they will probably be found to be complementary rather than competitive.

APPENDIX 1

This appendix presents the results of a crosstabulation of the number of alarms occurring in each of the four six hour time periods defined in the text by the number occurring in each of the 51 census tracts in the City of London.

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                                                                                          13/07/76      PAGE    2
FILE    FIRES    (CREATION DATE =  05/07/76 )

* * * * * * * * * * * * * * * * * * * *   C R O S S T A B U L A T I O N   O F   * * * * * * * * * * * * * * * * * * * * *
    P                                                       BY  CTNO       CENSUS TRACT NUMBER
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                 CTNO
        COUNT   I
        ROW PCT I                                                                                              ROW
        COL PCT I                                                                                              TOTAL
        TOT PCT I      1.I      2.I      3.I      4.I      5.I      6.I      7.I      8.I      9.I     10.I
        --------I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
            1.  I    16  I     1  I     2  I     1  I     6  I     5  I     5  I     2  I     3  I     5  I     335
                I   4.8  I    .3  I    .6  I    .3  I   1.8  I   1.5  I   1.5  I    .6  I    .9  I   1.5  I    13.7
                I  22.9  I   2.9  I  11.8  I   2.9  I  15.0  I   8.3  I   7.7  I   8.0  I  10.0  I  11.9  I
                I    .7  I    .0  I    .1  I    .0  I    .2  I    .2  I    .2  I    .1  I    .1  I    .2  I
               -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
            2.  I    11  I     7  I     3  I     8  I     4  I     6  I    10  I     2  I     3  I     7  I     420
                I   2.6  I   1.7  I    .7  I   1.9  I   1.0  I   1.4  I   2.4  I    .5  I    .7  I   1.7  I    17.2
                I  15.7  I  20.0  I  17.6  I  23.5  I  10.0  I  10.0  I  15.4  I   8.0  I  10.0  I  16.7  I
                I    .5  I    .3  I    .1  I    .3  I    .2  I    .2  I    .4  I    .1  I    .1  I    .3  I
               -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
            3.  I    20  I    18  I     3  I    15  I    16  I    24  I    19  I    12  I    14  I    11  I     857
               -I   2.3  I   2.1  I    .4  I   1.8  I   1.9  I   2.8  I   2.2  I   1.4  I   1.6  I   1.3  I    35.1
                I  28.6  I  51.4  I  17.6  I  44.1  I  40.0  I  40.0  I  29.2  I  48.0  I  46.7  I  26.2  I
                I    .8  I    .7  I    .1  I    .6  I    .7  I   1.0  I    .8  I    .5  I    .6  I    .5  I
               -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
            4.  I    23  I     9  I     9  I    10  I    14  I    25  I    31  I     9  I    10  I    19  I     832
                I   2.8  I   1.1  I   1.1  I   1.2  I   1.7  I   3.0  I   3.7  I   1.1  I   1.2  I   2.3  I    34.0
               .I  32.9  I  25.7  I  52.9  I  29.4  I  35.0  I  41.7 9I  47.7  I  36.0  I  33.3  I  45.2  I
                I    .9  I    .4  I    .4  I    .4  I    .6  I   1.0  I   1.3  I    .4  I    .4  I    .8  I
               -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
        COLUMN       70       35       17       34       40       60       65       25       30       42      2444
         TOTAL      2.9      1.4       .7      1.4      1.6      2.5      2.7      1.0      1.2      1.7     100.0
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                                                                                                    13/07/76       PAGE    3
FILE  FIRES    (CREATION DATE =  05/07/76 )

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   P                                                                   BY  CTNO       CENSUS TRACT NUMBER
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               CTNO
    COUNT   I
    ROW PCT I                                                                                                          ROW
    COL PCT I                                                                                                          TOTAL
    TOT PCT I      11.I      12.I      13.I      14.I      15.I      16.I      17.I      18.I      19.I      20.I
    --------I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          1.  I       5  I       3  I       1  I       9  I       1  I       5  I       2  I       6  I       2  I       4  I     335
              I     1.5  I      .9  I      .3  I     2.7  I      .3  I     1.5  I      .6  I     1.8  I      .6  I     1.2  I    13.7
              I    15.6  I    14.3  I     2.1  I    25.0  I    11.1  I    27.8  I     5.4  I     8.1  I     8.3  I     8.9  I
              I      .2  I      .1  I      .0  I      .4  I      .0  I      .2  I      .1  I      .2  I      .1  I      .2  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          2.  I       3  I       7  I      11  I       7  I       0  I       1  I       7  I      10  I       3  I       9  I     420
              I      .7  I     1.7  I     2.6  I     1.7  I       0  I      .2  I     1.7  I     2.4  I      .7  I     2.1  I    17.2
              I     9.4  I    33.3  I    22.9  I    19.4  I       0  I     5.6  I    18.9  I    13.5  I    12.5  I    20.0  I
              I      .1  I      .3  I      .5  I      .3  I       0  I      .0  I      .3  I      .4  I      .1  I      .4  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          3.  I      11  I       8  I      18  I      10  I       3  I       6  I      16  I      25  I      14  I      17  I     857
              I     1.3  I      .9  I     2.1  I     1.2  I      .4  I      .7  I     1.9  I     2.9  I     1.6  I     2.0  I    35.1
              I    34.4  I    38.1  I    37.5  I    27.8  I    33.3  I    33.3  I    43.2  I    33.8  I    58.3  I    37.8  I
              I      .5  I      .3  I      .7  I      .4  I      .1  I      .2  I      .7  I     1.0  I      .6  I      .7  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          4.  I      13  I       3  I      18  I      10  I       5  I       6  I      12  I      33  I       5  I      15  I     832
              I     1.6  I      .4  I     2.2  I     1.2  I      .6  I      .7  I     1.4  I     4.0  I      .6  I     1.8  I    34.0
              I    40.6  I    14.3  I    37.5  I    27.8  I    55.6  I    33.3  I    32.4  I    44.6  I    20.8  I    33.3  I
              I      .5  I      .1  I      .7  I      .4  I      .2  I      .2  I      .5  I     1.4  I      .2  I      .6  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
       COLUMN        32         21         48         36          9         18         37         74         24         45      2444
        TOTAL       1.3         .9        2.0        1.5         .4         .7        1.5        3.0        1.0        1.8     100.0
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             I   18.3  I   19.3  I   23.1  I    5.1  I   23.7  I   15.3  I   18.5  I      0  I      0  I   14.3  I
             I     .5  I    1.9  I     .6  I     .2  I     .6  I     .4  I     .6  I      0  I      0  I     .2  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          2. I      6  I     51  I      8  I     16  I     11  I     11  I      9  I      2  I      4  I      8  I     420
             I    1.4  I   12.1  I    1.9  I    3.8  I    2.6  I    2.6  I    2.1  I     .5  I    1.0  I    1.9  I    17.2
             I    8.5  I   21.4  I   12.3  I   20.5  I   18.6  I   18.6  I   11.1  I    8.3  I   22.2  I   19.0  I
             I     .2  I    2.1  I     .3  I     .7  I     .5  I     .5  I     .4  I     .1  I     .2  I     .3  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          3. I     25  I     70  I     23  I     28  I     18  I     23  I     36  I     13  I      7  I      9  I     857
             I    2.9  I    8.2  I    2.7  I    3.3  I    2.1  I    2.7  I    4.2  I    1.5  I     .8  I    1.1  I    35.1
             I   35.2  I   29.4  I   35.4  I   35.9  I   30.5  I   39.0  I   44.4  I   54.2  I   38.9  I   21.4  I
             I    1.0  I    2.9  I     .9  I    1.1  I     .7  I     .9  I    1.5  I     .5  I     .3  I     .4  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          4. I     27  I     71  I     19  I     30  I     16  I     16  I     21  I      9  I      7  I     19  I     832
             I    3.2  I    8.5  I    2.3  I    3.6  I    1.9  I    1.9  I    2.5  I    1.1  I     .8  I    2.3  I    34.0
             I   38.0  I   29.8  I   29.2  I   38.5  I   27.1  I   27.1  I   25.9  I   37.5  I   38.9  I   45.2  I
             I    1.1  I    2.9  I     .8  I    1.2  I     .7  I     .7  I     .9  I     .4  I     .3  I     .8  I
            -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
      COLUMN        71       238        65        78        59        59        81        24        18        42       2444
       TOTAL       2.9       9.7       2.7       3.2       2.4       2.4       3.3       1.0        .7       1.7      100.0
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              CTNO
     COUNT  I
   ROW PCT  I                                                                                                   ROW
   COL PCT  I                                                                                                   TOTAL
   TOT PCT  I     31.I     32.I     33.I     34.I     35.I     36.I     37.I     38.I     39.I     40.I
  ---------I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
        1.  I      6  I     16  I     15  I     12  I      2  I      5  I      4  I      5  I      5  I      5  I    335
            I    1.8  I    4.8  I    4.5  I    3.6  I     .6  I    1.5  I    1.2  I    1.5  I    1.5  I    1.5  I   13.7
            I    9.0  I   20.5  I   15.8  I   15.2  I   16.7  I    9.3  I   13.8  I    9.8  I   12.5  I   23.8  I
            I     .2  I     .7  I     .6  I     .5  I     .1  I     .2  I     .2  I     .2  I     .2  I     .2  I
           -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
        2.  I     17  I     12  I     21  I     16  I      3  I      8  I      8  I     13  I      8  I      3  I    420
            I    4.0  I    2.9  I    5.0  I    3.8  I     .7  I    1.9  I    1.9  I    3.1  I    1.9  I     .7  I   17.2
            I   25.4  I   15.4  I   22.1  I   20.3  I   25.0  I   14.8  I   27.6  I   25.5  I   20.0  I   14.3  I
            I     .7  I     .5  I     .9  I     .7  I     .1  I     .3  I     .3  I     .5  I     .3  I     .1  I
           -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
        3.  I     26  I     23  I     32  I     24  I      5  I     20  I     10  I     19  I     17  I      6  I    857
            I    3.0  I    2.7  I    3.7  I    2.8  I     .6  I    2.3  I    1.2  I    2.2  I    2.0  I     .7  I   35.1
            I   38.8  I   29.5  I   33.7  I   30.4  I   41.7  I   37.0  I   34.5  I   37.3  I   42.5  I   28.6  I
            I    1.1  I     .9  I    1.3  I    1.0  I     .2  I     .8  I     .4  I     .8  I     .7  I     .2  I
           -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
        4.  I     18  I     27  I     27  I     27  I      2  I     21  I      7  I     14  I     10  I      7  I    832
            I    2.2  I    3.2  I    3.2  I    3.2  I     .2  I    2.5  I     .8  I    1.7  I    1.2  I     .8  I   34.0
            I   26.9  I   34.6  I   28.4  I   34.2  I   16.7  I   38.9  I   24.1  I   27.5  I   25.0  I   33.3  I
            I     .7  I    1.1  I    1.1  I    1.1  I     .1  I     .9  I     .3  I     .6  I     .4  I     .3  I
           -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
     COLUMN        67       78       95       79       12       54       29       51       40       21      2444
      TOTAL       2.7      3.2      3.9      3.2       .5      2.2      1.2      2.1      1.6       .9     100.0
(CONTINUED)
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                                                                                    13/07/76     PAGE    6
FILE   FTMPS    (CREATION DATE = 05/07/76 )

* * * * * * * * * * * * * * * * *  C R O S S T A B U L A T I O N   O F  * * * * * * * * * * * * * * * * *
                                                  BY  CTMO       CENSUS TRACT NUMBER
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * PAGE  5 OF  6

               FTMO
       COUNT  I
     ROW PCT  I                                                                                              ROW
     COL PCT  I                                                                                              TOTAL
     TOT PCT  I    41.I    42.I    43.I    44.I    45.I    46.I    47.I    48.I    49.I    50.I
     ---------I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          1.  I      1 I      5 I      7 I     18 I      3 I      4 I      2 I      9 I      3 I      2 I    335
              I     .3 I    1.5 I    2.1 I    5.4 I     .9 I    1.2 I     .6 I    2.7 I     .9 I     .6 I   13.7
              I    2.8 I   10.9 I   11.9 I   17.1 I   11.1 I   13.3 I    8.7 I   25.0 I    9.1 I   11.8 I
              I     .0 I     .2 I     .3 I     .7 I     .1 I     .2 I     .1 I     .4 I     .1 I     .1 I
             -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          2.  I      7 I      5 I     12 I     15 I      2 I      4 I      6 I      6 I      4 I      4 I    420
              I    1.7 I    1.2 I    2.9 I    3.6 I     .5 I    1.0 I    1.4 I    1.4 I    1.0 I    1.0 I   17.2
              I   19.4 I   10.9 I   20.3 I   14.3 I    7.4 I   13.3 I   26.1 I   16.7 I   12.1 I   23.5 I
              I     .3 I     .2 I     .5 I     .6 I     .1 I     .2 I     .2 I     .2 I     .2 I     .2 I
             -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          3.  I     14 I     17 I     22 I     36 I      9 I      8 I      9 I      6 I     12 I      6 I    857
              I    1.6 I    2.0 I    2.6 I    4.2 I    1.1 I     .9 I    1.1 I     .7 I    1.4 I     .7 I   35.1
              I   38.9 I   37.0 I   37.3 I   34.3 I   33.3 I   26.7 I   39.1 I   16.7 I   36.4 I   35.3 I
              I     .6 I     .7 I     .9 I    1.5 I     .4 I     .3 I     .4 I     .2 I     .5 I     .2 I
             -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
          4.  I     14 I     19 I     18 I     36 I     13 I     14 I      6 I     15 I     14 I      5 I    832
              I    1.7 I    2.3 I    2.2 I    4.3 I    1.6 I    1.7 I     .7 I    1.8 I    1.7 I     .6 I   34.0
              I   38.9 I   41.3 I   30.5 I   34.3 I   48.1 I   46.7 I   26.1 I   41.7 I   42.4 I   29.4 I
              I     .6 I     .8 I     .7 I    1.5 I     .5 I     .6 I     .2 I     .6 I     .6 I     .2 I
             -I--------I--------I--------I--------I--------I--------I--------I--------I--------I--------I
       COLUMN       36       46       59      105       27       30       23       36       33       17     2444
       TOTAL       1.5      1.9      2.4      4.3      1.1      1.2       .9      1.5      1.4       .7    100.0
(CONTINUED)
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FILE   TIMES    (CREATION DATE = 05/07/76 )                                  13/07/76     PAGE    7

* * * * * * * * * * * * * * * * *   C R O S S T A B U L A T I O N   O F   * * * * * * * * * * * * * * * * *
                                            BY  CTNO   .  CENSUS TRACT NUMBER
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * PAGE  6 OF  6

             CTNO
   COUNT   I
   ROW PCT I              ROW
   COL PCT I              TOTAL
   TOT PCT I      51.I
   --------I---------I
        1.  I        0 I    335
            I       .0 I   13.7
            I       .0 I
            I       .0 I
           -I---------I
        2.  I        1 I    420
            I       .2 I   17.2
            I     11.1 I
            I       .0 I
           -I---------I
        3.  I        4 I    457
            I       .9 I   18.1
            I     44.4 I
            I       .2 I
           -I---------I
        4.  I        4 I    452
            I       .9 I   14.6
            I     44.4 I
            I       .2 I
           -I---------I
   COLUMN            9     2444
    TOTAL           .4    100.0

RAW CHI SQUARE =   184.52000 WITH   150 DEGREES OF FREEDOM.  SIGNIFICANCE =   .0275
CRAMER'S V =     .15864
CONTINGENCY COEFFICIENT =     .26406
KENDALL'S TAU B =    -.01420
KENDALL'S TAU C =    -.01794
GAMMA =    -.01968
SOMERS'S D (ASYMMETRIC) =  -.01188 WITH R        DEPENDENT, =  -.01889 WITH CTNO     DEPENDENT.
SOMERS'S D (SYMMETRIC) =  -.01401
NUMBER OF MISSING OBSERVATIONS =      15
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APPENDIX 2

Explanation of Selected Census Terms

Rent

Figures for "cash" rent relate to tenant-occupied, non-farm dwellings only, regardless of type. Averages have been determined on the basis of "stated" rent, excluding cases in which "no cash rent" was paid.

Period of construction

Refers to the date of completion of the original building, not to any later remodeling, additions or conversions. Figures for 1971 extend to June 1, 1971 only.

Vacation home (owned)

Refers to a home owned by a member of the household and used only for vacation or recreational purposes on a seasonal basis. This term does not include trailers, houseboats or other movable dwellings.

Automobile

Includes any car or station-wagon owned or operated by a member of the household, if used at least part-time for non-business purposes. Not included are panel or other trucks, or passenger cars used entirely for business purposes.

Wage-earners

Refers to persons 15 years and over who indicated that in the job reported they were mainly working for wages, salaries, tips or commissions or were self-employed in an incorporated company.

Household

For census purposes, a household consists of a person or group of persons occupying one dwelling. It usually consists of a family group with or without lodgers, employees, etc. However, it may consist of two or more families sharing a dwelling, of a group of unrelated persons or of one person living alone. Every person is a member of some household and there is a one-to-one relationship between households and occupied dwellings except in the case of certain special households, such as those of military and diplomatic personnel stationed overseas, from which no housing information was collected.

Appendix 2 cont'd

Family

A census family consists of a husband and wife (with or without children who have never been married, regardless of age) or a parent with one or more children never married, living in the same dwelling. A family may consist, also, of a man or woman living with a guardianship child or ward under 21 years for whom no pay was received.

Total income

Refers to the total income received during 1970 from wages and salaries, business or professional practice, farm operations, family and youth allowances, government old age pensions, other government payments, retirement pensions from previous employment, bond and deposit interest and dividends, other investment sources, and other sources.

Employment income

Refers to the total of income received in 1970 as wages and salaries, net income from business or professional practice and/or net farm income.

Household income

Refers to the sum of the incomes received by all members of the household 15 years and over, from all sources, during the calendar year 1970.

Average and median incomes

For individuals and family/household heads, these figures are calculated only for persons reporting income. In the case of families, households and non-family persons, however, these figures are calculated for all families, households or non-family persons, respectively. Average and median employment incomes for individuals are calculated only for persons reporting some income from employment. All medians are calculated from the grouped data shown.

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