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by

Howard D.F. Veregin

A thesis
presented to the Faculty of Graduate Studies
the University of Manitoba
in partial fulfillment of the
requirements for the degree of
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Department of Geography

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FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read a Master's thesis entitled: EMPIRICAL ANALYSIS OF THE DETERMINANTS OF ROOF TEMPERATURE: AERIAL THERMOGRAPHY APPLIED TO CEILING HEAT LOSS DETECTION IN RESIDENTIAL BUILDINGS

submitted by HOWARD DONELL FRANCIS VEREGIN

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ABSTRACT

The study examines the application of aerial thermography to ceiling heat loss detection in residential buildings. The main objective is to identify features of house structure that have a significant effect on roof temperature. The presence of such features lowers the correlation between roof temperature and ceiling heat loss, on which thermographic heat loss detection is based. The study introduces a method whereby the effects of house structure can be reduced, thus increasing the reliability of aerial thermography for heat loss detection.

A sample of 209 houses in a residential area in northwestern Winnipeg was examined. Seven structural features were measured for the sample houses: attic insulation R-value, attic ventilation, roof orientation, roof pitch, lot frontage, house quality and the presence of an upper half story. These features were collected via telephone and ground surveys and interpretation of false-colour infrared aerial photographs. Roof temperature was measured for the houses from colour-enhanced sliced thermographs.

The relationship between roof temperature and each structural feature was examined with the aid of bivariate and multiple regression analysis and computer-generated maps.

Bivariate regression analysis facilitated comparison with previous research, in which it was the primary statistical technique employed. Multiple regression analysis enabled the relationship between roof temperature and each structural feature to be established with all other features entered as controls.

Partial residuals were derived from the multiple regression model as a method of reducing the effects of house structure on roof temperature. Partial residuals were defined as that component of the variation in roof temperature unaccounted for by all features in the multiple regression model except insulation R-value. On the assumption that R-value accurately depicts variations in ceiling heat loss, partial residuals were presented as a more precise index of ceiling heat loss than roof temperature.

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"Nothing is so good as it seems beforehand." - Marian Evans

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Chapter I

INTRODUCTION

This thesis is concerned with the application of aerial thermography to ceiling heat loss estimation in residential buildings. Aerial thermography is a branch of remote sensing dealing with the measurement of radiant energy with an airborne infrared line scanner (IRLS). This device is sensitive to radiation in the thermal infrared region of the electro-magnetic spectrum (EMS), ranging in wavelength between 3 and 14 um. The IRLS measures the thermal radiant energy emitted and reflected by terrestrial objects within ground-resolution cells, or pixels, of approximately equal size arranged in a matrix pattern over the terrestrial scene. This pattern is created in tandem by the forward motion of the aircraft along the flight line and the oscillation of a mirror within the IRLS that reflects radiation to the thermal sensing device.

The application of this technique to ceiling heat loss detection in residential buildings is based on the relationship between radiance and temperature. All objects above absolute zero (0°K or -273°C) emit radiation, the intensity of which is dependent on the temperature of the object. To calculate roof temperatures from thermographic data, the measured radiance values of the pixels covering the roof surface are related to the radiance values of two reference plates located within the IRLS, the temperatures of which bracket the temperature range of the terrestrial scene and which are imaged along with the scene at the time of overflight. The emittance characteristics of these reference plates approximate theose of a blackbody, the theoretical perfect emitter which neither reflects nor transmits energy and emits it at the same rate at which it is absorbed (Artis and Carnahan 1982, 313). Roof temperatures thus calculated are referred to as apparent roof temperatures to denote the fact that they represent the temperature at which a blackbody would be in order to emit the same amount of radiation as the roof. Like other terrestrial objects, roofs are known as greybodies since they emit radiation in varying proportion according to their physical properties.

Thermographic estimation of ceiling heat loss is based on the premise that there is a causal relationship between heat loss and roof temperature. High temperatures are assumed to be the result of high levels of heat loss. This assumption, however, is valid only for buildings with flat roofs. In these buildings, interior heat is transferred to the roof surface directly through the insulation layer. In contrast, most residential buildings contain a ventilated attic air space, which separates the roof from the insulation layer. In these buildings, warm air that has been transferred to the attic from the building interior is removed through the attic ventilation system. Heat lost from the interior is dissipated before reaching the roof surface; thus roof temperature is dependent, not only on the level of ceiling heat loss, but on the rate of attic ventilation.

In most residential buildings, the roof surface is inclined from the horizontal. This poses an additional problem for heat loss detection, since it results in the reception by the roof of radiation emitted by neighbouring terrestrial objects. This radiation may be either absorbed by the roof and later re-radiated, or reflected directly to the IRLS where it will be interpreted as emitted radiation. In either case, a higher roof temperature will be recorded than if the roof received no radiation. Roof temperature is therefore partially dependent on the level of radiation received by the roof, which is determined primarily by roof pitch, the orientation of the roof relative to neighbouring terrestrial objects and the proximity of such objects.

The effects of attic ventilation and the reception of incident radiation contradict the basic premise that roof temperature is determined primarily by the level of ceiling heat loss. Roof temperature variations may arise solely from structural differences among houses. Such differences must therefore be accounted for if accurate heat loss estimates are to be obtained from thermographic data. The objectives of the present study are:

1. to examine the relationship between roof temperature and house structure in order to identify structural features that have a significant effect on roof temperature; and
2. to introduce a method for reducing the dependence of roof temperature on such features, thereby increasing the accuracy of aerial thermography for heat loss estimation.

The rationale behind the present study lies in the fact that aerial thermography has the potential to reduce the demand for energy and lower home heating costs. In Canada, home heating accounts for approximately 15% of the country's total energy consumption (EMR and CMHC 1976, 4). Policy makers have thus come to recognize the necessity of adequate insulation and appreciate the importance of retrofitting as a means of reducing residential energy requirements. This concern is shared by homeowners who must bear the burden of spiralling energy costs. However, heat loss can occur at many locations in the home and arise from air exfiltration, insulation deterioration or inadequacy, or poor heating habits (Veregin 1984). It is thus often difficult to ascertain the exact cause, location and level of heat loss in the home.

Aerial thermography can provide a partial solution to this problem by providing a means of estimating relative levels of ceiling heat loss. The technique provides information needed by the homeowner to estimate the amount of retrofit materials required, assess the financial benefits of retrofitting and schedule repairs on the basis of the severity of heat loss. Retrofitting of attic insulation can significantly lower heating costs, since heat lost through the ceiling accounts for up to 30% of the total heat losses of a residential building, depending on its design and the amount of insulation present in other areas of the house. Excessive ceiling heat loss can often be rectified more easily and at less expense than heat lost through the walls and around windows and doors. As a diagnostic tool, aerial thermography is also relatively cost-effective, due to its ability to survey thousands of houses on a single overflight.

Chapter II

REVIEW OF LITERATURE

Previous research indicates that thermographic measurements of roof temperature are affected by three factors related to house structure: the level of ceiling heat loss, the rate of heat dissipation through the attic vents and the amount of incident radiation received by the roof. To a lesser degree, temperatures may also be affected by roof emissivity, house age and style and the presence of anomalous structural features.

2.1 ATTIC INSULATION LEVEL

The amount of internal heat reaching the roof surface is directly affected by the level of ceiling heat loss. Ceiling heat loss includes both conductive and convective losses. Conduction refers to the transfer of interior heat through the attic insulation layer. The rate of conduction is dependent on the R-value, or thermal resistance, of the insulation and the temperature differential between internal and ambient air. Convection refers to the exfiltration of interior air through gaps in the ceiling vapour barrier. The rate of convection is determined primarily by the size and location of these gaps and the pressure differential between the interior and exterior of the house.

Previous research has focused almost exclusively on conductive heat loss, due in part to the difficulty of estimating the ratio of conductive to convective losses for individual buildings. It has generally been assumed that conductive heat loss constitutes the larger component of the total ceiling heat losses of residential buildings. Thus, under the assumption that the internal-ambient air temperature differential is identical for all houses being studied, the R-value of the attic insulation layer has been employed as an index of the level of ceiling heat loss.

Research indicates that a negative relationship exists between roof temperature and insulation R-value. Treado and Burch (1981) examined this relationship for three test-houses in Springfield, Missouri, which had similar construction styles but varying amounts of attic insulation. A series of thermographs of the houses was obtained at various altitudes and under different environmental conditions. Roof temperature was estimated qualitatively from thermographs using visual interpretation techniques. It was found that at all altitudes and under all environmental conditions, roof temperature was a reliable indicator of the amount of attic insulation present. Image tones indicating warmer roof temperatures were consistently observed for houses having less insulation.

Hathout (1980, 1981) examined the relationship between apparent roof temperature and insulation depth for houses in two residential areas of Winnipeg, Manitoba, one composed mainly of houses 50 years of age or more, and the other containing many houses built in the last decade. Apparent roof temperatures for over 4400 houses were obtained from sliced thermographs on which each slice, or shade of grey, represented a unique temperature range. Each house was classified according to the predominant temperature range covering the roof.

Analysis of a sample of these houses revealed a negative relationship between apparent roof temperature and insulation depth. Well insulated houses tended to have lower roof temperatures than poorly insulated houses. However, substantial overlap in roof temperatures between well and poorly insulated houses was observed. This finding was attributed to the effects of other structural features.

Lawrence, Ellis and Smith (1978) examined the relationship between apparent roof temperature and attic insulation thickness using linear regression analysis. They sought to derive an equation whereby insulation thickness for a given house could be estimated on the basis of roof temperature. Apparent roof temperatures for a sample of 864 houses in Stratford, Ontario, were obtained from sliced thermographs. Houses were assigned a numerical code indicative of the temperature range that predominated on the roof.

The coefficients of determination for the regression of insulation thickness on apparent roof temperature were 0.59, 0.48 and 0.69 for bungalows, one-and-a-half and two story buildings, respectively. The researchers concluded that it was possible to estimate attic insulation thickness accurately on the basis of roof temperature alone. The relatively high correlation observed between temperature and insulation thickness, however, was in part attributable to the fact that "all houses with anomalies" were excluded from the analysis (Lawrence, Ellis and Smith 1978, 246). Anomalies included attic heating ducts and moisture-damaged insulation. Houses were also excluded if insulation thickness was not known precisely or if roof temperatures appeared to be excessively high or low based on the amount of insulation present. All split-level houses were also excluded, since they showed limited insulation depth variation (Lawrence, Ellis and Smith 1978, 247), and exhibited temperature variations on different roof levels that could not be accounted for by the level of insulation alone.

Brown, Cihlar and Teillet (1981) examined the relationship between apparent roof temperature and attic insulation level in a study of 97 residential buildings in Ottawa, Ontario. Thermographic data were acquired on three separate occasions under different environmental conditions. The average apparent roof temperature for each house was obtained for each set of thermographic data using a computerized image analysis system. This system made it possible to measure the radiance associated with each pixel and convert these radiance values to apparent temperatures by relating them to the radiance values of two blackbody reference plates within the IRLS.

Regression analysis revealed an indirect relationship between apparent roof temperature and insulation level. However, insulation level accounted for a relatively small proportion of the variation in temperature. The coefficients of determination for the regression of temperature on insulation R-value were 0.09, 0.01 and 0.11 for bungalows, one-and-a-half and two story buildings. The researchers concluded that apparent roof temperature did not accurately reflect variations in insulation level. In contrast to Lawrence, Ellis and Smith (1978), these researchers did not exclude all houses with anomalous features from the sample. This factor accounts in part for the lower level of explanatory power observed in the study. The researchers suggested that such features had a significant effect on roof temperature.

2.2 ATTIC VENTILATION RATE

Roof temperature is also directly affected by the rate of attic ventilation. The function of attic ventilation is to remove warm, moist air from the attic and replace it with ambient air. This process serves to minimize attic condensation and prevent the development of ice-jams on the roof surface. Attic ventilation causes some of the heat lost from the building interior to be dissipated from the attic before it reaches the roof surface. The greater the rate of heat dissipation, the lower the amount of heat transferred from the building interior to the roof surface, <u>ceteris paribus</u>. The rate of attic ventilation is determined by the physical characteristics of the ventilation system, including the type, number, size, location and operating efficiency of the vents. In addition, it is affected by environmental factors such as wind speed and direction.

Brown, Teillet and Cihlar (1978) examined a sample of 72 houses in Ottawa in order to determine the extent to which apparent roof temperature was dependent on the rate of attic ventilation. Apparent roof temperatures of the sample houses were calculated with the aid of a computerized image analysis system. Using a heat loss model detailed by Brown (1978) which emulated the processes of heat dissipation from the attic of a model residential building, the researchers were able to estimate attic insulation R-values for the sample houses on the basis of apparent roof temperature.

Model estimates of R-value were first obtained for a subsample of 26 houses under the assumption that none of the houses contained an attic ventilation system. It was found that R-values tended to be over-estimated when actual ventilation rates were high and closer to actual R-values when ventilation rates were low. This finding indicated that, when attic ventilation was not incorporated into the model, roof temperature variations associated with the rate of attic ventilation were mistakenly assumed to arise from differences in insulation R-value.

The researchers then used values of 10, 5 and 0 to represent actual rates of attic ventilation for the 26 houses and re-calculated R-values with the modelling procedure. A significant increase in the correspondence between actual and estimated R-values was observed. The coefficient of determination for the regression of actual R-values on estimated R-values increased from 0.09 to 0.41 when attic ventilation rates were incorporated into the procedure. Similar results were obtained for an additional subsample of 46 houses for which attic ventilation rates were estimated from aerial photographs.

The researchers concluded that the use of aerial thermography for measuring ceiling heat loss from residential buildings had to be approached "very cautiously" due to the dependence of roof temperature on the rate of attic ventilation (Brown, Teillet and Cihlar 1978, 219-20). They noted that

> ...attic ventilation must be taken into account when quantitative predictions of attic insulation level are made from aerial thermograms (Brown, Teillet and Cihlar 1978, 222).

The study also demonstrated the feasibility of applying a corrective technique in order to minimize the effects of attic ventilation, thereby increasing the level of correspondence between roof temperature and the R-value of the attic insulation.

The effects of attic ventilation on roof temperature were further examined by Brown, Cihlar and Teillet (1981). The researchers hypothesized that attic ventilation rate, and thus the relationship between attic ventilation and roof temperature, was dependent on environmental conditions such as wind speed and direction. They argued that such conditions increased the dependence of attic ventilation rate on the physical characteristics of the ventilation system.

Under the assumption that ventilation system characteristics would differ among houses of different ages, they regressed apparent roof temperature on house age for two separate data sets acquired under different environmental conditions. The coefficient of determination for the first data set, obtained when wind speed was high (in excess of 22 km/hr), was 0.23; for the second data set, obtained when wind speed was considerably lower (10 km/hr), the coefficient was not significantly different from zero. It was concluded that under windy conditions, the physical characteristics of the ventilation system became more important in determining the rate of attic ventilation and thus had a significant deterministic effect on roof temperature.

2.3 INCIDENT RADIATION

Roof temperature is also affected by the level of incident radiation received by the roof. Incident radiation may be either reflected or absorbed. Reflection results in an increase in the amount of radiation received from the roof by the IRLS. Absorption causes roof temperature to rise, which in turn results in more radiation being emitted by the roof. Whether reflected or absorbed, incident radiation causes an increase in thermographic measurements of roof temperature that is unassociated with any increase in the level of ceiling heat loss.

The amount of incident radiation received by the roof is determined primarily by three factors: roof orientation, roof pitch and the proximity of neighbouring terrestrial objects. Previous research indicates that roofs that face the street network generally receive lower levels of incident radiation than those that face neighbouring buildings. In the former case, the primary source of incident radiation is the sky, whereas in the latter, a greater proportion of the total radiation incident on the roof is emitted by terrestrial objects. As terrestrial objects have higher apparent temperatures than the sky, relatively more radiation is received by the roof in the latter case.

Hathout (1980, 1981) found a strong relationship between roof orientation and apparent roof temperature in both residential areas of Winnipeg that were examined. In one area, 24.5% of all houses with apparent roof temperatures above the midpoint value exhibited an east-west orientation of roof ridge-lines. In the second area, the percentage was 22.4%. Houses with this roof orientation were generally those for which the roof surfaces faced the street network. Thus, roof surfaces facing the street network tended to have lower temperatures than those facing neighbouring buildings.

Roof pitch also affects the amount of incident radiation received by the roof. A positive relationship has consistently been observed between roof temperature and roof pitch. In comparison to roofs of low pitch, those of high pitch receive a greater proportion of total incident radiation from neighbouring terrestrial objects. Roofs of high pitch therefore tend to have higher temperatures than those of low pitch, _ceteris paribus_.

Hathout (1980, 1981) found that high apparent roof temperatures were more frequently associated with roofs of high pitch: 57.8% of the houses with apparent roof temperatures above the midpoint value had roofs of high pitch. Brown, Cihlar and Teillet (1981) found that temperature increased in direct proportion to roof pitch. Roof pitch accounted for approximately 10% of the variation in apparent roof temperature. The researchers concluded that changes in pitch produced significant variations in roof temperature that were unrelated to the level of ceiling heat loss.

A third factor affecting the level of incident radiation received by the roof is the proximity of neighbouring terrestrial objects. Radiation intensity varies inversely as the square of distance (Wiebelt 1966, 18). Thus the increase in roof temperature associated with the exchange of radiation between buildings should be proportional to the inverse of the square of the distance between them. This effect should be most pronounced when roof pitch is high and the roof faces neighbouring terrestrial objects.

The effects of incident radiation on roof temperature were examined by Tanis and Sampson (1977). They sought to calculate ceiling heat losses for residential buildings using a modelling procedure that simulated the roof energy gains associated with the reception of incident radiation. Heat losses were calculated for a model building by emulating the processes of heat transfer from the building interior. The combined effect of roof orientation, roof pitch and the proximity of neighbouring terrestrial objects was incorporated into the modelling procedure using an index of the fraction of total roof exposure occupied by terrestrial objects, given one of two combinations of features: a roof of high pitch that faced neighbouring objects and was in close proximity to them; or a roof of low pitch that did not face neighbouring objects and was not in close proximity to them. These two combinations were assumed to approximate conditions in older and newer residential areas, respectively.

Heat losses were calculated using the modelling procedure as successive increases were made in roof temperature. This made it possible to graph the relationship between temperature and heat loss. Separate graphs were produced for each of the two combinations of structural features. Apparent roof temperatures for 256 houses in Ypsilanti, Michigan, were obtained from thermographs and used to estimate heat loss levels from the graphs. These heat loss estimates were compared to information on attic insulation levels and home energy use obtained directly from homeowners. The researchers found that estimates were generally accurate and concluded that the technique could be used to distinguish between insulated and uninsulated houses. They noted, however, that there was still too much variation in roof temperature to be able to estimate precise levels of ceiling heat loss.

2.4 ROOF EMISSIVITY

Theoretically, roof temperature should also be affected by roof emissivity. Roof emissivity is defined as the ratio of the total emissive power of a roof at a given temperature to the total emissive power of a blackbody at the same temperature. Total emissive power refers to the total thermal radiant energy emitted by an object into the entire volume above the object per unit time and area (Wiebelt 1966, 15). A blackbody is a theoretical perfect emitter of radiant energy and thus its emissivity is equal to unity.

Terrestrial objects such as roofs are referred to as grey-bodies since they emit less energy than a blackbody at the same temperature. The emissivity of any terrestrial object is therefore less than unity.

Variations in roof emissivity affect the amount of thermal radiation emitted by the roof. The IRLS measures the apparent temperature of a roof, or the temperature at which a blackbody would be in order to emit the same amount of radiation as the roof. Two roofs with similar kinetic temperatures but different emissivities will therefore appear to have different temperatures when measured with thermography. The apparent temperature of a roof is typically several degrees lower than its kinetic temperature. The relationship between apparent and kinetic temperature is given by the following equation:

$$T_k = \frac{T_a}{E^{1/4}} \qquad (2.1)$$

where

T_k = Kinetic roof temperature

T_a = Apparent roof temperature

E = Roof emissivity

Roof emissivity is determined primarily by the physical characteristics of the roof surface, including its colour, chemical composition and texture. Previous research indicates that variations in the emissivity of common roofing materials are of such low order as to have an insignificant effect on roof temperature. Anomalous roofing materials such a slate or metal, however, have very low emissivities and therefore tend to be associated with low apparent temperatures.

Brown, Cihlar and Teillet (1981) examined the effects of roof colour and degree of weathering on roof emissivity in order to test the hypothesis that emissivity differences accounted for some of the variation in apparent roof temperature. Asphalt shingles of several colours were subjected for one year to the weathering effects of sun and precipitation. Their emissivities were then measured with an infrared spectrometer. It was found that the emissivities of these shingles did not vary significantly from the emissivities of unweathered shingles. The researchers concluded that variations in roof emissivity caused by roof colour and degree of weathering would have a negligable effect on roof temperature.

The effects of weathering were further assessed by examining the relationship between apparent roof temperature and house age. The researchers hypothesized that observable variations in roof temperature would arise from differences in roof emissivity among houses of different ages, since these houses would experience different degrees of weathering. The correlation between age and temperature was not, however, significantly different from zero. This finding indicated that variations in degree of weathering associated with house age had a negligable effect on roof emissivity and thus on roof temperature.

A similar conclusion was reached by Artis and Carnahan (1982), who analyzed thermographic data for 1411 houses in Terre Haute, Indiana, in order to assess the extent of roof emissivity variation. The modal emissivity value for each house was obtained and the distribution of these values for the sample houses was then examined. The houses were found to exhibit a limited spread of emissivity variation: 98.8% of the roofs had emissivities between 0.89 and 0.95. The researchers noted that the standard deviation of the distribution was of the same order as the possible error in emissivity measurements due to random measurement error (Artis and Carnahan 1982, 327). They concluded that, with the exception of anomalous roofing materials such as slate and metal, emissivity variations among roofs have a negligable effect on roof temperature (Artis and Carnahan 1982, 328).

2.5 HOUSE AGE AND STYLE

Research has consistently identified a positive relationship between roof temperature and house age. In their study of Stratford, Lawrence, Ellis and Smith (1978) discovered that newer houses tended to have lower apparent roof temperatures than older houses. This finding was attributed to higher levels of attic insulation in newer houses.

Hathout (1980, 1981) compared apparent roof temperatures for two residential areas of different ages. In the older area, 62.6% of all houses had temperatures above the mid-point value; in the newer area, the percentage was 4.6%. Hathout attributed this finding to higher levels of attic insulation in newer houses and the repetition of certain structural features in houses built at the same time or by the same contactor (Hathout 1980, 15).

Brown, Cihlar and Teillet (1981) examined thermographic data acquired under different environmental conditions and found that a significant relationship existed between apparent roof temperature and house age only when wind speed was relatively high. They attributed this finding to differences in attic ventilation system characteristics for houses of different ages. They argued that these differences became important in determining the rate of heat dissipation from the attic when the number of attic air exchanges per hour was high. Under less windy conditions, such differences had only a marginal effect on the rate of heat dissipation, since the number of air exchanges was relatively low regardless of the characteristics of the ventilation system.

Research has also identified a significant relationship between roof temperature and house style. Lawrence, Ellis and Smith (1978) found that bungalows and split-level houses generally had lower apparent roof temperatures than one-and-a-half or two story houses. They suggested that this phenomenon was due to the amplification of convective currents within taller buildings, resulting in higher levels of convective heat loss through the ceiling.

Brown, Cihlar and Teillet (1981) also found significant apparent roof temperature differences between bungalows, one-and-a-half and two story buildings. On average, the temperature of bungalows was lower than that of one-and-a-half story houses, and the temperature of one-and-a-half story houses lower than that of two story houses. They noted that these temperature differences were probably due to structural variations among the three house styles, but did not identify the exact mechanism causing the difference.

2.6 ANOMALOUS STRUCTURAL FEATURES

Anomalous features, usually present in only a small number of houses in the population of interest, may also affect roof temperature. Among the most common anomalies are porches, verandas, attached garages, overhanging vegetation, flat roofs and cathedral ceilings. Porches, verandas and garages are frequently unheated or uninsulated and thus their inclusion in roof temperature calculations may bias temperature measurements for the house proper. Overhanging vegetation tends to mask areas of the roof and prevent the accurate measurement of roof temperature for these areas. In houses with either flat roofs or cathedral ceilings, heat is transferred to the roof surface from the building interior by conduction alone, since no attic air space exists and no attic ventilation occurs. Moreover, flat roof surfaces receive no radiation from neighbouring terrestrial objects. The roof temperatures of such houses cannot be directly compared to those of houses with vented loft roof systems, for which roof temperature is partially dependent on attic ventilation and the reception of incident radiation.

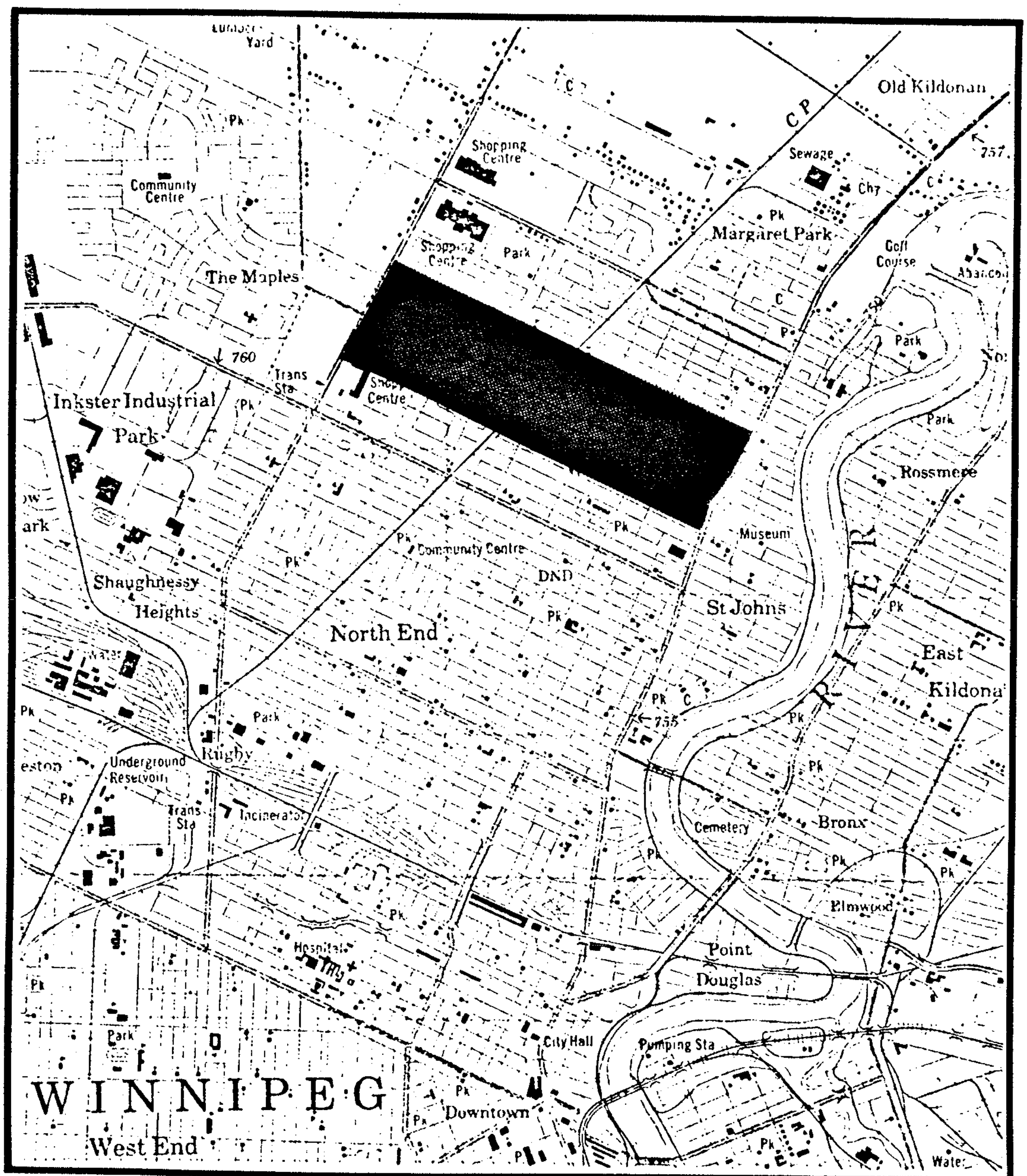
Chapter III

PROCEDURE

In the present study, roof temperature and house structure were measured for a sample of houses located in a residential district in the north-western part of Winnipeg, Manitoba. The study area extends for a distance of 2.5 km along Jefferson Avenue, between Main Street and McPhillips Street and contains over 1700 houses (Figure 3.1). This area was selected because of the diversity in the age and structure of houses, which provided a wide range of roof temperature variation. A second reason for selecting the area was the availability of false colour infrared (FCIR) aerial photographs and colour-enhanced thermographs of the area, which were produced in 1978 by Dr. S.A. Hathout. The following is a brief description of the field methods, laboratory methods, computer mapping techniques and methods of statistical analysis employed in the study.

3.1 FIELD METHODS

Structural features were measured for a sample of 561 houses in the study area. The following procedure was employed in sample selection:



Scale - 1:50.000

Source - Topo sheet 62 H/14

FIGURE 3.1

Location of Study Area

1. The address of each house in the study area was obtained from cadastral maps produced by the Department of Environmental Planning of the City of Winnipeg.
2. The occupant, telephone number and tenancy of each house was obtained from the 1979 Henderson Directory using address information obtained in the previous step.
3. Every fourth house in the area was then selected for inclusion in the sample unless it was not owner-occupied. In this case, the preceding house was chosen, subject to the same constraint. Selection then continued from the last house chosen.
4. Occupants and telephone numbers for sample houses were verified against the most recent telephone directory. This enabled the identification of cases in which homeowners had moved or the telephone number had changed in the interim between thermographic data collection and survey administration.

A telephone survey was designed and administered for the sample in order to obtain information on insulation levels and attic ventilation system characteristics, which could otherwise be obtained only by <u>in situ</u> observation. As thermographic data for the study area had been acquired in 1978, it was necessary to assess conditions that existed some five years previous to the administration of the survey. This was achieved by eliciting information on the history of retrofitting activity for each house. Each homeowner was first asked if retrofitting of attic insulation had ever been carried out and if so, when it occurred and what type of insulation was added. The homeowner was then asked if the additional insulation had been placed on top of existing insulation or if existing insulation had been removed. This process continued until the layer of insulation installed at the time of construction was identified. A similar procedure was followed to assess attic ventilation system characteristics. It was thus possible to determine the insulation and ventilation conditions existing at any time since house construction. The questionnaire form is reproduced in Appendix A.

Information on insulation conditions included the type and installation date of each layer of insulation present in the attic. Information on insulation thickness was not collected, on the assumption that homeowners would have experienced difficulty in recalling such information. R-values were thus calculated under the assumption that each layer of insulation was of the same thickness. The resistivity, or R-value per inch thickness, was obtained for each type of insulation present in the sample from data tabulated by Energy, Mines and Resources Canada and Canada Mortgage and Housing Corporation (1976, 42). The R-value of the insulation for each house was calculated as the sum of the resistivities of each type of insulation present in the attic at the time of thermographic data collection.

Attic ventilation was measured as present or absent and no attempt was made to determine the type, number and location of vents. As expected, many homeowners experienced difficulty in describing the characteristics of the ventilation system and recalling the installation dates of additional vents. Attic ventilation was thus equal to 0 when vents were not present and to 1 when they were present.

Information on structural anomalies was also obtained in the telephone survey. Houses with flat roofs and cathedral ceilings were identified on the basis of questionnaire responses. These houses were eliminated from the sample since the heat transfer mechanisms in the roof systems of such houses are not directly comparable to those in vented loft roof systems.

Table 3.1 shows the response rate for the telephone survey. Of a total sample of 561, 300 (53.5%) participated in the survey and 261 (46.5%) did not. 217 (72.3%) of the participants were able to provide answers to all questions and 83 (27.7%) were able to answer some of them. 84 (32.2%) of all non-participants were homeowners who could not be reached by telephone, although each sample house was called a maximum of ten times at different times of the day and on different days of the week. 177 (67.8%) of the non-participants were individuals who refused to take part in the survey for one of the following reasons:

Group	Frequency	Percentage of Group	Percentage of Total Sample
Participants:			
Answered all questions	217	72.3	38.7
Answered some questions	83	27.7	14.8
Total	300	100.0	53.5
Non-Participants:			
Refused interview	177	67.8	31.5
Not contacted	84	32.2	15.0
Total	261	100.0	46.5
Total Sample	561	-	100.0

TABLE 3.1

Response Rate for Telephone Survey

1. lack of interest in home energy conservation;
2. conviction that the survey was actually being conducted by a private contractor for the purpose of identifying houses in need of additional insulation;
3. lack of knowledge about insulation conditions in the house; or
4. general unwillingness to divulge information.

Additional field work was required to measure house quality and lot frontage. House quality was employed as a surrogate measure of house age. Lot frontage was assumed to portray variations in the distance between houses. House quality was obtained for the sample houses from maps prepared by the Department of Environmental Planning of the City of Winnipeg. These maps were based on evidence of structural deterioration discerned from external visual inspections of individual houses. Four categories of quality were defined: good, fair, poor and very poor. Few of the sample houses fell into the latter three categories, however, and thus they were amalgamated to form one group. Low house quality was denoted by a value of 0 and high quality by a value of 1. Lot frontage values for the sample houses were obtained from property tax rolls located at Winnipeg City Hall.

3.2 LABORATORY METHODS

Additional information on house structure was obtained from FCIR aerial photographs of a scale of 1:3000 for the 217 houses for which attic insulation and ventilation conditions had been acquired. Forward overlap on successive photographs was approximately 60%, making it possible to view the houses stereoscopically. The interpretation techniques employed were based on methods developed for the identification of parameters of house structure and location indicative of house quality, including roof condition, landscaping and the presence of refuse, vegetation and off-street parking. Several researchers have found that FCIR photography is most suitable for the collection of these data at both the parcel and aggregate levels (Wellar 1968b; Marble and Horton 1969; Lindgren 1971). FCIR photography enhances detail and increases contrast between built-up and non-built-up areas.

In the present study, four features of house structure were interpreted from aerial photographs: roof surface material, roof orientation, roof pitch and the presence of an upper half story. Interpretation of roof surface materials was based primarily on textural differences among roofs; in addition, certain materials, such as tar and gravel, are usually found only when roofs are of low pitch. The type of material present was used to estimate roof emissivity, which enabled kinetic roof temperatures to be calculated for the sample houses. Two types of roofing material were identified, asphalt shingles and tar and gravel, both of which have emissivities of approximately 0.97 (Colcord 1981, 239).

Roof orientation was measured in terms of the proportion of total roof surface facing neighbouring buildings. Values of 0.0, 0.5 and 1.0 were assigned, respectively, to houses with roof surfaces facing the street network, those with hip-type roofs or roof dormers and those with roof surfaces facing neighbouring buildings.

Roof pitch and the presence of an upper half story were interpreted using a mirror stereoscope, which facilitated stereoscopic viewing of the aerial photographs. Houses were assigned to one of two roof pitch categories, low or high, which were assigned values of 0 and 1 respectively. These categories reflected construction practices in the study area, as roofs tended to be either nearly flat or inclined at an angle of approximately 45°. Houses with an upper half story were identified on the basis of the height of the house, the shape of its shadow and the presence of features such as roof dormers, which are characteristic of houses with an upper half story. The presence of an upper half story was denoted with by a value of 1 and its absence by a value of 0.[1]

Thermographic data were acquired for the study area at 1:00 a.m. on 6 April 1978. These data were collected at an altitude of 490 metres ASL when skies were clear, ambient air temperature was 2.8°C, wind speed was 11 km/hr and roof-tops were free of snow and ice.

Roof temperatures for the sample houses were calculated from colour-enhanced thermographs produced with a density slicer. Each colour on the thermographs represented a unique apparent temperature range. The thermographs were

[1] The original research design called for the measurement of the number of stories. However, as very few sample houses had two stories, measurement of this feature was abandoned in favour of the presence or absence of an upper half story.

displayed on a CRT monitor and photographed using 35mm slide film. The following procedure was employed in the calculation of roof temperature:

1. The slides were projected and each house in the sample was delineated with the aid of the FCIR photographs.
2. The boundaries between each temperature range on the roofs were delineated.
3. The proportion of total roof area covered by each temperature range was calculated with a planimetric technique. Areas obscured by overhanging vegetation and porches, verandas and attached garages were identified from the FCIR photographs and excluded from these calculations.
4. The areal measurements obtained in the previous step were multiplied by the midpoint value of the corresponding apparent temperature range. These products were then summed for each house to give the weighted apparent roof temperature in $^{\circ}K$. Apparent temperatures were converted to kinetic roof temperatures by accounting for roof emissivity (equation 2.1). Roof emissivity was the same for both types of roof surface material identified in the sample. A WATFIV programme was written to perform these calculations (Appendix C).

A total of 8 houses were deleted from the sample because they could not be discerned clearly on the thermographs; the final sample therefore contained 209 houses. Table 3.2 describes the data items collected for the sample houses. All items represent conditions that existed in 1978, when thermographic data were acquired. For attic insulation and ventilation, 1978 conditions were assessed on the basis of responses to querries about previous retrofitting projects. For all other characteristics, it was necessary to assume that conditions had not changed in the period since thermographic data collection.

3.3 COMPUTER MAPPING TECHNIQUES

A WATFIV programme (SPOTMAP) was written to produce computer maps of each data item for the sample houses (Appendix D). The location of each house, defined in terms of its Cartesian co-ordinates relative to a specified origin point, was first digitized from maps of the study area produced by Dr. S.A. Hathout. SPOTMAP was then run to convert these co-ordinates to row and column locations in a two-dimensional array. Data values for the sample houses were read in from a separate file. Map symbolism and class intervals were also read in and SPOTMAP then assigned the appropriate symbol to each house. Maps were output on a line-printer. Finally, streets and important street names were added by hand to improve map legibility.

Feature	Source	Description	Values
Roof temperature	Colour-enhanced thermographs	Kinetic roof temeparture (°K)	Continuous
Attic insulation R-value	Telephone survey	R-value of insulation assuming equal thickness of all insulation layers	Continuous
Attic ventilation	Telephone survey	Presence or absence of an attic ventilation system	0 = absent; 1 = present
Roof orientation	Air photo interpretation	Proportion of roof surface facing neighbouring buildings	0.0 = faces street network; 0.5 = faces both directions; 1.0 = faces neighbouring buildings
Roof pitch	Air photo interpretation and field survey	Pitch of roof	0 = low; 1 = high
Lot frontage	Property tax rolls	Frontage of lot in feet	Continuous
House quality	Department of Environmental Planning	Index of house quality based on structural deterioration	0 = low; 1 = high
Upper half story	Air photo interpretation and field survey	Presence or absence of an upper half story	0 = absent; 1 = present

TABLE 3.2

Data Items Collected

3.4 DATA ANALYSIS

The following outlines the methods of data analysis employed in the study.

3.4.1 Accuracy Test

The accuracy of air photo interpretation was assessed with a statistical test that enabled the level of accuracy in the entire sample to be inferred on the basis of the number of incorrect interpretations in a subsample of houses. The following equation:

$$P = \sum_{i=0}^{X} \frac{n!}{X!(n-X)!} Q^{n-X} (1-Q)^{X} \qquad (3.1)$$

where

X = Number of incorrect interpretations in the subsample

n = Size of the subsample

Q = Proportion of correct interpretations in the sample

gives the cumulative binomial probability, P, of obtaining X or fewer incorrect interpretations in a subsample of size n given an accuracy level of Q in the sample (Aronoff 1982, 1301). If Q is set to the minimum acceptable level of accuracy required, the equation can be used to test the hypothesis that the actual level of accuracy in the sample is less than the acceptable level. Obtainment of a low probability indicates that it is unlikely that only X incorrect interpretations would be encountered in the subsample if in fact the accuracy level in the sample was no higher than Q. One would therefore reject the hypothesis and conclude, in effect, that the accuracy level in the sample was not less than the acceptable level. Conversely, obtainment of a high probability would afford no justification for rejecting the hypothesis and thus one would conclude that the level of accuracy in the sample was in fact less than the acceptable level.

This test is designed to minimize the risk of erroneously concluding that sample accuracy is not less than the acceptable level (Aronoff 1982, 1305). There is, however, a concomitant high risk of erroneously concluding that sample accuracy is less than the acceptable level. In the present study, the former type of error would result in the use of a set of incorrectly interpreted structural features, which would introduce bias into the statistical analysis. The latter type of error would necessitate re-interpretation of structural features, thereby increasing the time and cost of data collection. It was reasoned that bias would cause more serious problems than data re-interpretation, due to the fact that the main statistical technique emloyed in the study, regression analysis, is based on certain restrictive assumptions concerning the absence of measurement error in the explanatory variables.

Interpretation accuracy was tested for three features: roof orientation, roof pitch and the presence of an upper half story. A random-stratified sampling method was used to select subsamples of houses for statistical testing. A total of 20 houses was chosen at random from each interpreted category, or stratum, of each of the three features examined. Once selected, a house was returned to the sample and therefore could be included in the subsample more than once. This approach, called sampling with replacement, was necessitated by the assumptions of the statistical test employed (Huntsberger and Billingsley 1981, 138).

After subsample selection, a field survey was conducted for the purpose of determining whether each subsample house actually belonged to the stratum to which it had been assigned by air photo interpretation. Table 3.3 compares the results of the field survey with those of air photo interpretation. The number of incorrect (X) and correct (n-X) interpretations is presented for each stratum of each feature. Also shown is the cumulative probability of obtaining up to X incorrect interpretations, given a value of 0.75 for Q in equation 3.1. These probabilities were calculated with the WATFIV programme presented in Appendix E.

As Table 3.3 indicates, interpretation errors occurred in three of the seven strata: high roof pitch and both the presence and absence of an upper half story. The number of incorrect interpretations for these strata are, respec-

Stratum	Subsample Size (n)	Number of Incorrect Interpretations (X)	Number of Correct Interpretations (n-X)	Probability of X or Fewer Incorrect Interpretations (p)
Roof orientation:				
Facing buildings	20	0	20	0.003
Facing street	20	0	20	0.003
Facing both directions	20	0	20	0.003
Roof pitch:				
Low	20	0	20	0.003
High	20	15	5	1.000
Upper half story:				
Present	20	10	10	0.996
Absent	20	3	17	0.225

TABLE 3.3

Results of Interpretation Accuracy Testing tively, 15, 10 and 3; corresponding probabilities obtained with equation 3.1 are 1.000, 0.996 and 0.225. For all three strata, the calculated probabilities exceed 0.05, used in the present study as the cutoff level for the hypothesis rejection region. It was therefore concluded that the level of accuracy in the sample for the three strata was less than the acceptable level of 0.75.

Roof pitch had previously been interpreted from aerial photographs for the houses in the study area by Hathout (1980, 1981). Application of the accuracy testing procedure indicated, however, that these data were not interpreted with sufficient accuracy to justify their employment in the present study in place of the incorrect roof pitch values. Of a total of 20 houses chosen randomly from each of the two roof pitch strata identified by Hathout, low and high, the number of incorrect interpretations were 1 and 5 respectively. These values correspond to probabilities of 0.024 and 0.617, given a value of 0.75 for Q.[2]

Interpretation errors in the present study were attributed to the difficulty of measuring variations in roof pitch and number of stories using stereoscopic techniques. For this reason, accurate measurement of these characteristics was not possible without modifying the interpretation tech-

[2] As the interpretation of roof pitch involves considerable subjective judgement, it is possible that these interpretation errors reflect nothing more than a minor difference in the definitions of high and low pitch used by Hathout and the present researcher.

niques employed. In order to ensure complete accuracy, air photo interpretation was abandoned in favour of a ground survey. Each misinterpreted stratum was re-measured from the ground for all houses originally assigned to the stratum by air photo interpretation. As Goldstein and Hazard (1979, 10) noted, for areal units of 40 to 50 square miles or less, a ground-based survey is as economical as an aerial survey for the acquisition of information on house structure. This observation was borne out in the present study; the field survey of three strata expended approximately one-quarter of the man-hours required for air photo interpretation and accuracy testing for all seven strata.

3.4.2 Bivariate Regression Analysis

Bivariate regression analysis was employed in the present study to examine the relationships between roof temperature and individual structural features. This statistical technique is useful for assessing the form and significance of the relationship between two variables measured for the same set of observations when one of the variables is hypothesized to be dependent on the other. Regression analysis involves the estimation of an equation in which the value of the dependent variable is contingent on the value of the explanatory variable. This equation is calculated such that the sum of the squared deviations between actual values of the dependent variable and those predicted by the regression equation is at a minimum.

A separate regression analysis was performed with each of the following structural features assuming the role of the explanatory variable: attic insulation R-value, the presence of an attic ventilation system, roof orientation, roof pitch, lot frontage, house quality and the presence of an upper half story. In each case, roof temperature constituted the dependent variable. This approach facilitated comparison with previous research, in which bivariate regression analysis has been the main statistical technique employed to examine the relationship between roof temperature and house structure.

The following conditions were assumed to hold in regression analysis:

1. no error in the explanatory variable;
2. uncorrelated error terms;
3. homoscedastic errors; and
4. a random explanatory variable.

These conditions, if satisfied, guarantee no bias and maximum efficiency of the estimated coefficients, assuming there are no omitted explanatory variables that are correlated with the explanatory variable in the regression model. Bias is introduced by non-compliance with the first condition. Non-compliance with the second and third conditions reduces efficiency and thus may reduce the significance of the estimated coefficients.

Compliance with the second condition was tested using the Durbin-Watson statistic. A WATFIV programme (ERRTEST) was written for this purpose (Appendix F). This programme also tests for normality of the distribution of the error terms, so as to assess the applicability of standard confidence limits. Normality was tested with the Kolmogorov-Smirnov statistic, modified for calculation with sample estimates of the population mean and variance (Stephens 1974).

3.4.3 Multiple Regression Analysis

Multiple regression analysis was employed to examine the combined effect of all structural features on roof temperature. This technique enabled the proportion of total variation in roof temperature accounted for by all structural features to be determined. It facilitated measurement of the change in roof temperature associated with a unit change in a given feature, while controlling for the effects of all other features included in the model. All possible models containing between one and seven structural features were examined in the analysis. The coefficient of determination obtained in each of these models was then compared to that obtained in the model containing all seven features using an F-test described by Kmenta (1971, 370-71).

Multiple regression results were used to re-evaluate the findings of bivariate regression analysis, both in the present study and in previous research. Previous researchers have clearly not recognized that sample coefficients derived with bivariate regression analysis will be biased estimates of population coefficients if a set of intercorrelated variables affects the dependent variable (Kmenta 1971, 394). Thus bivariate regression analysis is not a reliable technique for assessing the precise form and significance of the relationships between roof temperature and features of house structure.

The four conditions assumed to hold for bivariate regression analysis were also assumed to be satisfied in multiple regression analysis. It was also assumed that there were no omitted explanatory variables that were correlated with the explanatory variables in the regression model and that the matrix of explanatory variables was of full rank. The programme ERRTEST was employed to assess the degree of correlation in the error terms and the normality of the distribution of error terms.

3.4.4 Partial Residuals

The derivation of partial residuals from the multiple regression equation is proposed as a method for reducing the dependence of roof temperature on features of house structure unassociated with ceiling heat loss. The technique is based on a method of deriving partial residuals outlined by Larsen and McCleary (1972). In the present study, partial residuals are defined as the difference between actual temperatures and the temperatures predicted by the multiple regression equation, given a constant value for insulation R-value for all sample houses. By assigning a constant value to R-value, the technique serves to eliminate roof temperature variation associated with all features in the regression model except R-value. Partial residuals therefore represent that component of the variation in roof temperature that is unaccounted for by all features except R-value. On the assumption that R-value is proportional to the level of ceiling heat loss, it is hypothesized that partial residuals will more accurately depict ceiling heat loss variations than roof temperature.

Successful application of this technique requires that all significant sources of roof temperature variation have been identified and included in the multiple regression model. Non-compliance with this assumption implies that the effects of some structural features will not have been eliminated from roof temperature in the calculation of partial residuals.

The technique also assumes that insulation R-value is orthogonal to all other structural features included in the multiple regression model. If this assumption is not met, a portion of the variation in roof temperature accounted for by R-value will be eliminated in the calculation of partial residuals. In the present study, non-compliance with this assumption was rectified using a Gram-Shmidt transformation.

Each significant structural feature in the model was regressed on R-value. Residual values of each feature were then calculated as the difference between actual and expected values calculated with the derived bivariate regression equation. In contrast to the original values of these features, residual values were orthogonal to R-value, as they represented that component of the variation in the feature that was not accounted for by R-value variations. Once orthogonalized, the features could be employed in the calculation of partial residuals without causing the elimination of variation in temperature associated with R-value.

The next step in the calculation of partial residuals involved the regression of roof temperature on insulation R-value and the orthogonalized equivalents of all significant structural features. Partial residuals (r) for each observation were then obtained using the following equation:

$$r = Y - a - \sum b_i X_i \qquad (3.2)$$

where

Y = Roof temperature

a = Intercept coefficient

b_i = Slope coefficient for orthogonalized feature i

X_i = Value of orthogonalized feature i

Coefficients used in this equation were obtained from the multiple regression model. Insulation R-value was not used in equation 3.2 to calculate partial residuals. However, R-value was included in the multiple regression model in order not to induce bias in the regression coefficients used in the equation.

Chapter IV

RESULTS

The following presents the results of data analysis. The first section deals with bivariate regression analysis, the second with multiple regression analysis and the third with partial residuals.

4.1 BIVARIATE REGRESSION ANALYSIS

Table 4.1 presents the results of the regression of roof temperature on attic insulation R-value. The relationship is negative, indicating that higher temperatures are associated with lower levels of insulation. The slope coefficient is highly significant. The coefficient of determination (R^2) indicates that 6.0% of the variation in roof temperature is accounted for by R-value variations. The Durbin-Watson statistic indicates that the error terms are positively correlated. The modified Kolmogorov-Smirnov statistic (d) indicates that the distribution of error terms is not normal in form. Examination of the histogram of residual values suggests that the distribution of error terms is positively skewed. Log and semi-log transformations involving both roof temperature and R-value failed to produce a normal distribution or significantly increase explanatory power. Similar results were obtained for square, square root and inverse transformations of roof orientation.

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	275.911	0.261	1058.204	<0.001
Slope	-0.316	0.087	-3.620	<0.001

R^2	F-Statistic	Significance
0.060	13.103	<0.001

Durbin-Watson Statistic	Significance
1.505	<0.05

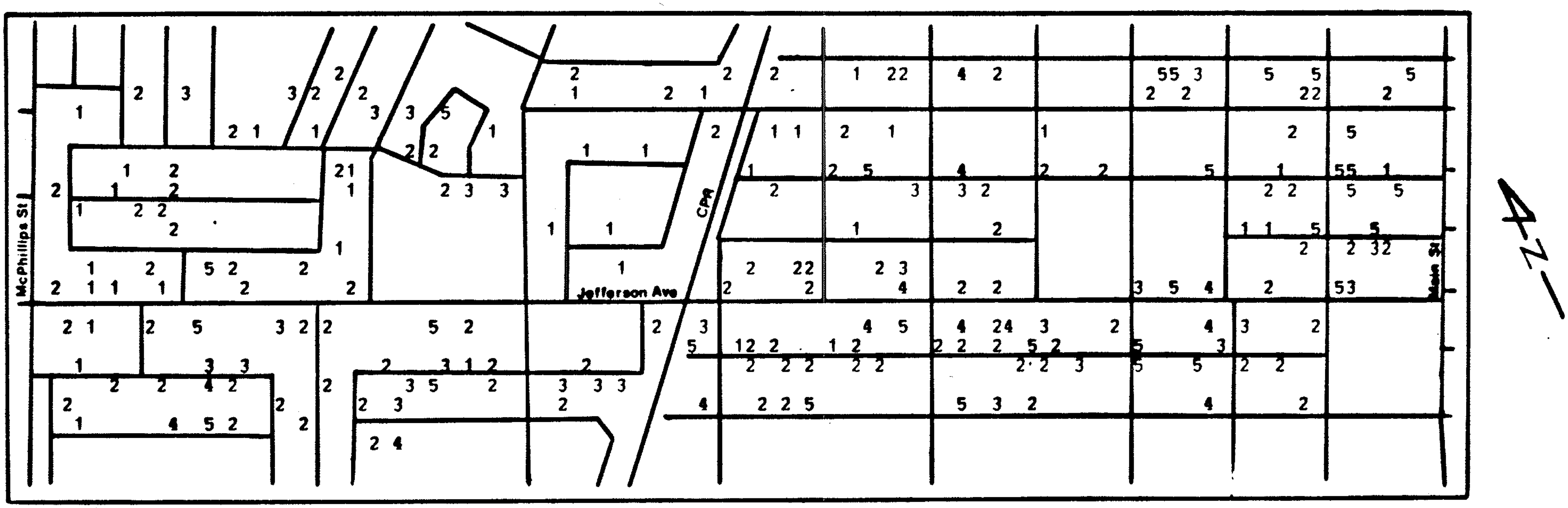
d-statistic	Significance
2.505	<0.01

TABLE 4.1

Regression of Roof Temperature on Insulation R-Value

The computer-generated maps presented in Figures 4.1 and 4.2 illustrate the relationship between roof temperature and insulation R-value. A negative relationship can be observed between these two features in the study area, especially in the older residential area east of the CPR tracks. In the newest area, located west of the tracks and north of Jefferson Avenue, roof temperatures are relatively low despite low levels of insulation.

Table 4.2 presents the results of the regression of roof temperature on the presence of an attic ventilation system. The relationship is positive, such that roof temperatures tend to be higher when a ventilation system is not present. The slope coefficient is significant and the coefficient of



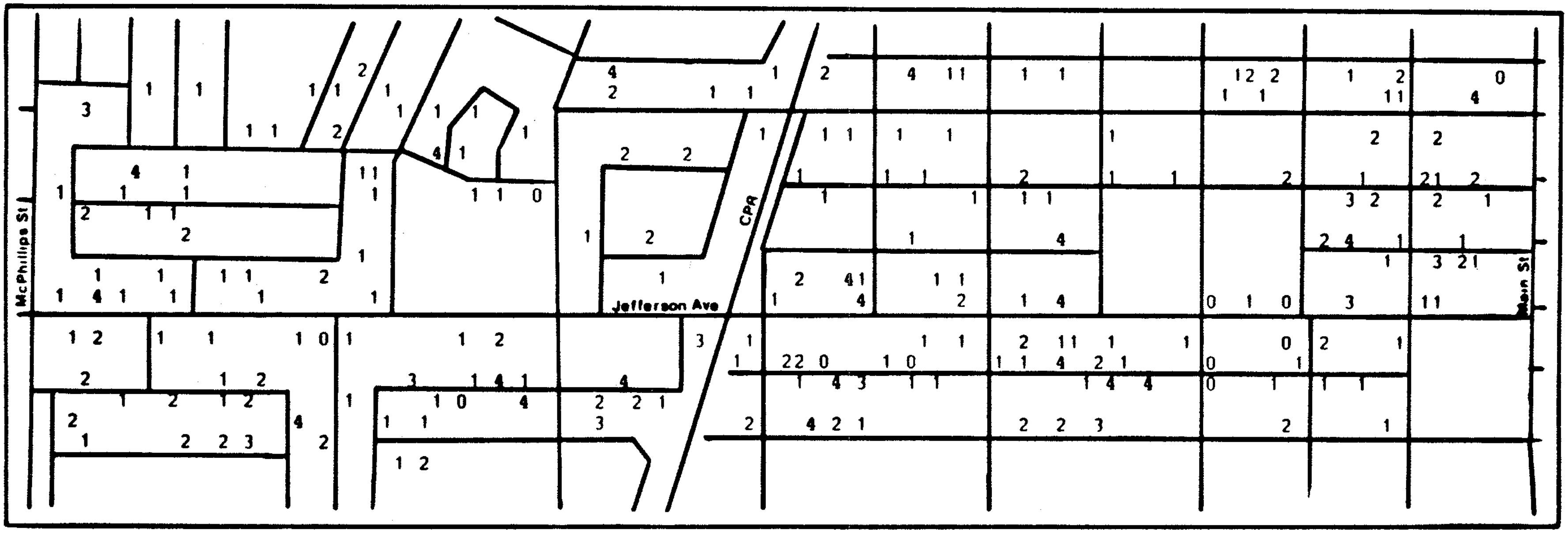
Scale - 1:12,500

LEGEND

1	< 274.0°K
2	274.0 - 274.9°K
3	275.0 - 275.9°K
4	276.0 - 276.9°K
5	≥ 277.0°K

FIGURE 4.1

Map of Roof Temperature



Scale - 1:12,500

LEGEND

0	No insulation
1	< R 2.5
2	R 2.5 - 3.4
3	R 3.5 - 4.4
4	> R 4.5

FIGURE 4.2

Map of Attic Insulation R-Value

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	275.833	0.312	885.323	<0.001
Slope	-0.888	0.329	-2.694	0.008

R^2	F-Statistic	Significance
0.034	7.259	0.008

Durbin-Watson Statistic	Significance
1.531	<0.05

d-statistic	Significance
2.735	<0.01

TABLE 4.2

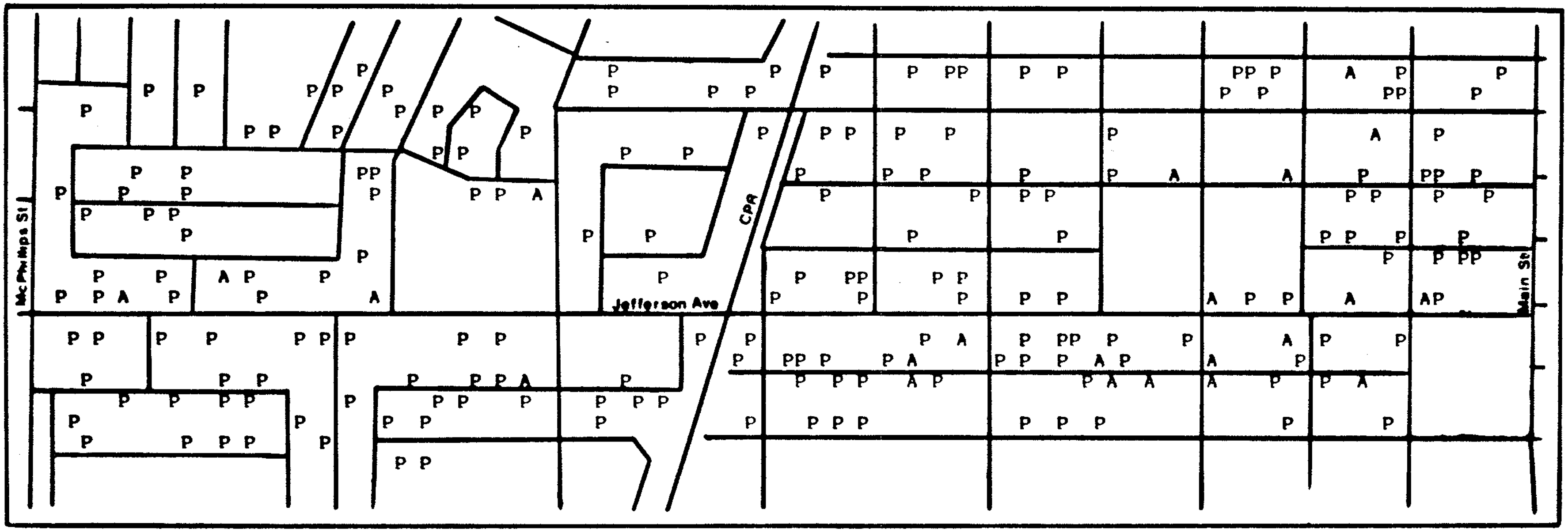
Regression of Roof Temperature on Attic Ventilation

determination indicates that 3.4% of the variation in roof temperature is accounted for by the presence of an attic ventilation system. The Durbin-Watson statistic indicates that the error terms are positively correlated. The d-statistic indicates that the distribution of error terms is not normal in form. Examination of the histogram of residual values suggests that the distribution is positively skewed. The log transformation of roof temperature failed to produce a normal distribution or significantly increase explanatory power. Transformations of attic ventilation had no effect on normality or explanatory power, since attic ventilation is a dichotomous variable.

The relationship between roof temperature and attic ventilation is illustrated in Figures 4.1 and 4.3. A relatively large proportion of those houses without an attic ventilation system have high roof temperatures. The proportion is much lower for houses that contain this feature.

Table 4.3 presents the results of the regression of roof temperature on roof orientation. The relationship is positive, indicating that roof temperatures are on average higher when the roof surface faces neighbouring buildings. The slope coefficient is significant and the coefficient of determination indicates that 2.9% of the variation in roof temperature is accounted for by roof orientation. The Durbin-Watson statistic indicates that the error terms are positively correlated. The d-statistic reveals that the distribution of error terms is not normal in form. Positive skewness was observed in the histogram of residual values. Log and semi-log transformations involving both roof temperature and roof orientation did not produce a normal distribution of error terms and reduced explanatory power. Similar results were obtained for the square, square root and inverse transformations of roof orientation.

The relationship between roof temperature and roof orientation is illustrated in Figures 4.1 and 4.4. In the area east of the CPR tracks, roof temperatures are generally higher when the roof surface faces neighbouring buildings than when it faces the street network. Roofs facing in both



Scale - 1 12,500

LEGEND
A Absent
P Present

FIGURE 4.3

Map of Attic Ventilation

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	274.538	0.225	1219.919	<0.001
Slope	0.970	0.389	2.495	0.013

R^2	F-Statistic	Significance
0.029	6.224	0.013

Durbin-Watson Statistic	Significance
1.571	<0.05

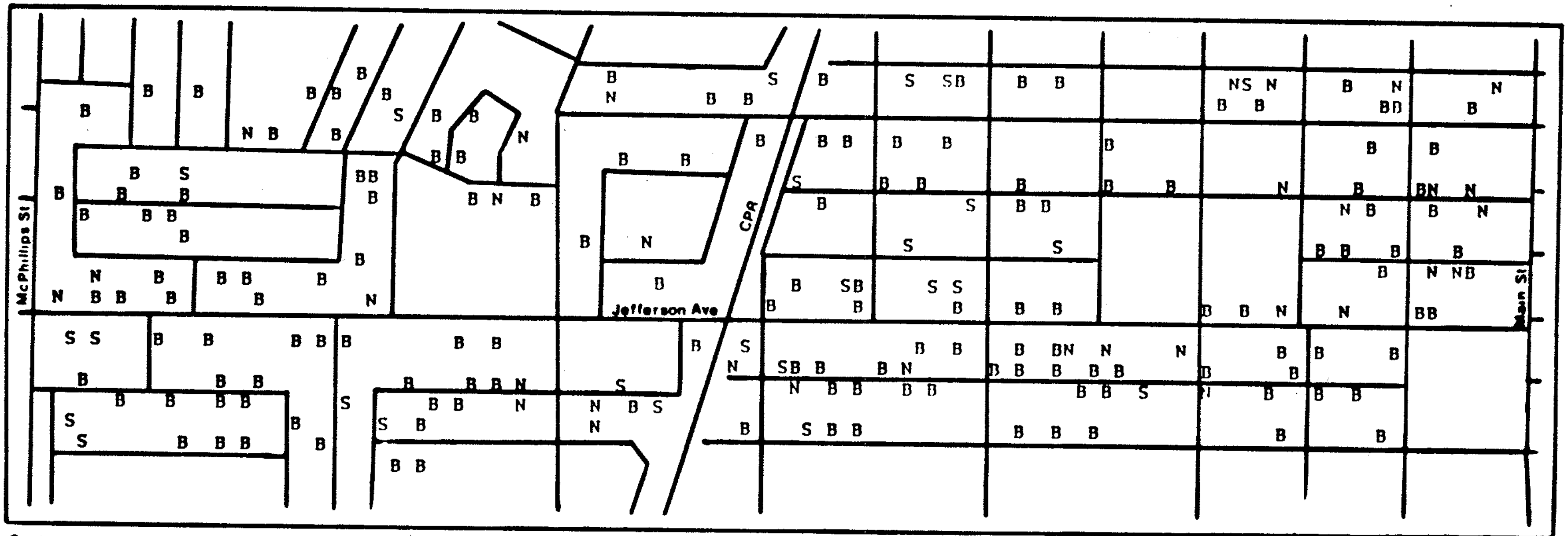
d-statistic	Significance
2.692	<0.01

TABLE 4.3

Regression of Roof Temperature on Roof Orientation

directions tend to fall between these two extremes. In the area west of the tracks, this relationship is not so readily apparent; silmilar roof temperatures occur regardless of the orientation of the roof.

Table 4.4 presents the results of the regression of roof temperature on roof pitch. The relationship is positive, such that roofs of high pitch are warmer on average than those of low pitch. The slope coefficient is highly significant and the coefficient of determination indicates that roof pitch accounts for 14.4% of the variation in roof temperature. The Durbin-Watson statistic indicates that the error terms are not positively correlated. The d-statistic indicates that the distribution of error terms is not normal



Scale = 1:12 500

<u>LEGEND</u>

S Faces street
N Faces neighbouring buildings
B Faces both directions

FIGURE 4.4

Map of Roof Orientation

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	274.787	0.104	2635.512	<0.001
Slope	1.505	0.255	5.908	<0.001

R^2	F-Statistic	Significance
0.144	34.903	<0.001

Durbin-Watson Statistic	Significance
1.698	>0.05

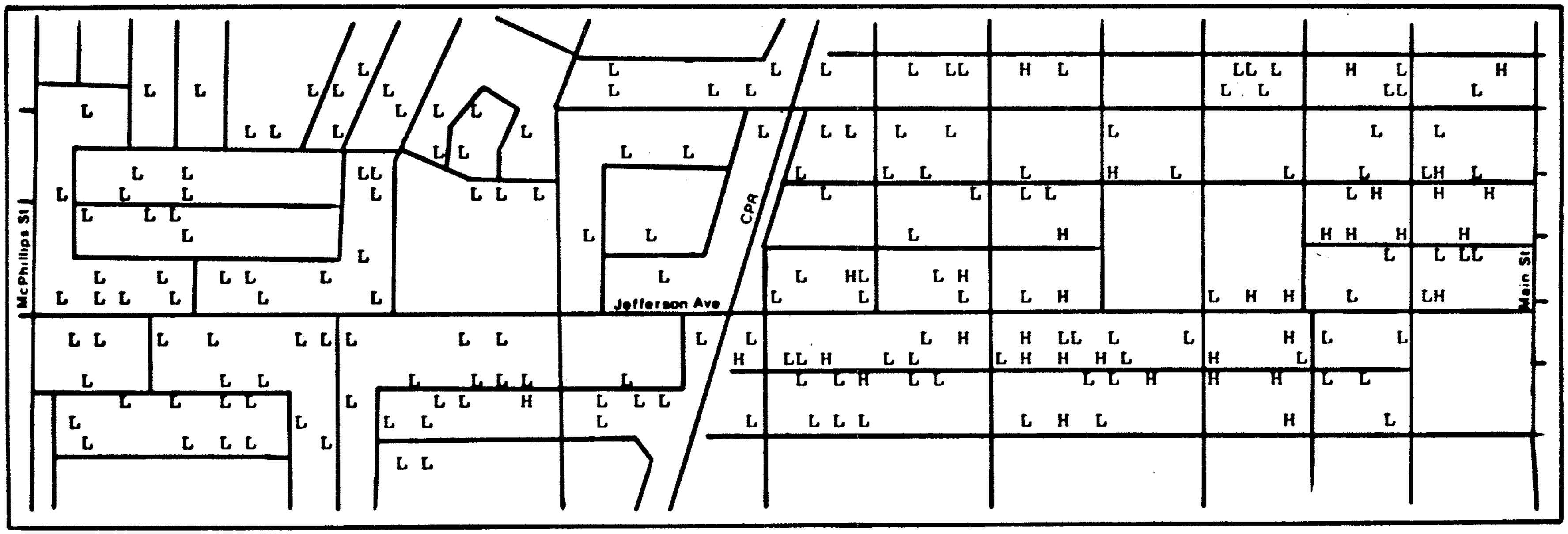
d-statistic	Significance
2.303	<0.01

TABLE 4.4

Regression of Roof Temperature on Roof Pitch

in form. Positive skewness was observed in the histogram of residual values. The log transformation of roof temperature failed to produce a normal distribution of error terms and did not increase explanatory power.

The relationship between roof temperature and roof pitch is illustrated in Figures 4.1 and 4.5. In the area east of the CPR tracks, a relatively large proportion of houses with roofs of high pitch have high roof temperatures. In comparison, most houses with roofs of low pitch have low roof temperatures. In the area west of the tracks, almost all roofs are of low pitch and therefore no relationship between roof temperature and roof pitch is apparent.



Scale = 1:12,500

LEGEND

L	Low
H	High

FIGURE 4.5

Map of Roof Pitch

Table 4.5 presents the results of the regression of roof temperature on the inverse of the square of lot frontage. The relationship is positive, indicating that roof temperature varies inversely as the square of lot frontage. The slope coefficient is highly significant and the coefficient of determination reveals that 11.4% of the variation in roof temperature is accounted for by lot frontage. The Durbin-Watson statistic indicates that the error terms are not positively correlated. The d-statistic indicates that the error terms are not normally distributed. Examination of the histogram of residual values suggests that the distribution is positively skewed. Log and semi-log transformations involving roof temperature and lot frontage did not produce a normal distribution or significantly increase explanatory power. Similar results were obtained for the square, square root and inverse transformations of lot frontage.

The relationship between roof temperature and lot frontage is illustrated in Figures 4.1 and 4.6. Throughout the study area, high roof temperatures are found in association with small lots, while low roof temperatures are more common when lots are large.

Table 4.6 presents the results of the regression of roof temperature on house quality. The relationship is negative, such that roof temperature tends to be lower when house quality is high. The slope coefficient is significant and

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	273.993	0.225	1219.814	<0.001
Slope	2246.130	435.371	5.159	<0.001

R^2	F-Statistic	Significance
0.114	26.616	<0.001

Durbin-Watson Statistic	Significance
1.799	>0.05

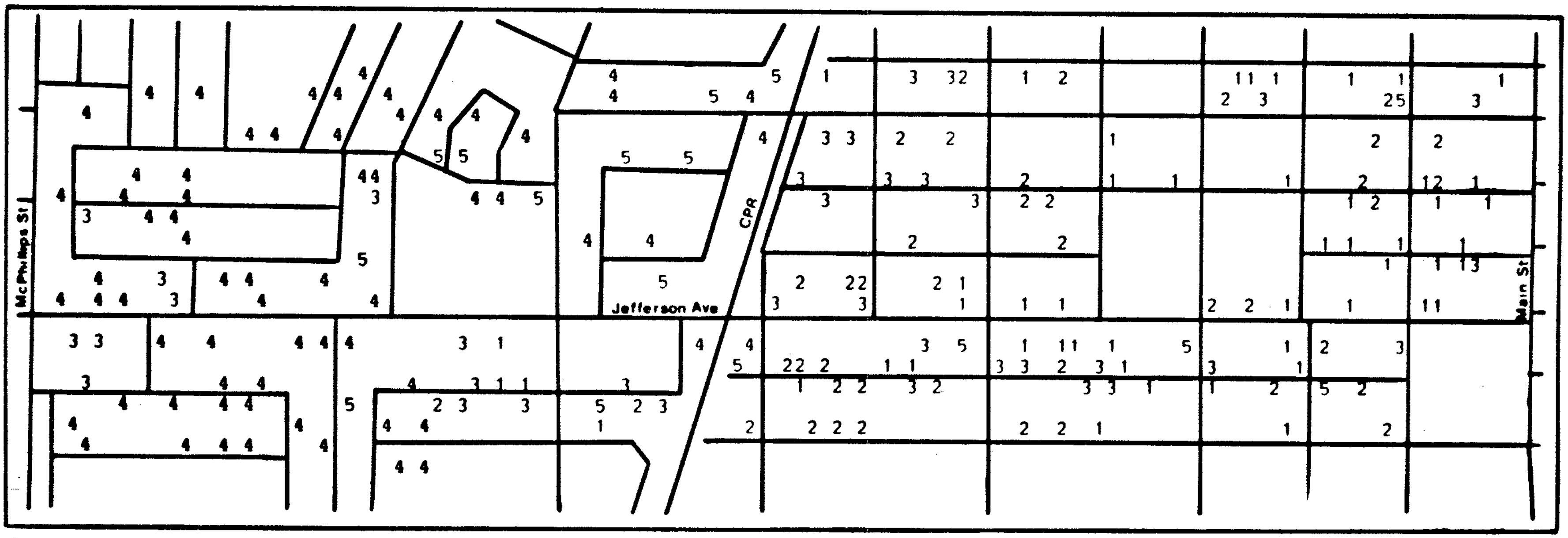
d-statistic	Significance
2.524	<0.01

TABLE 4.5

Regression of Roof Temperature on Inverse of Square of Lot Frontage

the coefficient of determination indicates that house quality accounts for 4.9% of roof temperature variation. The Durbin-Watson statistic indicates that the error terms are positively correlated. The d-statistic reveals that the distribution of error terms is not normal in form. Positive skewness was observed in the histogram of residual values. The log transformation of roof temperature neither produced a normal distribution nor increased explanatory power.

The relationship between roof temperature and house quality is illustrated in Figures 4.1 and 4.7. In the area east of the CPR tracks, a relatively large proportion of houses of low quality have high roof temperatures. In comparison, houses of high quality tend to have low roof temp-



Scale - 1:12 500

<u>LEGEND</u>

1	< 45.0′
2	45.0 - 49.9′
3	50.0 - 54.9′
4	55.0 - 59.9′
5	≥ 60.0′

FIGURE 4.6

Map of Lot Frontage

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	276.145	0.352	785.468	<0.001
Slope	-1.204	0.367	-3.281	0.001

R^2	F-Statistic	Significance
0.049	10.765	0.001

Durbin-Watson Statistic	Significance
1.539	<0.05

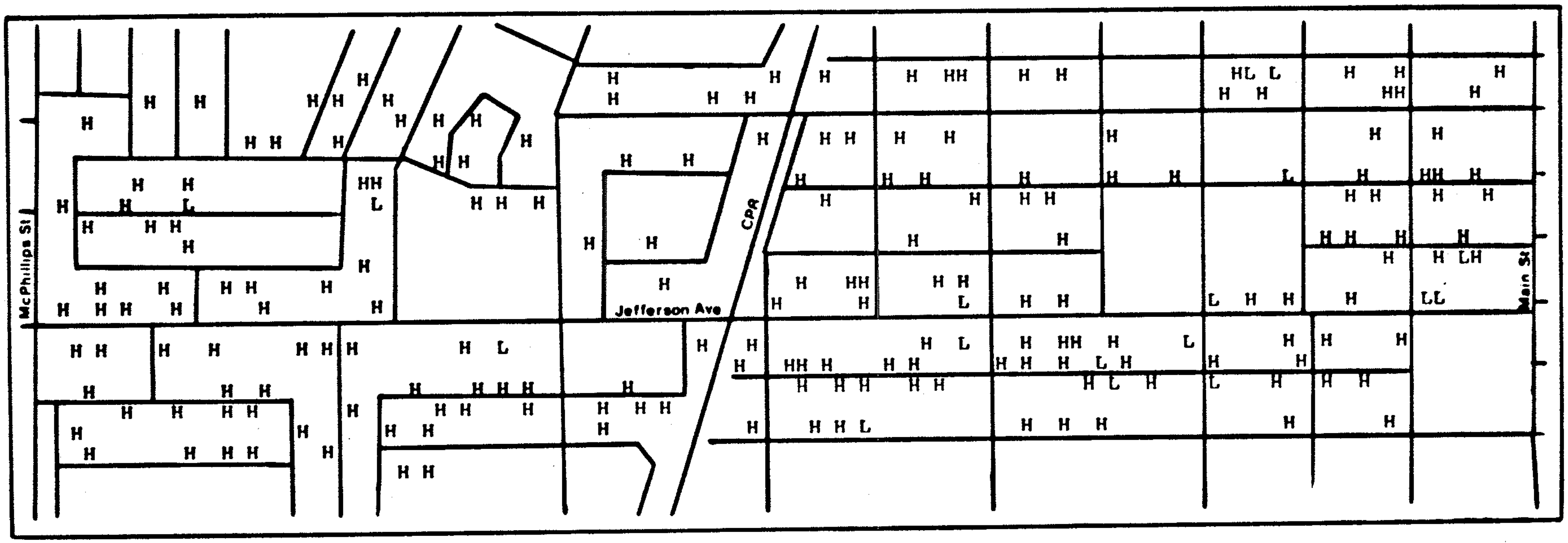
d-statistic	Significance
2.859	<0.01

TABLE 4.6

Regression of Roof Temperature on House Quality

eratures. In the area west of the tracks, very few houses are of low quality and thus a relationship between temperature and quality is not apparent.

Table 4.7 presents the results of the regression of roof temperature on the presence of an upper half story. The relationship is positive, indicating that roof temperature tends to be higher when the house contains an upper half story. The slope coefficient is significant and the coefficient of determination indicates that the presence or absence of an upper half story accounts for 12.7% of the variation in roof temperature. The Durbin-Watson test is inconclusive. The d-statistic indicates that the distribution of error terms is not normal in form. Positive skewness was



Scale - 1:12,500

LEGEND

L Low

H High

FIGURE 4.7

Map of House Quality

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	274.815	0.104	2631.799	<0.001
Slope	1.464	0.267	5.485	<0.001

R^2	F-Statistic	Significance
0.127	30.085	<0.001

Durbin-Watson Statistic	Significance
1.675	inconclusive

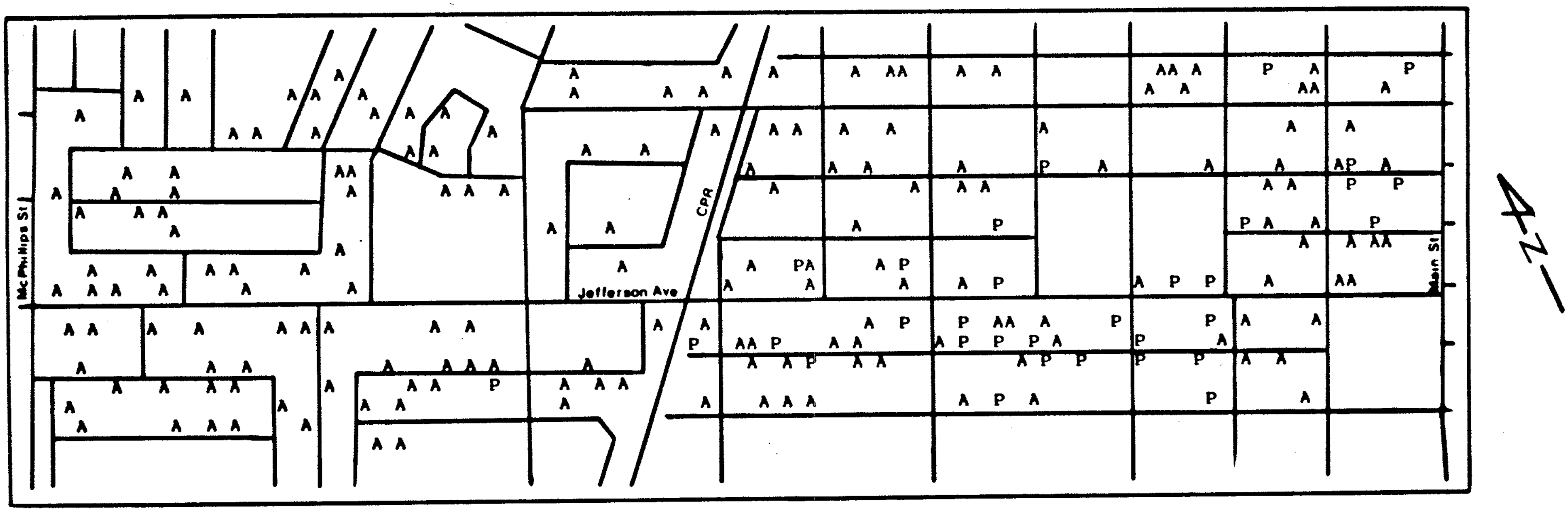
d-statistic	Significance
2.352	<0.01

TABLE 4.7

Regression of Roof Temperature on Presence of an Upper Half Story

observed in the histogram of residual values. The log transformation of roof temperature did not produce a normal distribution or increase explanatory power.

The relationship between roof temperature and the presence of an upper half story is illustrated in Figures 4.1 and 4.8. In the area east of the CPR tracks, a relatively large proportion of houses with an upper half story have high roof temperatures. In comparison, houses without this feature more frequently have low roof temperatures. In the area west of the tracks, a relationship between these two features is not apparent, as few houses contain an upper half story.



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LEGEND

A Absent
P Present

FIGURE 4.8

Map of the Presence of an Upper Half Story

4.2 MULTIPLE REGRESSION ANALYSIS

Table 4.8 presents the results of multiple regression analysis. The signs of the slope coefficients for all seven structural features are in accordance with expectations and agree with the results of bivariate regression analysis. However, three features are highly insignificant in the multiple regression model: attic ventilation, roof orientation and the presence of an upper half story. The coefficient of determination indicates that the seven features combined account for 28.8% of the variation in roof temperature. The Durbin-Watson statistic indicates that the error terms are not positively correlated. The d-statistic indicates that the error terms are not normally distributed. Examination of the histogram of residual values suggests that the distribution is positively skewed. The log transformation of roof temperature neither produced a normal distribution nor increased explanatory power.

Examination of all models containing between one and seven features revealed that as long as insulation R-value, house quality, the inverse of the square of lot frontage and either roof pitch or the presence of an upper half story were included in the model, all other features could be excluded without significantly reducing explanatory power. Neither insulation R-value nor house quality nor the inverse of the square of lot frontage could be removed from the model without a significant reduction in explanatory power.

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	275.549	0.525	525.179	<0.001
Insulation R-value	-0.294	0.080	-3.673	<0.001
Attic ventilation	-0.054	0.313	-0.173	0.863
Roof orientation	0.270	0.357	0.756	0.451
Roof pitch	0.934	0.509	1.834	0.068
1/Lot frontage^2	1426.709	439.946	3.243	0.001
House quality	-0.719	0.346	-2.077	0.039
Upper half story	0.320	0.524	0.611	0.542

R^2	F-Statistic	Significance
0.285	11.430	<0.001

Durbin-Watson Statistic	Significance
1.842	>0.05

d-statistic	Significance
1.684	<0.01

TABLE 4.8

Multiple Regression Results (7 Features)

Explanatory power was also reduced if roof pitch and the presence of an upper half story were simultaneously removed; however, removal of only one of these two features did not significantly reduce explanatory power if the other feature remained in the model. In all models containing both roof pitch and the presence of an upper half story, the latter feature was consistently insignificant.

For all models examined, the lowest Cp statistic was observed for the four-feature model containing insulation R-value, roof pitch, house quality and the inverse of the square of lot frontage. The Cp statistic indicates a relatively favourable trade-off between explanatory power and the number of features in the model. The four features identified correspond to those features that are not highly insignificant in the original seven-feature model (Table 4.8)

Table 4.9 presents the results of regression analysis for the four-feature model. All features are significant and the signs of the slope coefficients conform to expectations. The coefficient of determination indicates that the four features combined account for 28.1% of the variation in roof temperature. This percentage is not significantly different from that obtained in the original seven-feature model ($p = 0.778$). The Durbin-Watson statistic indicates that the error terms are not positively correlated. The d-statistic reveals that the distribution of error terms is not normal in form. Examination of the histogram of residual values suggests that the distribution is positively skewed. The log transformation of roof temperature failed to produce a normal distribution or increase explanatory power.

Due to the presence of dichotomous explanatory variables in the regression model, tests of significance are not necessarily robust against non-normality of the error terms. Until a normal distribution of error terms can be obtained, either by a transformation of roof temperature or measurement of the explanatory variables in continuous units, the significance of the explanatory variables remains in doubt. More research is required to rectify this problem.

Coefficient	Estimate	Standard Error	t-Statistic	Significance
Intercept	275.707	0.440	626.599	<0.001
Insulation R-value	-0.306	0.077	-3.964	<0.001
Roof pitch	1.206	0.246	4.907	<0.001
1/Lot frontage^2	1487.090	422.057	3.523	<0.001
House quality	-0.782	0.330	-2.373	0.019

R^2	F-Statistic	Significance
0.281	19.909	<0.001

Durbin-Watson Statistic	Significance
1.839	>0.05

d-statistic	Significance
1.759	<0.01

TABLE 4.9

Multiple Regression Results (4 Features)

Correlation coefficients were obtained for all pairs of structural features to assess the effects of intercorrelation on the regression results. The correlation matrix is presented in Table 4.10. Examination of the matrix reveals that roof pitch and the presence of an upper half story are the most highly correlated structural features in the data set (r = 0.877). In addition, attic ventilation and roof orientation are both significantly correlated with most of the other features in the data set.

4.3 PARTIAL RESIDUALS

Partial residuals were calculated from the four-feature model presented in Table 4.9. The Gram-Shmidt transformation

	Insulation R-value	Attic ventilation	Roof orientation	Roof pitch	1/Lot frontage^2	House quality
Attic ventilation	0.179*					
Roof orientation	-0.173*	-0.128				
Roof pitch	-0.013	-0.139*	0.045			
1/Lot frontage^2	0.020	-0.179*	0.237*	0.289*		
House quality	0.059	0.297*	-0.115	-0.054	-0.212*	
Upper half story	-0.004	-0.201*	0.075	0.877*	0.230*	-0.117

* significant at <0.05

TABLE 4.10

Correlation Matrix

was performed to orthogonalize roof pitch, house quality and the inverse of the square of lot frontage relative to insulation R-value. Roof temperature was then regressed on R-value and the three orthogonalized features. Partial residuals were calculated with equation 3.2.

As hypothesized, the correlation between partial residuals and insulation R-value ($r = -0.277$) was found to be higher than that between roof temperature and insulation R-value ($r = -0.244$). The difference between these two correlation coefficients was evaluated with a t-test described by Ferguson (1959, 154-55). The test indicated that the difference was not highly significant (1-tailed $p = 0.154$).

Chapter V

DISCUSSION

Bivariate regression analysis revealed significant relationships between roof temperature and each of the seven structural features examined in the study. A negative relationship was observed between roof temperature and attic insulation R-value. This finding is in agreement with those of Lawrence, Ellis and Smith (1978), Hathout (1980, 1981), Brown, Cihlar and Teillet (1981) and Treado and Burch (1981). In the present study, R-value was observed to account for 6.0% of the variation in roof temperature. This finding agrees with Brown, Cihlar and Teillet (1981), who found that R-value accounted for between 1.0 and 11.0% of apparent roof temperature variation, depending on house style. Lawrence, Ellis and Smith (1978) found that up to 69.0% of the variation in apparent roof temperature was accounted for by insulation thickness. The higher level of explanatory power achieved in their study, however, is in part attributable to the fact that the researchers excluded all houses with anomalous features from the sample.

In the present study, the relationship between roof temperature and insulation R-value was also examined on computer-generated maps of the sample houses. These maps showed a tendency for houses with low levels of insulation to have high roof temperatures, especially in the older parts of the study area. Substantial temperature variation was observed for houses with similar levels of insulation. The latter finding suggests that features other than R-value also have a significant effect on roof temperature. Thus, roof temperature does not consistently portray variations in the level of attic insulation present in residential buildings.

Bivariate regression analysis also revealed a significant negative relationship between roof temperature and the presence of an attic ventilation system. Houses containing a ventilation system thus have roof temperatures that are lower on average than those of houses without this feature. This relationship was also observed in the computer-generated maps of these two features. This finding agrees with those of Brown, Teillet and Cihlar (1978) and Brown, Cihlar and Teillet (1981). These researchers found that attic ventilation reduces the amount of interior heat reaching the roof surface and thus tends to lower roof temperature.

In the present study, the presence of an attic ventilation system was observed to account for only 3.4% of the variation in roof temperature. In contrast, Brown, Cihlar and Teillet (1981) found that up to 23.0% of the variation in apparent roof temperature was accounted for by the rate of attic ventilation. The discrepancy between these findings can be ascribed in part to the fact that attic ventilation was measured as a dichotomous variable in the present study, taking values of 1 and 0 to denote the presence or absence of a ventilation system. Houses classified as having a ventilation system, however, may exhibit significant variations in attic ventilation rate that affect roof temperature. Such variations may arise from the physical characteristics of the ventilation system, including the type, number, size, location and operating efficiency of the vents.

As Brown, Cihlar and Teillet (1981) observed, the relationship between roof temperature and attic ventilation is also highly dependent on environmental conditions such as wind speed and direction. They found that attic ventilation has a significant effect on roof temperature only when wind speed is relatively high (ie., greater than 10 to 15 km/hr). Under such conditions, the rate of air exchange from the attic varies according to the physical characteristics of the ventilation system. At lower wind speeds, differences in system characteristics cause no significant changes in roof temperature, due to the fact that the rate of air exchange from the attic remains relatively constant. In the present study, thermographic data were collected during a period of relatively low wind speed (11 km/hr), which suggests that attic ventilation rate may have had a minimal effect on roof temperature.

Bivariate regression analysis revealed significant relationships between roof temperature and three features associated with the amount of incident radiation received by the roof: roof orientation, roof pitch and lot frontage. A positive relationship was observed between roof temperature and roof orientation. Thus, roof temperature is higher on average when the roof surface faces neighbouring buildings. This relationship was also observed in the computer-generated maps of these two features, especially in the older residential area. Similar results were obtained by Hathout (1980, 1981).

Roof pitch was also found to be positively related to roof temperature. Roof temperatures are therefore higher on average for roofs of high pitch. Computer-generated maps revealed that this relationship was most apparent in the older residential area, since most houses in the newer area had roofs of low pitch. Hathout (1980, 1981) and Brown, Cihlar and Teillet (1981) also observed a positive relationship between roof temperature and roof pitch. The latter researchers found that roof pitch accounted for approximately 10% of the variation in apparent roof temperature. The percentage was higher in the present study, at 14.4%.

A positive relationship was also observed between roof temperature and the inverse of the square of lot frontage. Various transformations of lot frontage failed to increase explanatory power, indicating that roof temperature varies inversely as the square of the distance between buildings. The relationship between roof temperature and lot frontage was observed in maps of the study area; houses with small lots were more frequently found to have high roof temperatures.

The significance of roof orientation, roof pitch and lot frontage in bivariate regression analysis agrees with the results of Tanis and Sampson (1977). These researchers found that by accounting for these three features, estimates of relative levels of ceiling heat loss for residential buildings could be obtained from thermographic data. In their study, the features were incorporated into a single index of roof exposure. This approach recognizes explicitly that these features do not operate independently, but instead have an interactive effect on the amount of incident radiation received by the roof. Hence, formulation of an interactive variable in the present study may have significantly increased explanatory power.

Bivariate regression analysis revealed a negative relationship between roof temperature and house quality, indicating that temperatures are on average lower for houses of high quality. This relationship was also observed in the computer-generated maps, especially in the older area. This finding is not directly comparable to previous research, since no researchers have examined the relationship between roof temperature and house quality. However, Lawrence, Ellis and Smith (1978), Hathout (1980, 1981) and Brown, Cihlar and Teillet (1981) observed a significant positive relationship between roof temperature and house age. This relationship was variously attributed to differences in attic insulation levels, attic ventilation system characteristics and other structural features in houses of different ages. On the assumption that house quality generally declines with advancing age, similar differences are likely to be observed in houses of different quality.

A significant positive relationship was observed between roof temperature and the presence of an upper half story in bivariate regression analysis. Thus, houses with an upper half story tend to have higher roof temperatures than those without this feature. This relationship was apparent in the computer-generated maps of the two features, especially in the older area where houses with an upper half story were more prevalent. A similar relationship between roof temperature and the presence of an upper half story was observed by Lawrence, Ellis and Smith (1978) and Brown, Cihlar and Teillet (1981). The former group of researchers found that apparent roof temperatures of one-and-a-half story houses were generally higher than those of bungalows or split-level houses. The latter group of researchers found that one-and-a-half story houses generally had higher apparent roof temperatures than bungalows. This relationship may be attributed to variations in the amount of convective heat loss from taller buildings, lower levels of insulation in the walls and sloping ceilings of the upper story, or lower attic ventilation rates due to compartmentalization of the attic air space. Alternatively, the relationship may arise from an increase in the amount of incident radiation received by the roof, due to the presence of roof dormers and a roof of high pitch needed to ensure sufficient living space on the upper story of the house.

While all seven structural features were significant in bivariate regression analysis, three features were found to be highly insignificant in the initial multiple regression model: attic ventilation, roof orientation and the presence of an upper half story. It was found that attic ventilation and roof orientation could be removed from the model without significantly reducing explanatory power. Correlation analysis revealed that these two features were significantly correlated to most other features in the model. The existence of these correlations made it difficult to separate the individual effects of attic ventilation and roof orientation. These features may in fact have no significant effect on roof temperature, in which case their observed significance in bivariate regression analysis is attributable to their correlation with other structural features. Conversely, they may be significant, but not account for any additional temperature variation not accounted for by the features with which they are correlated.

It was observed that the presence of an upper half story could be removed from the multiple regression model without a significant loss of explanatory power as long as roof pitch remained in the model. If roof pitch was removed, the presence of an upper half story could not also be removed without causing a significant reduction in explanatory power. These findings can be attributed to the high correlation existing between these two features. There is a close correspondence in the sample houses between the presence of a roof of high pitch and the presence of an upper half story. Presumably, a roof of high pitch is required to provide sufficient living space on the upper half story of the house.

Examination of alternative regression models revealed that in models containing both roof pitch and the presence of an upper half story, the latter feature was consistently insignificant. This observation suggests that the inclusion of the presence of an upper half story in the model is redundant if the model already contains roof pitch. However, the high correlation between these two features makes it difficult to separate their individual effects and establish reliably the significance of each feature.

Truncation of the multiple regression model to include only four features, insulation R-value, roof pitch, house quality and the inverse of the square of lot frontage, did not significantly reduce explanatory power relative to the original seven-feature model. The coefficient of determination for the truncated model was 0.281. This model had the highest coefficient of determination of all four-feature models and the highest Cp statistic of all possible subsets of between one and seven features. The Cp statistic indicated a relatively favourable trade-off between explanatory power and the number of features included in the model. In contrast to the original seven-feature model, all features in the truncated model were significant. It was concluded that attic ventilation, roof orientation and the presence of an upper half story did not contribute significantly to explanatory power once the other four features were included in the model.

Comparison of the original and truncated models indicated that the standard errors of all regression coefficients in the truncated model were reduced relative to those in the original seven-feature model. This phenomenon results from the elimination of intercorrelated features, the presence of which tends to induce upward bias in the standard errors (Chiswick and Chiswick 1975, 189). Thus elimination of such features in the truncated model in effect made the regression coefficients more precise estimates of population coefficients.

Multiple regression analysis also facilitated the derivation of partial residuals from the regression equation. As hypothesized, the correlation between partial residuals and insulation R-value was higher than that between roof temperature and insulation R-value. This difference was not, however, statistically significant. This evidence does not support the hypothesis that partial residuals are a more precise index of ceiling heat loss than roof temperature, due to a reduction in the effects of house structure. This conclusion is contingent on the assumption that ceiling heat loss variations are accurately portrayed by insulation R-value.

Lack of a significant difference can be attributed to the low explanatory power of the multiple regression model. A large proportion of the variation in roof temperature remains unaccounted for by the features included in the model. Partial residuals are therefore dependent on these sources of temperature variation, indicating that the effects of house structure have not been completely eliminated in the calculation of partial residuals.

Chapter VI

CONCLUSION

In the present study, the relationship between house structure and thermographic measurements of roof temperature were examined for a sample of houses in a residential district of Winnipeg. The main objectives were: to identify structural features of residential buildings that have a significant effect on roof temperature; and introduce a simple method for reducing the effects of house structure on roof temperature. The application of aerial thermography to ceiling heat loss estimation in residential buildings is based on the premise that roof temperature is determined primarily by the level of ceiling heat loss. However, research has revealed that structural features introduce variations in roof temperature that are unrelated to the level of ceiling heat loss. Consequently, roof temperature does not accurately portray ceiling heat loss variations among residential buildings.

Previous research indicates that roof temperature variations arise primarily from three sources: the level of ceiling heat loss, the rate of heat dissipation through the attic vents and the amount of incident radiation received by the roof. Temperature variations may also arise from differences in house age and style and the presence of anomalous roofing materials or structural characteristics.

Seven features of house structure were examined in the present study: attic insulation R-value, the presence of an attic ventilation system, roof orientation, roof pitch, lot frontage, house quality and the presence of an upper half story. Insulation R-value was assumed to be proportional to the level of ceiling heat loss. The presence or absence of an attic ventilation system indicated whether or not heat dissipation from the attic would occur. Roof orientation, roof pitch and lot frontage were hypothesized to affect the amount of incident radiation received by the roof. House quality was proposed as a surrogate measure of house age and assumed to reflect variations in the structural characteristics of houses of different ages. The presence of an upper half story was assumed to be associated with variations in both conductive and convective heat loss, attic ventilation and the amount of incident radiation received by the roof.

Bivariate regression analysis revealed a significant relationship between roof temperature and each of the seven features examined. All relationships were of the form hypothesized to exist and were in agreement with previous research. Positive relationships were observed for roof orientation, roof pitch, the inverse of the square of lot frontage and the presence of an upper half story. Negative relationships were observed for insulation R-value, attic ventilation and house quality. Thus higher roof temperatures were found to be associated with the following features: lower levels of attic insulation, the absence of an attic ventilation system, a roof that faced neighbouring buildings, a roof of high pitch, the presence of a narrow lot, low house quality and the presence of an upper half story. These relationships were also observed in computer-generated maps of the study area.

Although all seven features were significant in bivariate regression analysis, three features were highly insignificant in the initial multiple regression model: attic ventilation, roof orientation and the presence of an upper half story. Roof orientation and attic ventilation were found to be significantly correlated with most other features in the multiple regression model. It was thus difficult to separate the individual effects of these two features. Similarly, the individual effects of roof pitch and the presence of an upper half story could not be clearly established, as these two features were highly correlated. Examination of alternative regression models suggested that the inclusion of the presence of an upper half story in the model was redundant if the model already contained roof pitch. However, it could not be concluded that a significant relationship did not exist between roof temperature and the presence of an upper half story, since this relationship could have been masked by the correlation between this feature and roof pitch.

The truncated multiple regression model contained only four features: insulation R-value, roof pitch, house quality and the inverse of the square of lot frontage. The coefficient of determination for this model, 0.281, was not significantly lower than that obtained in the original seven-feature model. It was concluded that attic ventilation, roof orientation and the presence of an upper half story did not add significantly to explanatory power if the other four features were included in the model.

Results of multiple regression analysis necessitated re-evaluation of the conclusions based on the results of bivariate regression analysis. Due to the existence of correlations between structural features, it could not be concluded that all features observed as significant in bivariate regression analysis were in fact significantly related to roof temperature. If the dependent variable in a regression model is affected by a set of intercorrelated explanatory variables, the regression coefficients obtained with bivariate regression analysis will be biased estimates of population coefficients. It is therefore probable that in previous research, biased estimates of the effects of individual structural features were obtained, due to the reliance on bivariate regression analysis as the primary statistical technique employed in data analysis.

In the present study, derivation of partial residuals from the multiple regression equation was proposed as a method of reducing the dependence of roof temperature on features of house structure unrelated to ceiling heat loss variations. The technique eliminates that component of the variation in roof temperature associated with all features in the regression model except insulation R-value. On the assumption that R-value accurately portrays differences in the level of ceiling heat loss, partial residuals should reflect variations in the level of ceiling heat loss more accurately than roof temperature.

As hypothesized, the correlation between partial residuals and insulation R-value was higher than that between roof temperature and insulation R-value. The difference, however, was not statistically significant. Lack of a significant difference was attributed to the low explanatory power of the multiple regression model. Less than 30% of the variation in roof temperature was accounted for by the four features in the model. Hence, partial residuals were still dependent on sources of temperature variation not identified in the present study.

Additional research is needed to address the shortcomings of the present study and increase confidence in the results. Specifically, the problem of low explanatory power and intercorrelation should be addressed. Low explanatory power indicates that much of the variation in roof temperature is unaccounted for by the features included in the regression model. This phenomenon may be caused by a number of factors.

Relevant explanatory variables may have been inadvertantly omitted, due to lack of understanding of all relationships involved. Thus exploratory analysis may prove useful in identifying additional structural features that have a significant effect on roof temperature. Local variations in topography and wind speed and direction may also prove to be significant. Differences in sensor viewing angle associated with the interaction between roof orientation, roof pitch and the distance between the target house and the flight line of the aircraft may introduce variations in the amount of radiation received by the IRLS.

It is also possible that low explanatory power resulted in part from the measurement of certain continuous variables, including attic ventilation and roof pitch, as dichotomous variables. It has been noted that the empirical relationship between two variables is altered by the selection of cutpoints to facilitate dichotomization (Blalock 1964, 33). However, measurement of structural features operationally on a continuous scale may prove to be too difficult, costly, or time-consuming, making dichotomization a requirement of data collection.

A third cause of low explanatory power in the present study derives from the measurement of roof temperature from photographic slides of sliced thermographs. This measurement technique may have introduced error into roof temperature measurements due to distortions in roof area induced by the various devices employed to photograph and display the thermographs. In addition, actual variations in roof temperature exist within each temperature range delimited by the colours on the thermographs. The use of sliced thermographs thus tends to mask roof temperature variations among houses. An effort should be made to use digital image analysis to measure roof temperature whenever the requisite resources for such analysis are available.

The second problem identified in the study, intercorrelation, presents a unique problem in data analysis because it increases the difficulty of separating the individual effects of all structural features. High correlations between two or more explanatory variables in the regression model thus reduce the reliability of choosing between alternate models. Due to the possibility of intercorrelation existing in the data set, bivariate regression analysis is not a suitable statistical technique for examining the relationship between roof temperature and house structure.

In the present study, intercorrelation was observed to result from limited structural variation in the sample houses. Certain combinations of structural features were observed to occur far more frequently than others in the sample. The maximum number of unique combinations of structural features is equal to the product of the number of unique values for each structural feature. Grouping insulation R-value and lot frontage into three classes each, the total number of unique combinations is therefore 432. This value indicates that it is possible for each house in the sample to exhibit a unique combination of features. However, only 49 different combinations were observed in the entire sample, while in 87% of the sample, or 180 houses, only 20 unique combinations were observed.

One possible solution to the problem of intercorrelation involves the use of an alternative sampling strategy to that employed in the present study. One alternative is random-stratified sampling, in which the same number of observations is selected from each unique combination of structural features. This method of sampling would reduce intercorrelation but require the collection of a very large sample even if only a relatively small number of features was examined. Moreover, the approach assumes that all features can be non-arbitrarily classified into two or more discrete groups to facilitate sample selection.

Reducing the degree of intercorrelation and increasing explanatory power would facilitate employment of the technique described in the study for obtaining partial residuals from the regression model. Successful application of this technique would enable partial residuals to be employed as an index of the level of ceiling heat loss in place of roof temperature. Partial residuals for the entire population of interest could be obtained from the multiple regression equation derived from a sample of houses. This would improve the reliability of aerial thermography as a diagnostic tool for rapidly evaluating ceiling heat loss conditions in a residential area or estimating relative levels of heat loss for individual houses.

Appendix A

QUESTIONNAIRE

[Establish contact with homeowner.]

THIS IS ___________ CALLING FROM THE UNIVERSITY OF MANITOBA. I AM CONDUCTING A TELEPHONE SURVEY TO COLLECT INFORMATION FOR A STUDY ON INSULATION CONDITIONS IN YOUR AREA. WOULD YOU BE WILLING TO ANSWER SOME QUESTIONS ABOUT INSULATION LEVELS IN YOUR HOME?

NO → terminate

YES → continue

A NUMBER OF GOVERNMENT INSULATION PROGRAMMES EXIST THAT CAN BE USED BY HOMEOWNERS TO REDUCE THE COST OF ADDING INSULATION.

(1) ARE YOU FAMILIAR WITH CHIP, THE CANADA HOME INSULATION PROGRAM?

NO / YES → (2)

(2) ARE YOU FAMILIAR WITH MHILP, THE MANITOBA HOMEOWNERS' INSULATION LOAN PROGRAMME?

NO / YES → (3)

(3) ARE YOU FAMILIAR WITH CHRP, THE CANADA HOME RENOVATION PLAN?

NO ↓ YES ↓

ALL NO → 16

ANY YES → 4

(4) HAVE YOU EVER MADE USE OF ANY OF THESE PROGRAMMES TO UPGRADE INSULATION LEVELS IN YOUR PRESENT HOME?

16 ← NO

YES ↓

(5) WHICH PROGRAMME WAS IT - CHIP, MHILP, OR CHRP? OR DID YOU MAKE USE OF MORE THAN ONE?

____

(6) WHEN DID YOU MAKE USE OF IT?

____

(7) UNDER THIS PROGRAMME, WAS INSULATION INSTALLED INTO THE ATTIC OF YOUR HOME?

21 ← NO

YES ↓

(8) WHAT KIND OF INSULATION WAS INSTALLED?

____

(9) BEFORE YOU MADE USE OF THE PROGRAMME, WAS THERE ALREADY INSULATION IN THE ATTIC?

13 ← NO

YES ↓

(10) WHAT KIND OF INSULATION WAS THERE?

____

(11) WHEN WAS THIS INSULATION INSTALLED?

____

(12) WHEN THE NEW INSULATION WAS INSTALLED, WAS IT PLACED ON TOP OF THE EXISTING INSULATION, OR WAS THE EXISTING INSULATION REMOVED?

ON TOP   REMOVED

(13) DOES YOUR HOUSE HAVE ATTIC VENTS?

Terminate ← NO   YES

(14) WERE THE VENTS INSTALLED UNDER THE PROGRAMME, OR WERE THEY INSTALLED PREVIOUSLY?

Terminate ← PROGRAMME   PREVIOUSLY

(15) WHEN WERE THE VENTS INSTALLED?

Terminate ← __________

---

(16) IS THERE PRESENTLY INSULATION IN THE ATTIC OF YOUR HOME?

19 ← NO   YES

(17) WHAT KIND OF INSULATION IS IT?

____

(18) WHEN WAS IT INSTALLED?

____

(19) DOES YOUR HOUSE HAVE ATTIC VENTS?

Terminate ← NO YES

(20) WHEN WERE THE VENTS INSTALLED?

Terminate ← ____________

---

(21) IS THERE PRESENTLY INSULATION IN THE ATTIC OF YOUR HOME?

13 ← NO YES

(22) WHAT KIND OF INSULATION IS IT?

____

(23) WHEN WAS IT INSTALLED?

13 ← ____________

THOSE ARE ALL THE QUESTION I HAVE. THANK YOU FOR YOUR TIME AND COOPERATION.

Appendix B

DATA

OBS = Observation number

RT = Roof temperature (°K)

RINS = R-Value of attic insulation

AV = Attic ventilation (0 = absent; 1 = present)

RO = Roof orientation (0.0 = faces street network;
0.5 = faces both directions;
1.0 = faces neighbouring buildings)

RP = Roof pitch (0 = low; 1 = high)

FR = Lot frontage (feet)

HQ = House quality (0 = low; 1 = high)

UHS = Upper half story (0 = absent; 1 = present)

OBS	RT	RINS	AV	RO	RP	FR	HQ	UHS
1	274.00	2.90	1	0.0	0	55.07	1	0
2	274.02	2.40	1	0.5	0	55.00	1	0
3	273.58	2.40	1	0.0	0	55.00	1	0
4	273.94	2.90	1	0.5	0	50.00	1	0
5	273.61	2.90	1	0.0	0	50.00	1	0
6	274.14	2.40	1	0.0	0	50.00	1	0
7	274.06	2.40	1	1.0	0	55.00	1	0
8	273.28	6.00	1	0.5	0	55.00	1	0
9	273.92	2.40	0	0.5	0	55.00	1	0
10	273.96	2.40	1	0.5	0	53.00	1	0
11	274.25	2.40	1	0.5	0	53.00	1	0
12	273.52	2.40	1	1.0	0	55.00	1	0
13	274.21	2.40	1	0.5	0	55.00	1	0
14	273.74	3.70	1	0.5	0	55.00	1	0
15	274.65	2.40	1	0.5	0	57.00	1	0
16	275.24	2.40	1	0.5	0	57.00	1	0
17	274.57	2.40	1	1.0	0	55.00	1	0
18	273.60	2.40	1	0.5	0	55.00	1	0
19	275.14	2.40	1	0.5	0	55.00	1	0
20	274.37	2.40	1	0.5	0	55.00	1	0
21	273.97	2.90	1	0.5	0	55.00	1	0

22	274.58	2.90	1	0.5	0	55.00	1	0
23	274.59	2.40	1	0.0	0	55.00	1	0
24	273.44	5.40	1	0.5	0	55.00	1	0
25	273.25	2.40	1	0.5	0	55.00	1	0
26	274.38	2.40	1	0.5	0	55.00	0	0
27	274.35	2.40	1	0.5	0	55.00	1	0
28	274.02	2.40	1	0.5	0	55.00	1	0
29	273.74	2.90	1	0.5	0	52.71	1	0
30	274.86	2.90	1	0.5	0	58.60	1	0
31	273.32	2.40	1	0.5	0	69.00	1	0
32	274.05	2.40	1	0.5	0	55.00	1	0
33	272.95	2.40	1	0.5	0	55.00	1	0
34	272.49	2.40	1	0.5	0	50.00	0	0
35	274.62	2.40	0	1.0	0	55.00	1	0
36	274.82	2.40	1	0.5	0	55.00	1	0
37	277.04	2.40	0	0.5	0	58.00	1	0
38	274.77	2.40	1	0.5	0	58.00	1	0
39	274.58	2.90	1	0.5	0	55.00	1	0
40	274.64	0.00	1	0.5	0	55.00	1	0
41	274.70	2.90	1	0.5	0	55.00	1	0
42	274.25	6.10	1	0.5	0	55.00	1	0
43	275.00	2.90	1	0.5	0	59.00	1	0
44	275.45	2.40	1	0.5	0	59.00	1	0
45	274.51	2.40	1	0.5	0	59.00	1	0
46	277.90	2.40	1	0.5	0	59.00	1	0
47	275.11	2.40	1	0.5	0	55.00	1	0
48	274.84	2.90	1	0.5	0	55.00	1	0
49	276.75	2.40	1	0.5	0	55.00	1	0
50	274.60	3.00	1	0.5	0	55.00	1	0
51	276.39	2.90	1	0.5	0	55.00	1	0
52	278.07	2.90	1	0.5	0	55.00	1	0
53	274.40	3.70	1	0.5	0	55.00	1	0
54	274.23	2.40	1	0.0	0	60.00	1	0
55	274.74	2.40	1	0.5	0	55.00	1	0
56	277.49	2.40	1	0.5	0	50.00	1	0
57	274.88	3.00	1	0.5	0	37.50	0	0
58	274.66	2.40	0	1.0	0	40.00	1	0
59	273.71	5.30	1	0.5	0	44.00	1	0
60	275.01	2.40	1	0.5	0	50.00	1	0
61	274.53	3.70	1	0.5	0	55.00	1	0
62	274.64	2.40	1	0.5	0	55.00	1	0
63	276.99	2.90	1	0.5	0	55.00	1	0
64	275.22	2.40	1	0.5	0	55.00	1	0
65	274.72	2.40	1	0.0	0	55.00	1	0
66	275.02	2.40	1	0.5	0	45.00	1	0
67	277.52	0.00	1	0.5	0	50.00	1	0
68	274.17	4.80	1	1.0	1	50.00	1	1
69	274.48	3.70	1	1.0	0	30.00	1	0
70	275.10	2.90	1	1.0	0	75.00	1	0
71	275.90	2.90	1	0.5	0	45.00	1	0
72	275.35	2.40	1	0.0	0	50.00	1	0
73	274.53	3.70	1	0.5	0	56.50	1	0
74	274.32	5.70	1	0.0	0	50.00	1	0
75	273.89	3.00	1	0.5	0	60.00	1	0
76	273.26	3.00	1	0.5	0	60.00	1	0

77	273.11	2.40	1	0.5	0	55.00	1	0
78	273.85	2.90	1	1.0	0	55.00	1	0
79	273.84	2.40	1	0.5	0	60.00	1	0
80	274.33	2.40	1	0.5	0	55.00	1	0
81	273.95	2.40	1	0.5	0	55.00	1	0
82	274.12	2.40	1	0.5	0	60.00	1	0
83	272.87	2.90	1	1.0	0	55.00	1	0
84	272.75	2.40	1	1.0	0	55.00	1	0
85	274.39	5.40	1	0.5	0	60.00	1	0
86	275.00	2.40	1	0.5	0	55.00	1	0
87	274.49	2.40	1	0.5	0	57.00	1	0
88	275.31	2.40	1	1.0	0	58.00	1	0
89	275.30	0.00	0	0.5	0	60.00	1	0
90	274.14	2.40	1	0.5	0	70.00	1	0
91	278.12	2.40	1	0.5	0	57.00	1	0
92	274.23	5.10	1	0.5	0	55.00	1	0
93	274.56	2.40	1	0.0	0	70.00	1	0
94	275.14	2.40	1	0.0	0	55.00	1	0
95	274.17	2.40	1	0.5	0	55.00	1	0
96	274.63	2.90	1	0.5	0	30.00	1	0
97	273.34	6.60	1	0.0	0	50.00	1	0
98	274.19	2.40	1	0.0	0	50.00	1	0
99	274.34	2.40	1	0.5	0	48.00	1	0
100	273.34	2.40	1	0.5	0	54.00	1	0
101	272.59	2.40	1	0.5	0	50.00	1	0
102	274.00	2.40	1	0.5	0	49.13	1	0
103	273.46	2.40	1	0.5	0	49.13	1	0
104	277.01	2.40	1	0.5	0	50.00	1	0
105	274.67	2.40	1	0.5	0	53.00	1	0
106	273.70	2.40	1	0.0	0	50.00	1	0
107	274.26	2.40	1	0.5	0	50.00	1	0
108	275.00	2.40	1	0.0	0	50.00	1	0
109	273.71	2.40	1	0.0	0	46.00	1	0
110	274.31	2.90	1	0.5	0	45.00	1	0
111	274.45	5.40	1	0.0	1	45.00	1	1
112	274.19	2.40	1	0.5	0	45.00	1	0
113	274.84	2.40	1	0.0	0	45.00	1	0
114	275.02	2.40	1	0.0	1	44.00	1	1
115	276.70	2.90	1	0.5	0	33.00	0	0
116	274.05	5.90	1	0.5	0	50.40	1	0
117	274.39	2.40	1	0.5	0	50.00	1	0
118	275.03	2.40	1	0.0	0	57.00	1	0
119	276.08	2.40	1	0.5	0	50.00	1	0
120	277.75	2.40	0	0.5	1	75.00	0	1
121	274.67	0.00	0	1.0	0	40.00	1	0
122	273.63	2.40	1	0.5	0	40.00	1	0
123	274.70	0.00	1	0.5	1	45.00	1	1
124	274.04	2.70	1	0.5	0	45.00	1	0
125	273.95	2.90	1	0.0	0	45.00	1	0
126	278.76	2.40	1	1.0	1	84.35	1	1
127	274.72	2.40	1	1.0	0	40.00	1	0
128	274.55	5.30	1	0.5	0	45.00	1	0
129	274.43	3.70	1	0.5	1	45.00	1	1
130	274.32	2.40	0	0.5	0	50.00	1	0
131	274.70	2.40	1	0.5	0	45.00	1	0

132	277.87	2.40	1	0.5	0	46.00	0	0
133	274.49	2.90	1	0.5	0	46.00	1	0
134	274.03	5.30	1	0.0	0	46.00	1	0
135	276.61	3.10	1	0.5	0	45.00	1	0
136	276.20	3.00	1	0.5	1	42.85	1	1
137	274.34	3.70	1	0.5	0	40.00	1	0
138	275.10	2.70	1	0.5	1	45.00	1	1
139	278.42	2.90	1	0.5	0	46.00	1	0
140	274.56	2.40	1	0.5	0	50.00	1	0
141	274.28	5.30	0	0.5	0	50.00	0	1
142	275.69	6.00	0	0.0	1	25.00	1	1
143	277.23	0.00	0	1.0	1	37.50	0	1
144	280.06	2.40	1	0.5	1	45.00	1	1
145	275.54	2.40	1	0.5	0	37.50	1	0
146	278.09	0.00	0	0.5	1	50.00	1	1
147	274.75	2.40	1	0.5	0	43.00	1	0
148	278.07	2.70	0	0.5	1	50.00	0	1
149	274.45	6.10	1	0.5	1	45.00	1	1
150	274.45	2.40	1	0.5	1	50.00	1	1
151	274.77	2.40	1	0.5	0	50.00	1	0
152	276.66	2.90	1	0.5	1	43.00	1	1
153	274.71	2.40	1	0.5	0	41.00	1	0
154	276.95	2.40	1	1.0	0	36.00	1	0
155	275.12	2.40	1	1.0	0	36.00	1	0
156	274.25	2.40	1	1.0	0	75.00	0	1
157	276.28	0.00	0	0.5	1	40.00	1	1
158	276.80	0.00	1	1.0	1	33.00	1	1
159	278.19	2.40	1	0.5	1	49.00	1	1
160	275.57	0.00	0	0.5	0	49.50	0	0
161	274.51	5.40	1	0.5	1	43.00	1	1
162	274.46	2.40	1	0.5	0	42.00	1	0
163	274.47	5.30	1	0.0	1	45.00	1	1
164	275.64	2.40	1	0.5	0	48.00	1	0
165	274.57	2.40	1	0.5	0	48.00	1	0
166	278.07	3.00	0	1.0	0	33.18	0	0
167	274.59	2.40	0	0.5	0	40.00	1	0
168	274.23	2.40	1	0.5	1	40.00	1	1
169	276.05	2.90	1	0.5	0	49.58	1	0
170	273.92	2.40	1	0.5	0	40.00	1	0
171	274.81	2.40	1	0.5	0	53.00	1	0
172	274.77	2.40	1	0.5	0	49.00	1	0
173	276.81	2.40	1	0.5	1	42.30	1	0
174	274.72	2.40	1	0.5	0	45.03	1	0
175	277.28	2.40	1	1.0	0	33.00	1	0
176	278.07	2.90	1	0.0	0	33.00	0	0
177	275.06	3.45	1	1.0	0	33.00	0	0
178	277.13	2.40	0	0.5	1	33.00	1	1
179	279.16	2.90	1	1.0	0	29.00	1	0
180	278.79	0.00	1	1.0	1	25.00	1	1
181	274.65	6.10	1	0.5	0	50.00	1	0
182	274.36	2.40	1	0.5	0	62.60	1	0
183	274.64	2.40	1	0.5	0	45.00	1	0
184	274.06	2.90	0	0.5	0	49.59	1	0
185	278.62	3.00	1	0.5	0	49.50	1	0
186	273.72	3.00	1	1.0	0	33.00	1	0

187	279.32	2.40	1	1.0	1	49.50	1	1
188	278.43	2.90	1	0.5	0	33.00	1	0
189	272.80	2.40	1	0.5	0	49.59	1	0
190	274.37	3.70	1	1.0	0	40.00	1	0
191	274.56	2.90	1	0.5	1	47.50	1	0
192	278.36	3.00	1	0.5	1	35.00	1	1
193	277.74	2.40	1	1.0	1	37.80	1	1
194	277.35	2.40	1	0.5	1	40.00	1	1
195	277.13	2.40	1	0.5	1	41.00	1	0
196	273.40	5.10	1	0.5	1	40.00	1	0
197	273.94	2.90	1	0.5	1	38.00	1	1
198	274.84	2.40	1	0.5	0	37.50	1	0
199	274.68	3.70	1	1.0	0	33.00	1	0
200	275.53	3.00	1	1.0	0	33.00	0	0
201	274.21	2.40	1	0.5	0	53.00	1	0
202	275.94	2.40	1	0.5	1	33.00	0	0
203	278.32	2.40	0	0.5	0	33.00	0	0
204	274.36	3.70	0	1.0	0	33.00	1	0
205	275.47	2.90	1	0.5	0	45.00	1	0
206	274.51	2.40	1	0.5	0	54.02	1	0
207	274.23	2.40	1	0.5	0	61.00	1	0
208	274.31	2.40	0	0.5	0	45.00	1	0
209	274.91	2.40	1	0.5	0	45.00	1	0

Appendix C

WATFIV PROGRAMME: RTCALC

```
$JOB  WATFIV    ,NOEXT,NOCHECK
C **********************************************************
C                           RTCALC
C **********************************************************
C This program calculates average kinetic roof temp on the
C basis of the proportion of the area of the roof covered
C by each colour coded temp range, as determined from
C colour-enhanced aerial thermographs. Variables LG, DB, LB,
C Y and W are colour codes with midpoint apparent temps of
C 281.12, 278.21, 275.29, 272.37 and 269.46 degrees K.
C Average apparent roof temp is divided by roof emissivity
C to the power of 1/4. Emissivity is assumed to be 0.97 for
C all houses.
C **********************************************************
      INTEGER HOUSE(209), N
      REAL LG(209), DB(209), LB(209), Y(209), W(209),
     + TOT, RT
C N=number of observations.
      N=209
      DO 1 I=1,N
C Input roof area of each colour code.
       READ 100, HOUSE(I), LG(I), DB(I), LB(I), Y(I), W(I)
C Calculate total roof area.
       TOT=LG(I)+DB(I)+LB(I)+Y(I)+W(I)
C Calculate kinetic roof temperature.
       RT=(LG(I)/TOT*281.12+DB(I)/TOT*278.21+LB(I)/TOT*
     +    275.29+Y(I)/TOT*272.37+W(I)/TOT*269.46)/0.99
       WRITE(14,200) HOUSE(I), RT
    1 CONTINUE
      STOP
  100 FORMAT(I4,5F3.0)
  200 FORMAT(I4,F8.2)
      END
$ENTRY
```

Appendix D

WATFIV PROGRAMME: SPOTMAP

```
$JOB  WATFIV   ,NOEXT,NOCHECK
C *********************************************************
C                         SPOTMAP
C *********************************************************
C This programme creates a line printer map of point
C observations using specified symbolism.
C *********************************************************
      INTEGER I, J, HOUSE(209), NCL, NCL1, MAXCOL, MAXROW,
     + ID(209), COL(209), ROW(209), N, M
      REAL  CLASS(1000), SCALE, VAL(209), X(209), Y(209)
      CHARACTER SYMBOL*1(1000), PLOT*1(300),
     + NAME*60(1000), MAP*1(200,200)
C Read number of observations (N), number of symbols less
C one (NCL), scale factor (SCALE).
      READ, N, NCL, SCALE
      NCL1=NCL+1
      M=N-1
C Read X and Y (coordinates) for all observations.
      DO 2 I=1,N
       READ, X(I), Y(I), ID(I)
    2 CONTINUE
C Read values to be mapped.
      DO 4 I=1,N
       READ 100, HOUSE(I), VAL(I)
    4 CONTINUE
C Read following information in alternate lines:
C Line 1: class symbol and name.
C Line 2: upper boundary of class.
C Repeat for remaining classes. There should be NCL1
C symbols and names and NCL boundaries.
      DO 6 I=1,NCL
       READ 300, SYMBOL(I), NAME(I)
       READ, CLASS(I)
    6 CONTINUE
      READ 300, SYMBOL(NCL1), NAME(NCL1)
C Calculate row and column positions for observations.
      MAXCOL=MAXROW=-1
      DO 8 I=1,N
       COL(I)=Y(I)*10*SCALE+1
       ROW(I)=X(I)*8*SCALE+1
       IF (COL(I).GT.MAXCOL) THEN DO
        MAXCOL=COL(I)
       END IF
       IF (ROW(I).GT.MAXROW) THEN DO
        MAXROW=ROW(I)
```

```
       END IF
     8 CONTINUE
C Assign symbolism to observations.
      DO 20 I=1,N
       PLOT(I)=SYMBOL(NCL1)
       DO 18 J=1,NCL
        IF (VAL(I).LT.CLASS(J)) THEN DO
         PLOT(I)=SYMBOL(J)
         GO TO 20
        END IF
   18  CONTINUE
   20 CONTINUE
C Printout of data and symbols.
      PRINT 199
      DO 15 I=1,N
       PRINT 200, I, HOUSE(I), VAL(I), PLOT(I)
   15 CONTINUE
C Check for overlapping data points.
      DO 22 I=1,M
       J=I+1
       DO 21 K=J,N
        IF (ROW(I).EQ.ROW(J)) THEN DO
         IF (COL(I).EQ.COL(J)) THEN DO
          PRINT 999, HOUSE(I), HOUSE(J)
         END IF
        END IF
   21  CONTINUE
   22 CONTINUE
C Initialize map matrix to blanks.
      DO 30 I=1,MAXROW
       DO 28 J=1,MAXCOL
        MAP(I,J)=' '
   28  CONTINUE
   30 CONTINUE
C Assign symbols to print locations.
      DO 40 I=1,N
       MAP(ROW(I),COL(I))=PLOT(I)
   40 CONTINUE
      PRINT 450
C Skip a few lines.
      DO 53 I=1,5
       PRINT 988
   53 CONTINUE
C Print map.
      DO 60 I=1,MAXROW
       PRINT 500, (MAP(I,J),J=1,MAXCOL)
   60 CONTINUE
C Print legend.
      PRINT 700
      PRINT 750
      DO 70 I=1,NCL
       PRINT 900, SYMBOL(I), NAME(I)
   70 CONTINUE
      PRINT 900, SYMBOL(NCL1), NAME(NCL1)
      PRINT 905
```

```
      PRINT 906
      PRINT 450
      STOP
  100 FORMAT(I4,35X,F9.2)
  199 FORMAT('1',17X,'OBS',7X,'ID',10X,'VALUE',5X,'SYMBOL')
  200 FORMAT(' ',10X,I10,4X,I5,5X,F10.2,8X,A1)
  300 FORMAT(A1,5X,A60)
  450 FORMAT('1')
  500 FORMAT(' ',9X,120A1)
  700 FORMAT('1',17X,'LEGEND')
  750 FORMAT('+',17X,'______')
  900 FORMAT(' ',17X,A1,7X,A60)
  905 FORMAT('1',47X,'MAP 6')
  906 FORMAT(' ',43X,'Lot Frontage')
  988 FORMAT('-')
  999 FORMAT(' ','OVERLAPPING DATA POINTS:',2I5)
      END
$ENTRY
```

Appendix E

WATFIV PROGRAMME: BIPROB

```
$JOB  WATFIV   ,NOEXT,NOCHECK
C *******************************************************
C                         BIPROB
C *******************************************************
C This programme calculates binomial probabilities for
C accuracy testing given N, X and Q.
C *******************************************************
      INTEGER N, X, M, J, I, L
      REAL Q, P, FACTN, FACTX, FACTM
C N=size of subsample.
      N=20
      L=N-1
C Q=selected value for acceptable proportion of
C correct interpretations in entire sample.
      Q=0.75
      PRINT 100, Q
      PRINT 200
C X=number of incorrect interpretations in subsample.
      X=0
C Calculate probability for X=0.
      P=Q**N
      PRINT 300, N, X, P
C Calculate probability for X=1,2,3,...,L.
      DO 10 X=1,L
       M=N-X
       FACTN=J=1
       DO 1 I=1,N
        FACTN=FACTN*J
        J=J+1
    1  CONTINUE
       FACTX=J=1
       DO 2 I=1,X
        FACTX=FACTX*J
        J=J+1
    2  CONTINUE
       FACTM=J=1
       DO 3 I=1,M
        FACTM=FACTM*J
        J=J+1
    3  CONTINUE
       P=FACTN/(FACTX*FACTM)*Q**M*(1-Q)**X
       PRINT 300, N, X, P
   10 CONTINUE
C Calculate probability for X=N.
      P=(1-Q)**N
```

```
      PRINT 300, N, N, P
      STOP
  100 FORMAT('1','P FOR Q = ',F5.2)
  200 FORMAT(' ',9X,'N',9X,'X',9X,'P')
  300 FORMAT(' ',2I10,F10.4)
      END
$ENTRY
```

Appendix F

WATFIV PROGRAMME: ERRTEST

```
$JOB  WATFIV   ,NOEXT,NOCHECK
C *********************************************************
C                          ERRTEST
C *********************************************************
C This program tests for normality and autocorrelation in
C regression error terms.
C *********************************************************
      INTEGER I, J, K, N
      REAL Y(209), X(209), YP(209), RES(209), SUMRES,
     + SUMDIF, Q, M, SUMR, MEAN, SS, S, Z(209),
     + MAXD, PR(209), PRN(209), NORMPR, DIF, ADIF, D, V
C N=number of observations.
      N=209
      M=FLOAT(N)
      SUMR=SUMRES=SUMDIF=0
      DO 4 I=1,N
C Read in values of dependent and explanatory variables.
       READ 100, Y(I), X(I)
C Compute expected values with derived regression equation.
       YP(I)=275.911-0.316*X(I)
C Calculate residual values.
       RES(I)=Y(I)-YP(I)
       SUMR=SUMR+RES(I)
    4 CONTINUE
C Calculate Q.
      DO 8 I=2,N
       J=I-1
       SUMDIF=SUMDIF+(RES(I)-RES(J))**2
       SUMRES=SUMRES+RES(I)**2
    8 CONTINUE
      Q=SUMDIF/SUMRES
      PRINT 150, Q
      MEAN=SUMR/N
      SS=0
C Calculate sum of squared residuals.
      DO 10 I=1,N
       SS=SS+(RES(I)-MEAN)**2
   10 CONTINUE
      V=SS/(M-1)
      S=SQRT(V)
C Calculate standard scores.
      DO 11 I=1,N
       Z(I)=(RES(I)-MEAN)/S
   11 CONTINUE
      MAXD=-1
```

```
C Calculate frequency of occurence of values smaller
C than the value of each observation.
      DO 14 K=1,N
       PR(K)=1
       DO 12 I=1,N
        IF(I.NE.K)THEN DO
         IF(Z(I).LE.Z(K))THEN DO
          PR(K)=PR(K)+1
         END IF
        END IF
   12  CONTINUE
C Calculate probability of a smaller value.
       PRN(K)=PR(K)/M
C Call IMSL routine MDNOR (areas of normal curve).
       CALL MDNOR(Z(K),NORMPR)
C Compare probablities in normal and observed distributions.
       DIF=NORMPR-PRN(K)
       ADIF=ABS(DIF)
C Find largest absolute deviation.
       IF(ADIF.GT.MAXD)THEN DO
        MAXD=ADIF
       END IF
   14 CONTINUE
C Calculate d-statistic.
      D=MAXD*((SQRT(M))-.01+.85/(SQRT(M)))
      PRINT 200, D
      PRINT 999
      STOP
  100 FORMAT(4X,F10.2,F8.2)
  150 FORMAT('1','Q-statistic:',F20.4)
  200 FORMAT('1','d-statistic:',F20.4)
  999 FORMAT('1')
      END
$ENTRY
```

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