Fire Research Report

Modelling Fire-Spread In and Around Urban Centres

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Two previously developed GIS models - a static and dynamic mode - were populated with data for buildings in Wellington city and simulations run to determine the consequence of post-earthquake fire. The models were corrected for shortcomings in the spread of fire between buildings with non-combustible claddings and the effect of vegetation between houses and suburbs.

Total property loss due to fire-spread between buildings with non-combustible claddings was assessed by developing and testing additional rules for the dynamic model. Using a survey of the buildings within the Wellington CBD, it was determined that the dominant fire-spread mechanism for these buildings was via non-fire rated roofs or openings in the walls.

Vegetation (between buildings and suburbs) facilitates fire-spread where it may not otherwise occur. Techniques were developed to incorporate vegetation into the static model. A pilot study in Karori suggests that loss estimates made without including vegetation may be 50% of those made with vegetation included, assuming all vegetation is flammable.

The dynamic fire-spread model was also modified to determine the spread of rural wildfire (fire-spread between built-up areas via intervening bush and scrub) in a pilot study. The cell-based technique of modelling used could not accurately model the effect of wind or slope when the direction of maximum spread was not a sub-cardinal direction.

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Confidential

By Dave Heron, Geoff Thomas, Jim Cousins, Biljana Lukovic, and Robin Schmid

Client Report
2003/96
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EXECUTIVE SUMMARY

Two preliminary GIS-based models of fire-spread, a static and a dynamic mode have been developed in previous studies. The models were populated with data for buildings in Wellington City and simulations run to determine the consequence of post-earthquake fire. Both models had two shortcomings: they ignored the spread of fire between buildings with non-combustible claddings and the effect of vegetation between houses and suburbs. These deficiencies are addressed in this report. The models have also been validated against the fires following the earthquake in Napier in 1931 and the results are presented in a separate report.

The effect on the total property loss due to fire-spread between buildings with non-combustible claddings was assessed by developing and testing additional rules for the dynamic model to allow its use in a typical city CBD. A survey of the buildings in the Wellington CBD indicated that the dominant fire-spread mechanisms between buildings with non-combustible claddings are via non-fire-rated roofs or openings in the walls. Rules for these modes of spread were included in the model. Simulations indicate that roof burn-through has little effect on the overall losses. If the windows are intact, the fire losses increase by 70% over the base case, but if the windows are broken the fire losses increase by 430%.

Vegetation (between buildings and between suburbs) facilitates fire-spread where it may not otherwise occur. Techniques were developed to incorporate vegetation into the static model. If not included, the effect of vegetation between buildings is likely to cause losses to be underestimated. The inclusion of vegetation data, however, is not straight forward. There is no readily available source of vegetation data at suitable spatial resolutions. Even if available, the data is unlikely to be classified according to species and flammability, and a significant effort would be required to do so. A pilot study in Karori suggests that loss estimates made without including vegetation may be 50% of those made with vegetation included, assuming all vegetation is flammable.

The dynamic fire-spread model could be used to determine fire-spread in rural areas and this could be combined with the existing model to incorporate fire-spread between built-up areas via intervening bush and scrub. The existing dynamic fire-spread model was modified and applied to the spread of rural wildfire in a pilot study. Whilst data on New Zealand vegetation fuel characteristics are far from complete, sufficient information was available to allow a model to be tested. Of the two techniques used to model wildfire-spread, a cell-based approach was considered the easiest to interface with the existing dynamic model. While preliminary tests of the influence of vegetation fuel characteristics, wind strength, and presence of barriers could be effectively modelled, the cell-based technique could not accurately model the effect of wind or slope when the direction of maximum spread was not a sub-cardinal direction (i.e. not N, NW, W, SW, S, SE, E, or NE). Whilst an ellipse-based technique is not troubled by this, this technique could not readily be included within the existing dynamic fire model.

1.0 INTRODUCTION

We have recently developed two preliminary models for the spread of uncontrolled fire in urban settings, one static and one dynamic [12,13,14,42]. These models ran in a Geographic Information System (GIS) and incorporated spatial data for Wellington City buildings positions, and their height, age, cladding, and value. The dynamic model was able to directly use wind direction and strength. Both models were most suitable for use in suburban environments, in flat terrain, and with no vegetation.

The current research has been focused on:
1: understanding fire-spread in closely-spaced medium- to high-rise buildings and developing and testing additional rules for the dynamic model to allow it to be used in a typical city Central Business District (CBD),
2: investigating the importance of vegetation (between buildings and between suburbs) and developing techniques to incorporate these into the static model,
3: modifying the existing dynamic fire-spread model and applying it to the spread of rural wildfire in a pilot study,
4: creating a digital model of 1931 Napier and testing both the static and dynamic fire-spread models to develop a set of calibration points,
5: refining the modelling of spread rate in the dynamic model by running the model for a variety of situations and comparing the predictions with the opinions of experienced fire service personnel and historical data.

This report presents the findings of all but the Napier work, which is reported separately [24].

1.1 Brief description of static fire model

The static fire-spread model [12,13,14,42] uses the idea of a "critical separation", which is defined as being the maximum distance that a fire can jump from one building to another. A GIS buffer operation is used to identify groups of buildings that are closer together than the "critical separation". The process takes a "birds-eye" plan of the buildings and draws a "buffer" of width equal to half the critical separation around each building. Where buffers touch or overlap the corresponding buildings are taken to belong to a "burn-zone", with the assumption being that whenever any building in a particular burn-zone is ignited, all buildings in that zone will be consumed. Fires do not spread from one burn-zone to another because, by definition, the distances between burn-zones are always greater than the critical separation.

The static model assumes that the fire will spread in all directions until it encounters a gap wider than the critical separation, and that the size of the critical separation is the same for all directions of spread. We expect this assumption to be valid for calm to moderate breeze conditions, when the wind is not strong enough to carry pieces of burning material any great distance and when radiated heat is the main cause of ignition across a gap. Under high wind conditions, "strong breeze" and stronger, we would expect the influence of the prevailing wind to overshadow any deviations in direction due to eddying and swirling, in which case the assumption of uniform spread would nearly always be invalid. The static model also does not take into account biasing factors such as ground slope and active suppression.

1.2 Brief description of dynamic fire model

The dynamic fire-spread model [12,13,14,42] uses a "cellular automaton" technique to model the spread of fire over time. A GIS is used to divide a map of the area of interest into a set of equal-sized square cells, and then each cell is allocated the properties of whatever fills it. A cell mostly occupied by a building is deemed to be fuel and takes on the properties of the building, i.e. the cladding material, roof type, height, proportion of windows, and so on. A cell that lies mostly over items like roadway, grassland, and paved areas, is deemed to be empty, and thus a hindrance to the spread of fire. Spread of fire from one cell to another (represented as a change of cell state) depends on the initial state of the cell (burning or not), cell attributes (fuel or not), and a set of rules.

The rules are complex and take into account such things as the size of the burning fire-front, the temperature of the fire, the decrease in heat flux with increasing distance (i.e. increasing size of gap), and the flammability of cladding materials. The dynamic model allows fire to spread to flammable structures by contact (for adjacent cells), spontaneous ignition (for cells heated by intense radiation across a gap), piloted ignition (through sparks falling on preheated surfaces), and branding (pieces of burning material blown across a gap by wind). Structures with non-flammable claddings can be ignited by piloted ignition following collapse of an adjacent non-fire-rated roof or by piloted ignition through openings like broken windows. The model includes factors for wind direction and strength but does not yet account for other biasing factors such ground slope and active suppression.

Because some of the mechanisms for fire-spread are not guaranteed to be successful, for example, burning brands may be blown onto a building but fail to ignite it because they fall on a non-combustible roof, the dynamic model allows a user to assign probabilities smaller than 100% to those particular mechanisms.

To run the model at least one initial cell, the fire source, is "ignited", and then all surrounding cells are interrogated, one at a time, to determine whether conditions are such that any of them will be ignited from the burning cell or cells. The mechanics of the process is that the entire set of cells is scanned repeatedly, cell by cell, in a raster fashion. During the scanning process cells are "activated" one at a time and, whilst activated, a cell's state is changed according to its current state and properties, the states of surrounding cells, and the fire-spread rules.

2.0 MODELLING FIRE-SPREAD IN THE CBD

2.1 Introduction

When applied to Wellington City as a case study, the original dynamic fire-spread model predicted losses of $90 to $300 million from damage to buildings, assuming 27 randomly located ignition points resulting from a Wellington Fault earthquake event. This is almost certainly an underestimate, because the original dynamic model assumed that fire is unable to spread either to or from buildings with non-combustible claddings.

Although fire-spread is less likely to buildings with non-combustible claddings than to buildings with combustible claddings, it does occur [6,10], and so the assumption of no spread results in significant underestimation of losses. Large high-value buildings are concentrated in the CBD of cities and towns. Buildings in some areas of the CBD of Wellington have a value of more than $10 million each, while the value of most residential property is less than $500,000 per property. The high-value buildings in the CBD also tend to have non-combustible claddings (Figure 2.1), so that if they are ignored in the fire-spread model the estimated losses will be far too low. Both of these issues are apparent in the CBD in Wellington which contains a large proportion of the value of the building stock in Wellington.

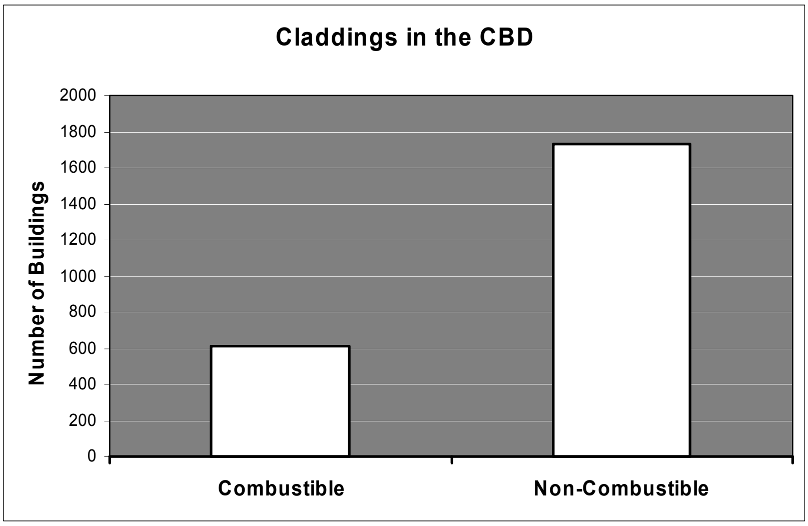


Figure 2.1 Proportion of buildings with combustible and non-combustible claddings, Wellington CBD.

While a non-combustible cladding itself will not catch fire, there are a number of other ways that fire may spread into a building that uses such a cladding. The most likely is via the windows to the combustible interior. Also these buildings, if they are assumed not to burn, "shield" the buildings behind them by acting as a fire break, reducing fire-spread, in some cases dramatically. The present research investigates the possibility of post-earthquake fire-spread between buildings with non-combustible claddings and aims to improve loss and spread estimates made by the dynamic simulation model. By improving the simulation, a more accurate estimation of the severity of loss due to post-earthquake fire may be made.

The dynamic fire-spread model developed in 2001[12,13,14,42] is based on a GIS model of Wellington City that contains information regarding construction and separation distances of each building in the city. It is therefore possible to simulate fire-spread based on parameters particular to the city. The model also contains information on the value of each building in Wellington enabling the expected loss of building stock to be estimated in monetary terms. In Wellington the area defined as the CBD for the present study is shown in Figure 2.2.

Figure 2.2 The Central Business District of Wellington as used in the present study. North is to the left.

The likelihood of fire-spread to buildings with non-combustible cladding was determined by investigating methods of fire-spread between such buildings. A physical survey was then carried out on a subset of the buildings in the study area to assess and record the critical constructional details of buildings. A new set of fire-spread "rules" was formulated for each type of fire-spread, based on the research and survey results. Since not all buildings in the CBD were surveyed, it was not possible to develop a new model of the city. The rules were included in the dynamic fire-spread in such a way as they could be related to the existing parameters in the existing buildings database. A series of simulations were then carried out so that the effect of non-combustible claddings on the estimates of losses in the CBD could be assessed.

2.2 Methods of spread

There are three main ways that fire can spread to buildings with non-combustible cladding. It can spread via openings, through fire-rated walls that have been damaged or destroyed in earthquake shaking, or, if a building has openings in its side and is adjacent to a lower building that does not have a fire-rated roof, fire can spread from the lower building to the higher via the roof.

2.2.1 Fire-spread via Openings

The most common method of fire-spread between non-contiguous buildings is by radiated heat [8]. Radiation spread can occur when there is a direct line of sight between the radiating building and the receiving building.

Where buildings have a non-combustible cladding, the cladding itself will not ignite, and so the fire-spread is confined to the openings in the façades of the buildings. The windows in a building that has non-combustible claddings are generally the only part of the façade that radiates heat to an adjacent building (Figure 2.3). The sizes of the windows and their distances from adjacent buildings affect the likelihood of fire-spread because the size and distance determine the configuration factor, a factor in the equation that determines the level of incident radiation on the target building. The size of window openings in the façade of a building is generally given as a percentage of the overall façade area.

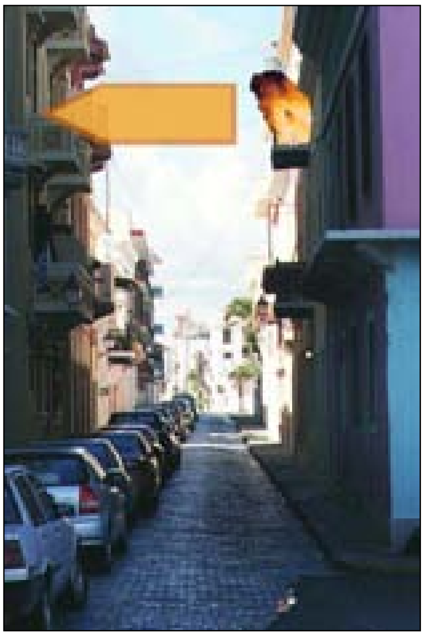


Figure 2.3 Fire-spread by radiation from windows in a building with non-combustible cladding.

Radiation from windows is a result of both radiation from the burning interior of the building and the heat from the flame projection at the window [33]. The radiation from the burning interior is generally dominant. Carlsson [8] found that the amount of radiation that is emitted by projected flames only contributes 12-18% to the total received radiation, and concluded that this is a relatively insignificant amount of radiation. However, the extra heat produced by flame projection has been incorporated into the dynamic model by specification of a slightly higher radiating area than normally expected.

In a fully developed fire, the windows in the burning building will normally break due to heat unless they are designed as fire-rated windows. In the target building (building adjacent to the burning building), windows may or may not break in the earthquake shaking. If the windows in the target building do not break then they will attenuate some of the radiation and prevent sparks from entering. If sparks are not present then a higher level of radiation is required to induce temperatures needed for spontaneous ignition of combustibles in the target building.

Wind conditions affect the distance and direction of spark travel, therefore wind will affect the severity of piloted ignition. In higher winds, sparks may travel much further and ignite buildings at much greater separation distances. Winds of over 50 km/h may cause sparks to ignite buildings more than 20m away [13]. However, wind patterns in the Wellington CBD are difficult to predict, because many of the tall buildings create significant eddies.

2.2.2 Fire-spread via damaged or collapsed buildings

In an earthquake some buildings may collapse, and when a building with a non-combustible cladding does so, the combustible contents will be exposed providing a continuous fuel bed over which the fire may spread.

The first New Zealand Building Code was implemented in 1935 [40]. A 1990s report on earthquake-risk buildings concluded that there was a distinct difference in the standard of construction according to whether the building was built before or after the implementation of the code [5]. The report categorised buildings constructed before 1936 as being of high risk of collapse in an earthquake, and those between 1936 and 1975 as potentially at risk. This is similar to the state of buildings in Kobe, Japan, at the time of the 1995 earthquake, where 55% of buildings constructed before 1970 collapsed [32].

In the previous fire-spread study, a building with non-combustible cladding that collapses was assumed to spread fire in a similar way to a building having a combustible cladding. The database lists building age by decade. Assuming that all buildings built before 1940 had combustible claddings, modelling resulted in a 30% increase in losses. When assuming all buildings built before 1980 had combustible claddings, modelling resulted in a 120% increase in losses.

Buildings that have undergone severe earthquake shaking may be damaged to such an extent that boundary walls defined as fire separations may be damaged. This is unlikely to occur if the boundary walls are designed to be part of the structure, as are concrete shear walls. Infill walls such as concrete masonry or light timber frame walls, on the other hand, need not be designed to resist the full effects of the earthquake and may be more prone to collapse. This problem is very difficult to quantify and has been ignored.

2.2.3 Spread from roof of building

In uncontrolled situations, such as those experienced after a large earthquake, fire is likely to reach the top of the building in which ignition occurs. If the construction of the roof is not fire-resisting, flames will issue from the roof of the building and may spread fire to the façade of an adjacent building. For this to occur, the building next to that on fire must be taller than the radiating building, and have glazing located on the critical side.

Very little conclusive research has been conducted on this type of fire-spread. Literature has identified this type of spread as being probable [31], but parameters for the spread have not been formulated. Research into this type of spread is lacking because, in normal fire situations, the neighbouring buildings are protected by Fire Service intervention and spread from the roof of the burning building its neighbours is unlikely. However, because intervention is unlikely following an earthquake, this type of spread may occur.

The only usable reference is in the Acceptable Solutions to the New Zealand Building Code [2]. This document states that if the roof of one building is not fire-rated, the adjacent building must be fire-rated 9m vertically, if it is within 5m of the adjacent building. The parameters of this spread are shown in Figure 2.4. The basis for these values is not known. The constraints are used to recommend building practice, and may be assumed to be somewhat inadequate in the post-earthquake situation considering post-earthquake fire is likely to be more intense than normal fire conditions.

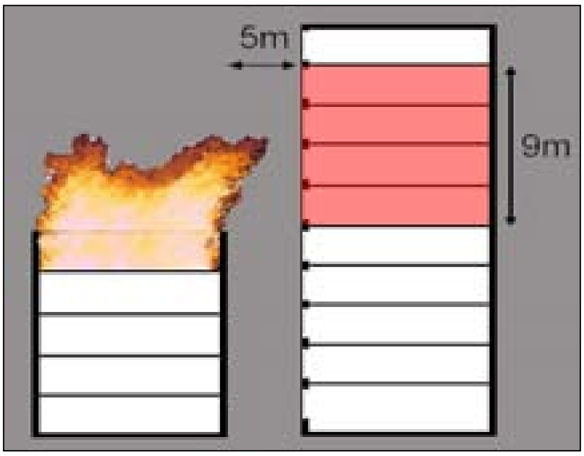


Figure 2.4 Fire-spread from the roof of an adjacent building.

2.2.4 Branding

It is unlikely that branding will occur in the Wellington CBD because most roof-claddings are non-combustible. Non-combustible wall and roof claddings mean that few brands are likely to be produced by a fire, and also that when brands fall onto a building, they are unlikely to cause ignition. Given the right conditions it would be possible for brands to 'fly' into a building through broken window. However, this is too difficult to accurately simulate and is unlikely to be a significant problem [8].

2.2.5 Flame contact

The flame itself contains a high level of heat, and if the projection is large enough for the flame to come into contact with an adjacent building, ignition may result. In the Kobe earthquake, flame contact was identified as being the most common way that fire-spread from one building to another; however the Kobe buildings were very close together [32].

The distance that a flame is likely to project may be related to the geometry of the window from which it is being projected. According to an approximate relationship [7], the flame projection from a typical window in the Wellington CBD is expected to be less than 1.3m horizontally. As seen in Table 2.1 (section 2.3.4), at separation distances of around 1m the fire will spread by spontaneous ignition anyway and, therefore, flame contact may be ignored in the dynamic model.

2.2.6 Dominant fire-spread mechanisms

The two methods of fire-spread that will be assessed, in addition to those used previously, are fire-spread via openings and via roofs. They will be described in more detail in the next two sections.

2.3 Fire-spread via openings

For fire to spread via the window openings of buildings, the windows in opposing walls must face one another. Many adjacent buildings in the CBD tend to have similar storey heights and orientations and so it is in fact relatively common for opposing windows to face another. When the windows in the burning building and the adjacent target building are parallel it can be assumed that fire will spread if the heat flux on the target building from the radiating building is high enough to allow fire to spread.

2.3.1 Heat flux equation

The heat flux equation takes account of the emissivity of the fire and the geometrical relationship between the radiating and the receiving buildings [16].

$$I_R = K_1 \Phi \varepsilon \sigma \left[(273 + T_e)^4 \right]$$

Φ configuration factor.
ε emissivity of the emitter.
σ Stefan-Boltzmann constant (56.7 x 10^{-12}(kW/m^{2}K^4))
T_e temperature of the emitting surface (C^o)
K_1 radiation reduction factor due to glazing.

Except for the configuration factor and the glazing reduction factor, the parameter values are the same as developed previously [13]. The glazing factor allows for attenuation of the radiation through fire-rated or non-fire-rated glazing and was not used in our previous study. The impact of this attenuation is described in the next section.

2.3.2 Heat transmission through glass

Glass is virtually opaque in the infra-red wavelengths associated with natural fires and hence significantly reduces the amount of heat flux that is transmitted through it. It is commonly held that if the glazing is intact, the reduction in heat-flux is around 50% [4,11]. If the glazing remains intact in the target building the contents can only ignite spontaneously, because the glass prevents sparks from igniting the contents (i.e. piloted ignition cannot occur). However, the amount of radiation required is much greater than for normal spontaneous ignition, as the glass itself reduces the transmission of heat by around 50%. Combined with the higher level of radiation required for spontaneous ignition rather than piloted ignition this means that fire-spread is far less likely if the glazing in the target building remains intact than if it is broken. The radiation levels needed for ignition in both glazing 'intact' and glazing 'broken' situations have been analysed.

2.3.3 Configuration factor

The configuration factor describes the geometrical relationship between the emitter and the receiver of radiation, or the building on fire and the target building. It is a measure of how much the target "sees" of the radiator. It is assumed that the radiator and receiving building are parallel as most buildings are built on a rectangular grid in the CBD. The separation distance is another parameter in determining the configuration factor and this is given by the building separation in the buildings database. The other two critical parameters are the height and the width of the radiator.

2.3.3.1 Height of radiator

After an earthquake, the likelihood that a fire will spread up a building is very high. As buildings in the CBD are typically much taller than those in suburban areas, the height of the surface radiating heat is potentially much greater. For modelling purposes the height of the radiating surface is taken as the number of storeys that are on fire at once.

Multi-storey buildings employ construction methods that are designed to resist inter-story fire-spread. The methods can, however, be relied on to resist the spread for a certain amount of time only, and their effectiveness may be greatly reduced by damage caused by earthquakes. Any fire ratings based on concrete or masonry construction are likely to be severely impaired after a major earthquake [28].

Figure 2.5 shows the sensitivity of the heat flux equation to the height of the radiator. The heights of radiator are given in multiples of four metres, as an approximation of storey height. At radiator heights greater than 12m, there is little change in the value of heat-flux. If it is assumed that 3 floors of 4.0 m height were burning at once, then 12.0m is a reasonable value for the height of the radiator. Storey heights in the CBD range between 3m and 4m. Adopting the upper-end value of 4m makes some allowance for vertical flame projection.

A survey of buildings in the CBD revealed that a significant proportion of the buildings are less than 12m high. However, most of the shorter buildings are over 8m, and when flame plume heights through non-fire-rated roofs typical of smaller buildings is taken into account, 12m is a reasonable assumption for the radiator height.

2.3.3.2 Width of radiator

It is assumed that in a post earthquake fire situation the entire floor of a burning building will be on fire at once. The Acceptable Solutions to the New Zealand Building Code (NZBC) states that the maximum area for an un-sprinklered fire-cell in an office is 2500m^2. A building of this floor-size is very rare in the CBD, and so it is unlikely that the internal separations in a typical office will be fire-rated [2]. Even if fire-rated divisions are in place, it is expected that the damage caused by an earthquake will compromise the divisions, allowing the fire to spread throughout the floor [28].

The width of the radiating surface is determined by the amount of window opening there is in the façade. The windows are assumed to be all adjacent to each other (Figure 2.6), so that the radiator width is the percentage openings multiplied by the building width. In most of the buildings surveyed, in walls where fire-spread was likely, the windows were concentrated in one area rather than distributed over the façade, and so the technique as used in the NZBC Acceptable Solutions [2] of factoring the radiation received from an enclosing rectangle by the percentage openings in that rectangle was not used.

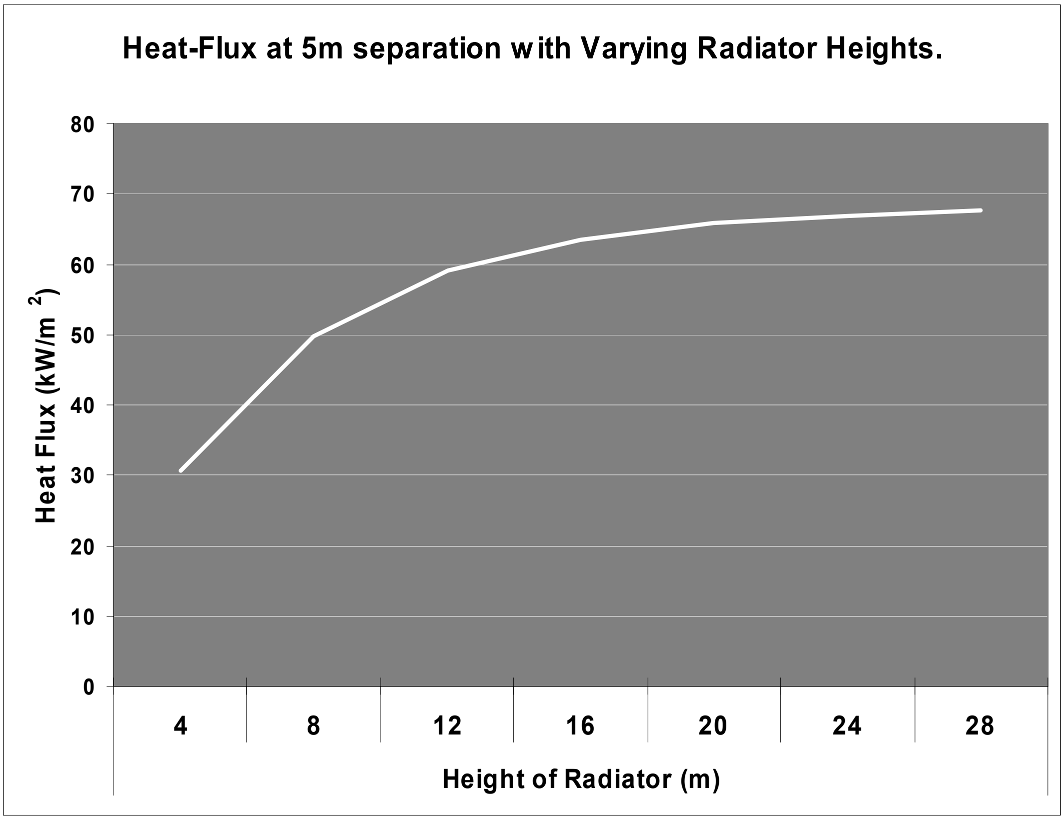
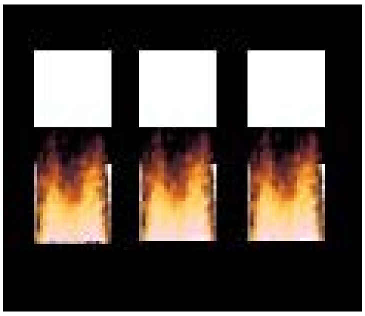


Figure 2.5 Affect of a radiator height on incident heat flux.



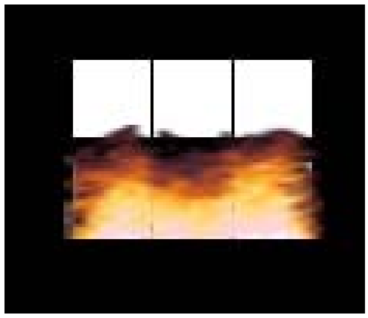


Figure 2.6 Typical layout of windows (left) and layout assumed for calculating the configuration factor (right).

2.3.4 Critical Separation Distances

The greatest distance at which a radiator of a given size will cause ignition of another building, by piloted ignition through broken windows or spontaneous ignition through intact windows, can be determined from the radiation heat flux equation and the size of the radiator. This is the critical separation distance and is given in Table 2.1.

Table 2.1 Critical Separation distances for intact and broken windows

Openings (%)	Glazing Condition	Façade Width (m)	Maximum Spread Distance (m)
10	Broken	10 20 30	6 7 10
	Intact	10 20 30	1 1 2
20	Broken	10 20 30	7 11 14
	Intact	10 20 30	1 3 5
30	Broken	10 20 30	10 14 18
	Intact	10 20 30	2 5 6
40	Broken	10 20 30	11 17 21
	Intact	10 20 30	3 6 7

Table 2.1 demonstrates that when the windows are broken, fire will spread to buildings more than twice as far away as when the windows are intact, hence the state of the windows is an important parameter. As the amount of glazing in the façade (percentage openings) increases, the distance that the fire will spread also increases.

2.3.5 Breakage of Windows

Two modes of glass breakage may occur in a post-earthquake fire situation. The glass may break either from the intensity of heat incident on it, or as a result of the earthquake shaking. In both cases, but more so in fires, the glass may crack but not fall out in which case the glass will continue to attenuate radiation.

2.3.5.1 Breakage from heat

Glass in a window will break when there is a difference in temperature between the centre of the pane and the edge where the window frame shields the glass from heat, thus inducing thermal stresses. The heat flux at which glazing is likely to break depends on the thickness and type of glass.

A number of studies have been conducted on the breakage of glazing under heat stress but no conclusive results have been recorded. The inconsistent nature of the results is summarised by the following quote. “Once a fire gets going, windows … may crack and break out. Or...they may not.” [25]. Table 2.2 illustrates the variety of observations from some of the studies.

Table 2.2 Summary of studies on the breakage of glass due to heat.

Glass Type	Temperature/Heat Flux	Condition
toughened	43 kW/m^2	falls out
3mm float	4-5 kWm^2	cracks
3mm float	16 kWm^2	doesn't fall out
normal float	150-200 ^{o}C	cracks
6mm toughened	300 ^{o}C	falls out
plain	150-175 ^{o}C	breaks
6mm plain	110 ^{o}C or 3 kWm^2	cracks
6mm plain	35 kWm^2	falls out
3mm plain	9 kWm^2	8-24% falls out
6mm plate	23 kWm^2	breaks and falls out

As shown in Table 2.2, the effect of heat on glass is highly variable, and studies do not present enough information to be conclusive.

The only firm conclusion that may be drawn is that the glass in the building containing the fire will break and fall out [7]. If the fire reaches flash-over, as most uncontrolled fires do, temperatures of around 600^{o}C are reached, and normal (i.e. non-fire-rated) glazing can be assumed to break and fall out. Therefore, the windows in the building in which the fire is situated will almost certainly break, and increased fire exposure to adjacent buildings must be considered.

2.3.5.2 Breakage from earthquake shaking

There is a lack of conclusive research on the performance of glazing systems in earthquakes. This is because the multi-cycle, dynamic motions experienced in an earthquake are very difficult to simulate [26]. Much of the literature regarding the breakage of glazing in past earthquakes is anecdotal and very little quantitative data has been collected on glazing performance in earthquake incidents.

Strongly shaken high-rise buildings are subjected to large inter-storey displacement, causing glazing to be broken. Therefore, the performance of the glazing depends on the type of structural system into which it is placed. Shear walls have less inter-storey drift than frame construction, which means that windows in buildings with frame construction are more likely to fall out than those in buildings with structural walls.

Similarly, the type of frame into which the glass is seated will affect glazing performance. Wooden frames use putty to seat the glass, creating a rigid bond with the glass. This means that the glass cannot move within the frame, and is likely to break. Most aluminium glazing methods have flexibility built into the system. Seismic forces may be resisted by tolerances allowed between the glass and the frame, or by the use of a sliding head joint [29]. Curtain-walls are mounted to the exterior of buildings, and are designed to accommodate a large amount of movement. Curtain-walls are consequently less likely to break than a glazing system where the pane is framed within the wall of the building.

Experiments conducted by the Building Research Association of New Zealand on curtain-wall glazing systems found that the systems performed well when installed in buildings designed to current code requirements [29, 43].

2.3.5.3 Glass breakage in modelling

It is difficult to determine with any degree of certainty whether glass breakage occurs in a target building and so simulations using the dynamic model have been carried out for both situations, i.e. with the glass in the target building intact and with it broken. The glass in the building on fire is always assumed to be broken.

2.3.6 Conditional probability of fire-spread

The GIS model that underpins the fire-spread models is essentially a map of Wellington City. Each building on the map has a set of parameters assigned to it, and fire-spread can be controlled by applying rules that relate to these parameters.

The model contains information on:

- total floor area,
- number of floors,
- footprint area,
- roof cladding,
- wall cladding,
- age (by decade),
- replacement value, and
- normally resident populations for day and night (1996 census).

Fire-spread via roofs and via windows, however, cannot be predicted directly from the values given in the database. These types of fire-spread must be simulated using "conditional probabilities" that relate values held in the database to information from a representative survey undertaken for buildings in the Wellington CBD. Given a certain value in the database then there is a probability, based on the survey information, that fire-spread will occur.

2.4 Survey of the Wellington CBD

The Wellington CBD was divided into five smaller areas so that significant trends in fire-spread could be differentiated. The five different areas were based on real-estate boundary definitions which roughly grouped similar types and ages of building together. Figure 2.7 shows the locations of the five different areas so defined.

Figure 2.7 Areas surveyed. North is to the left.

The CBD contains about 2500 buildings, and so it was decided to take a random sample of 250 buildings for detailed study. The potential for fire to spread to and from each of the buildings was assessed. To do this the critical constructional elements of each building and those surrounding it were recorded [39]. By cross-referencing with the database held in the model a profile of the different cladding types in the Wellington CBD was obtained (Figure 2.8).

The areas that contain the most buildings with non-combustible claddings are likely to exhibit the largest increase in losses when spread between buildings with non-combustible claddings is included. The only combustible cladding in Figure 2.8 is weatherboarding.

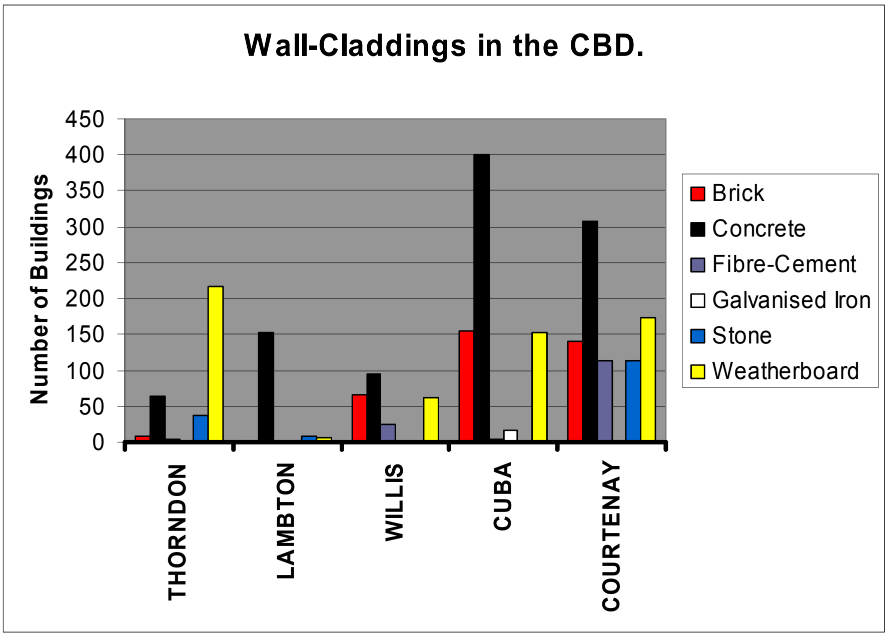


Figure 2.8 Wall-claddings of buildings in different areas of the Wellington CBD.

2.4.1 Recorded data

The factors that affect fire-spread, and the type of spread that it relates to is shown in Table 2.3. These factors were recorded in the survey. The roof cladding, building height and separation distance are found within the GIS model and database. The percentage openings and orientation are not.

2.5 New fire-spread rules

There are two methods of fire-spread in the CBD model that were not in the original model, fire-spread via openings and fire-spread via non-fire-rated roofs.

Table 2.3 Aspects of building constructional that affect fire-spread.

Spread due to:	Roof cladding	Building height	% area of glazing	Orientation of glazing	Separation dist.
Radiation from roof	X	X	X	X	X
Radiation from windows			X	X	X
Building collapse			X	X	X
Flame Projection				X	X
Branding	X				

2.5.1 Fire-spread via openings

Fire-spread via openings is dependent on the separation distance between buildings, their orientation to each other, whether the windows in the target building are intact and the percentage openings in both the building on fire and in the target building. The only parameter in the database is the separation distance and it is assumed that the building sides are parallel to each other due to the predominately rectangular grid layout of the CBD. Two rules for fire-spread through openings were developed, one to simulate intact glazing in the target building and the other to simulate broken glazing in the target building.

A total of 250 buildings were surveyed. The surrounding buildings were also surveyed and the façade details recorded for the façades facing the survey building. In some instances adjoining buildings were so far away that they were ignored.

The percentage glazing as a function of the separation distance is summarised in Table 2.4. For separation distances of more than 6m, the percentage of glazing was reasonably constant at 25%. Buildings with separation distances below 6m generally had reduced glazing areas, due to limitations on glazing required for compliance with building codes for resisting the spread of fire to a neighbouring property.

Table 2.4 Percentage glazing area compared to separation distances.

Separation (m)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-10	10-15	15-20	20+
Glazing %	2.3	12	15	17	18	14	23	23	25	25	26
# samples	446	43	71	48	49	64	27	258	229	64	56

Both the building on fire and the target building must have glazing in order for fire to spread if the claddings are non-combustible. Some buildings have very large areas of glazing very close to the boundaries. In order to determine if fire-spread will occur these factors have to be assessed on a case-by-case basis and the probability of fire-spread is simply the number of times the separation distance is less than or equal to the critical separation distance from Table 2.1 divided by the total number of cases that the separation distance occurs. This is done for the glazing intact and glazing broken cases separately.

2.5.1.1 Glazing intact

The average width of buildings in the CBD is around 20m and the furthest distance that the fire could spread is 6m with 40% glazing. The computer simulation is divided into a 3m grid, and so the probability of spread is formulated for separation distances under 3m, between 3m and 6m, and between 6m and 18m as shown in Table 2.5.

Table 2.5 Rules for spread with windows intact.

Separation (m)	≤ 3	3 – 6	6 -18
Prob. Fire-spread (%)	5	10	1

2.5.1.2 Glazing broken

The same parameters apply to spread between buildings where the glazing is broken, but the distances that the fire will spread are increased. This is because the heat-flux value of 12.5kW/m^2 may be used, and the heat-reduction of the glazing may be ignored.

Where glazing has fallen out, the fire may spread much further, so the potential for fire-spread between buildings up to 20m away must be assessed. At these larger separation distances, the average glazing area is consistently 25% of the total façade (Table 2.4). Therefore the maximum distance that the fire can spread is less than 18m. By analysing the survey data, there are 40 buildings at separation distances of between 6m and 18m from a total of 61 that may spread fire.

Table 2.6 Rules for spread with windows broken.

Separation (m)	≤ 3	3 - 6	6 -18
Prob. Fire-spread (%)	4	41	30

2.5.2 Fire-spread via combustible roofs

The spread of fire from the roof of one building to the façade of an adjacent building will occur if all of the following four requirements are met:-

- the roof construction is not fire-rated,
- the adjacent building is taller,
- the adjacent building is within 5m, and
- the adjacent building has glazing on the critical side.

The only way of determining the structure of a roof in the GIS model is by analysing the roof-cladding. A roof-cladding of corrugated iron is always assumed to be non-fire-rated as the structure that supports this type of cladding is unlikely to be fire-resisting. The model contains all of this information, except whether the receiving building has glazing overlooking the roof of the radiating building. The probability of the fourth requirement being met if the other three requirements are met is 30%.

2.6 Simulations

Using the additional rules defined in the previous section the dynamic fire-spread model was run with fires in 3% of the buildings in each of the 5 parts of the CBD. The rules that were tested were spread from roofs and spread via windows. As described previously, there is no conclusive evidence concerning whether the glazing in Wellington will fall out, and so both glazing conditions are tested in order to determine the severity of the condition. After each run, the simulation model produced information on the footprint area, number and value of buildings that had been burnt.

The dynamic model simulates the spread of fire by assessing the likelihood of spread to each building individually. When the fire encounters a building(s) that it cannot spread to, it will generally burn-out and the simulation stops. In the previous model, the simulated fire stopped when it encountered a building with a non-combustible cladding. With the new rules in place, it is expected that there will be situations where the fire will now spread to those buildings. The effect of this is that the fire will now consume more buildings, adding to the prediction of the loss. More importantly, the fire that has spread to the building with a non-combustible cladding may now spread to buildings beyond.

Table 2.7 shows the floor areas of building for each of the 5 areas that the CBD was divided into. The overall floor area of the CBD is about 3.4 million square meters, and hence the CBD is likely to sustain 10 ignitions following a major earthquake affecting Wellington [30].

Table 2.7 Floor area of construction.

Zone	Total Floor area (m^2)
Thorndon	456,268
Lambton	1,196,375
Willis	551,683
Cuba	629,127
Courtenay	573,965
Total	3,407,418

In each of the 5 areas, ignitions were located in 3% of the buildings as summarised below in Table 2.8. A total of 77 fires were simulated. It can be seen in Figure 2.7 that the survey areas are roughly similar in size, but the Cuba and Courtenay areas tend to have smaller buildings and hence a larger number.

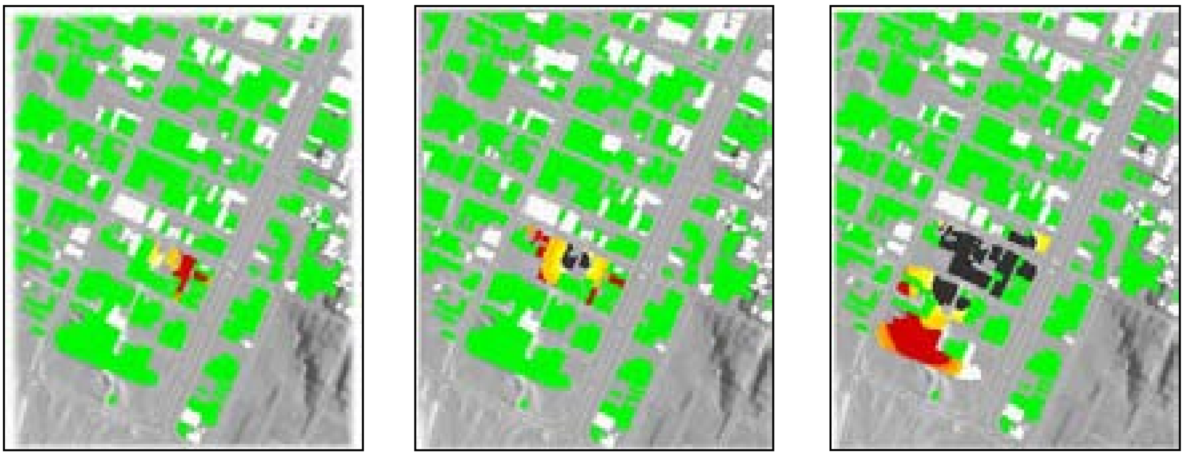
Table 2.8 Number of ignition locations simulated

Area	Total Value of buildings ($millions)	Number of Buildings	Average Value of Buildings ($)	No. Ignition Locations
Thorndon	547.5	379	1,445,000	7
Lambton	1,674.9	208	8,053,000	8
Willis	685.0	269	2,547,000	10
Cuba	626.1	771	812,000	23
Courtenay	551.7	902	612,000	29
Total	4,085.3	2529	1,615,000	77

The effect of the new fire-spread rules was tested by running the model 4 times for each ignition, with each run containing a different combination of rules. The first run for each ignition was a base condition that simply utilised the rules in the original model, where all buildings with non-combustible claddings did not catch fire. The newly-developed rules were tested by adding them to the base condition one at a time, as follows:

- Base case (original model) – fire-spread between buildings with non-combustible cladding not permitted. Fire-spread mechanism is piloted ignition (sparking),
- Base + Rule 1 – base case plus fire-spread via non-fire-rated roofs,
- Base + Rules 1&2 – as above plus fire-spread via window openings where the glazing is intact, and
- Base + Rules 1&3 – as above, except that all windows are broken.

Figure 2.9 shows how using the difference rules affect the fire-spread in one case.



Fire-spread by sparks and roof collapse.

Fire-spread by sparks, roof collapse, and through unbroken windows.

Fire-spread by sparks, roof collapse, and through broken windows.

Figure 2.9 Effect of fire-spread with different criteria for one ignition. White buildings have combustible cladding, green are non-combustible. Other colours show different fire states with orange representing the fire front and black representing the burnt out zone.

2.6.1 Results

The results from the 77 simulations were multiplied by 10 and divided 77 to give the expected loss for the 10 ignitions that are expected to occur in the CBD. These results are summarised in table 2.9.

Table 2.9 Fire losses for 10 ignitions in the CBD.

Case	Spark spread only	Spread via spark and roof burn-through	Spread via spark, roof burn-through, and intact windows	Spread via spark, roof burn-through, and broken windows
Area Burnt (m^2)	73,000	81,000	103,000	321,000
Value Lost ($million)	40	44	68	212

Roof burn-through has little effect on the overall losses, with a 10% increase in the area burnt and value lost. Adding spread via openings with windows intact, increases the fire losses by 70%, but if the windows are broken the fire losses increase by 430%. Losses are therefore highly dependent on whether the windows break or not. The previous study predicted losses of $89M in a moderate breeze. Including fire-spread between buildings with non-combustible cladding in the CBD would result in these losses increasing to between $117M to $261M depending on the proportion of windows that break.

The average loss per ignition for each of the study areas is summarised in Table 2.10.

Table 2.10 Average fire losses per ignition in the 5 areas ($1,000).

Case	Spark spread only	Spark and roof burn-through	Spark, roof burn-through, and intact windows	Spark, roof burn-through, and broken windows
Thorndon	1,733	1,733	1,733	2,794
Lambton	4,551	4,551	15,426	15,426
Willis	9,258	9,258	9,836	41,684
Cuba	3,433	4,279	7,220	33,783
Courtenay	2,969	3,528	4,362	10,120

There is little change in the Thorndon area, and in Lambton there is no difference if windows are intact or broken. The Thorndon area consists of a small number of large buildings, and light timber framed houses. The Lambton area is the area with generally the most recently built, largest and highest value buildings. The biggest change is in the Cuba area where losses are 10 times the base case if all windows are broken. This is an older area with buildings that generally have a lower level of compliance with the building code and includes some buildings with timber cladding. This area is similar to smaller suburban centres which in the previous study tended to stop fire-spread in the suburbs because they typically contained many buildings with non-combustible claddings.

2.7 Discussion

Potential mechanisms for fire-spread between buildings with non-combustible claddings have been implemented within the dynamic model fire-spread model based on a survey of buildings in the CBD of Wellington. Allowing for roof burn-through was found to have little effect on the overall losses, with a 10% increase in the area burnt and value lost. Allowing for fire-spread through openings with windows intact increased fire losses by 70%, but if the windows were broken the fire losses increased by 430%. Losses are therefore highly dependent on whether the windows break or not. The results also tend to suggest that the previous dynamic fire-spread model underestimates losses outside the central business district because of the numbers of buildings with non-combustible claddings.

3.0 EFFECT OF INNER-CITY VEGETATION

3.1 Introduction

The static fire-spread model developed previously [12,13,14,42] did not include vegetation between buildings as a fuel. However, much of urban Wellington is heavily vegetated. Trees and shrubs fill much of the space between houses and line many of the roads. Little of the vegetation is original, however, as the Wellington area was nearly completely cleared of virgin forest in the late 1800's. From then until about 1920 the urban area must have been rather desolate in appearance, but over the subsequent 20 years there was a concerted planting effort, including 1,000,000 pine, eucalypt and macrocarpa seedlings in the "Town Belt" and 40,000 pohutukawa seedlings along street berms [22].

Today the pohutukawa are still prominent along streets and mature stands of pine, eucalypt and macrocarpa make up a large proportion of the Town Belt. Much of the waste land between blocks of houses is filled with small trees and shrubs like mahoe (whitewood), ngaio and various coprosma species, and stands of highly flammable gorse occur on steep hillsides around the edges of the city.

The topic of this section is the spread of fire through the inner-city vegetation, i.e. through the relatively small trees and shrubs that are found between houses and along streets. A pilot study in Karori was undertaken to look at the availability of suitable vegetation data and effect of adding vegetation to the modelled estimates of fire-spread. The static fire model was used to generate "burn zones" with and without the vegetation and the results evaluated.

3.2 Availability of vegetation data

No suburban vegetation dataset is available for Wellington and it was necessary to capture vegetation data as part of the pilot study. Automated capture of vegetation can be achieved directly from some imagery (e.g. Landsat Multi Spectral Scanner, Landsat Thematic Mapper). Numerous indices (Vege.Index, IR/R, NDVI, TNDVI) have been developed using the red and infrared bands from this multi-spectral imagery to measure amount of biomass, vegetation health/stress, etc. However image resolution precludes its use in this study. TM imagery has a resolution of 120m. EnhancedTM imagery for Wellington is available at 60m resolution. High-resolution (4m) multi-spectral data (IKONOS, Quickbird) is available but extremely expensive. Consequently it was necessary to utilise colour aerial photography.

3.3 Vegetation data capture

GNS obtained colour vertical aerial photography for part of Karori (Figure 3.1) from Wellington City Council. The imagery was used to develop a GIS layer of vegetation.

Figure 3.1 Map of Wellington showing roads and the study area (red rectangle) in central Karori.

No attempt was made to map individual trees or to differentiate species from the aerial photographs. Two methods of capturing the vegetation data were used. First, boundaries of vegetated areas within the study area were captured over three blocks by manually digitising the vegetation outlines from the photographs. Only trees more than 2m tall casting significant shadows were captured. Second, the photographs were scanned and unsupervised colour classification was tested in an attempt to speed up data capture. This technique was used to automatically select areas from the aerial photographs with colours in the green range of vegetation. Once converted to polygons, these were compared to the manually digitised polygons for a small area. While the comparison was generally good, the process produced much smaller polygons representing only those parts of a single tree with colours in the desired range. This did not create a problem as often a single tree or clump of trees was represented by small polygons covering 50 to 70% of the vegetated area with a reasonable spatial distribution (Fig 3.2). It proved necessary to edit the automatically derived polygons to remove areas of low vegetation (e.g. mown grass), and a number of non-vegetation features (e.g. house roofs, cars). An additional nine blocks were captured using this method.

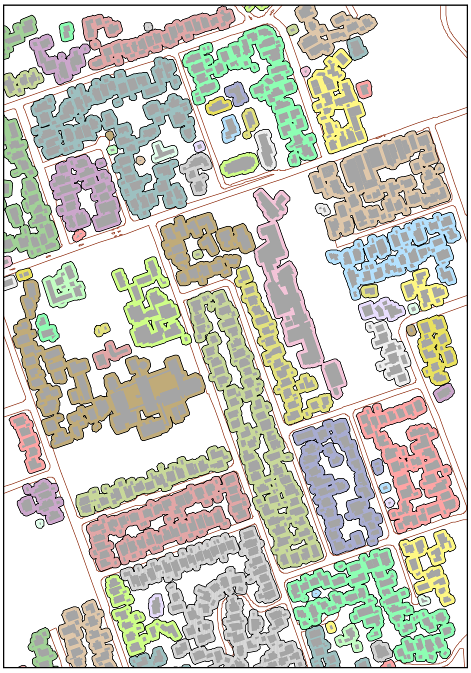
Figure 3.2 Study area, central Karori. Buildings are grey, vegetation green. The larger vegetation polygons (upper part of the study area) were captured by manual digitization. The more detailed polygons (lower part) were captured from scanned images using unsupervised classification.

3.4 Application to static fire-spread model

The static (burn-zone) fire-spread model has two main features [12,13,14,42]. One is the specification of a "critical separation", which is the maximum distance that a fire can jump from one building to another, and the other is the exclusion of all biasing factors such as wind, ground slope or active suppression. The reasons for not allowing any biasing factors are that the critical separation then is independent of the direction of fire-spread and, consequently, the size and shape of a burn-zone do not depend on which building within that burn-zone is ignited first. In other words the burn-zones can be uniquely defined by the critical separation alone. Once the critical separation has been selected the burn-zones are generated within the GIS and then summary data, such as values of buildings, are extracted for all burn-zones.

The static model was used to generate burn-zones, initially using the buildings alone, and then treating both buildings and vegetation as fuel.

As can be seen in Figure 3.3a, the shape and extent of the burn zones using buildings alone and a critical separation of 10 m is controlled by the road pattern. No burn-zones cross roads. The same is true for a 12m critical separation. The addition of vegetation as a fuel (Figure 3.3b) dramatically reduces the number of burn-zones created by both 12m and 10m critical separations. In both cases more than 90% of the buildings in the study area become joined into one large burn-zone (Figure 3.4).



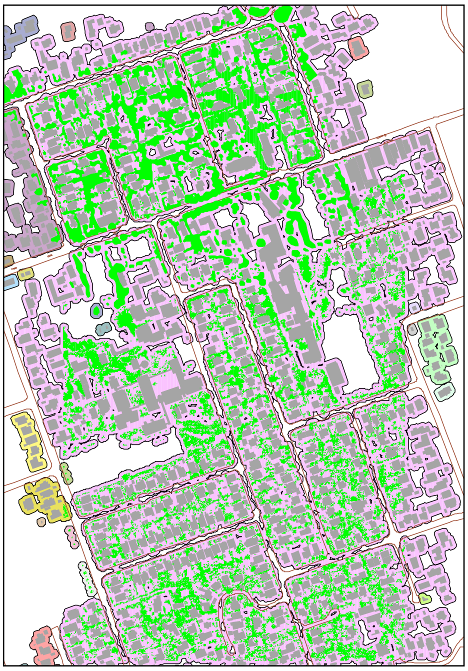
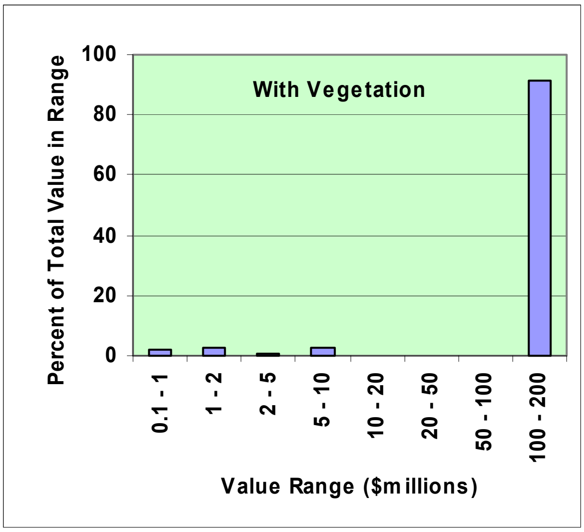


Figure 3.3a Left. Burn-zones using a 10m critical separation and treating only buildings as fuel. Separate burn-zones have different colours. Seventy-seven individual burn-zones were created.

Figure 3.3b Right. Burn-zones using a 10 m critical separation but treating both buildings and vegetation as fuel. Fifteen burn zones were created with one including more than 90% of the buildings in the study area.



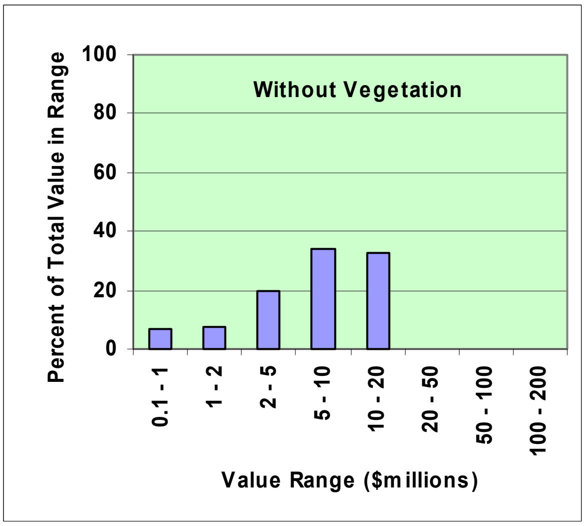


Figure 3.4 Distribution of value amongst burn-zones generated without and with vegetation. When the vegetation is treated as combustible and included in the buffering process more than 90% of the property value falls into one large burn-zone.

3.5 Modelling considerations

3.5.1 Fire-spread mechanisms

Four fire-spread mechanisms are relevant to vegetation, i.e. direct contact, spontaneous ignition, piloted ignition, and branding. "Direct contact" needs little discussion. If two trees are in contact and both are flammable, then spread of fire from one to the other is assumed always to be possible. "Branding" occurs when pieces of burning material that have been blown onto un-burning fuel have sufficient energy to cause ignition in the absence of radiant preheating.

Both spontaneous ignition and piloted ignition require radiant preheating of the target fuel. Spontaneous ignition is assumed to occur when the incident radiation on a piece of target fuel reaches 30 kW/m^2, and piloted ignition is assumed to require incident radiation of at least 12.5 kW/m^2 [13]. Assuming a flame (radiating) temperature of 800 °C for leafy vegetation burning in well-ventilated conditions, then a row of burning, spherical trees (Figure 3.5) is able to cause spontaneous and piloted ignition up to the distances given in Table 3.1. The distances suggest that neither spontaneous nor piloted ignition should be able to cause ignition across most roads, unless there is significant overhang of relatively large-diameter trees.

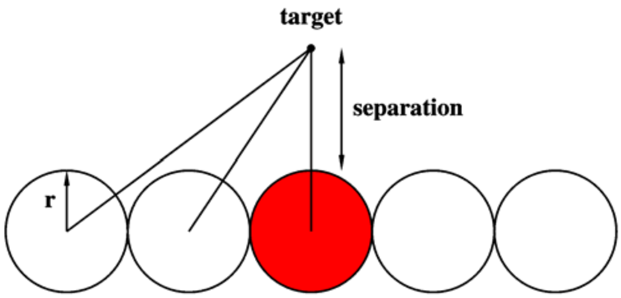


Figure 3.5 Radiation from a row of burning trees. The trees are modelled as spheres.

Table 3.1 Maximum distances over which spontaneous and piloted ignition can occur given a row of spherical burning trees radiating at 800 °C.

Tree diameter (m)	Number of trees in row	Maximum distance over which ignition can occur (m)	
		Spontaneous	Piloted
3	1	0.8	2.0
	3	1.8	4.1
	5	2.3	5.3
6	1	1.5	4.0
	3	3.5	8.2
	5	4.5	10.6

3.5.2 Flammability of the vegetation

Whether or not trees are flammable depends on the species of tree and climatic conditions. Fogarty [21] provides a guide to the flammability of some native plant species. Kanuka and manuka, the only species listed as high flammability, burn readily in low to moderate fire danger conditions. Neither is common in the study area. A further four species (including totora and tree ferns), listed as moderate to high flammability, either have flammable green foliage or produce litter which burns readily in moderate to high fire danger conditions. Nine species (including tawa, rimu, kauri, kahikatea, flax, and cabbage tree), listed as moderate flammability, produce large amounts of flammable litter that burn readily in high to very high fire danger conditions. Important omissions from the study include pohutukawa, kowhai, and red beech.

All the native species listed above are used in suburban plantings and many were recognised from the aerial photographs of the study area. However the above ratings were for dense stands of vegetation in the rural and urban fringe environments. Well-tended urban gardens tend to have mixed species of variable flammability and hanging and fallen dead material is commonly removed.

As was mentioned above, no attempt was made to differentiate between species when collecting data from the aerial photos. All vegetation included in the static fire model was assumed to be flammable.

3.6 Modelling

A probabilistic method for estimating potential losses from post-earthquake fire in urban areas has recently been developed [15]. It involved the following sequence of steps:

- estimation of the number (N) of spreading fires, taking into account strength of seismic shaking, area of property involved, and level of active suppression,
- selection of a wind speed (using recorded wind data) and hence the specification of a value for the critical separation,
- using the critical separation, development of a set of burn zones,
- estimation of losses by selection of N samples from the set of burn zones, and
- repeating the above for many (c. 1,000,000) years of model earthquakes.

Extending the above to include vegetation with buildings in the buffering process becomes complicated by the very large burn zones that result for relatively small values of critical separation. In applying the static fire-spread model it is assumed that if any building in a burn-zone is ignited all will burn. Applying this assumption to both buildings and vegetation would imply that selection of any building in study area, or piece of vegetation, would result in combustion of all, even for relatively small critical separations (and therefore low wind speeds). This is clearly unrealistic.

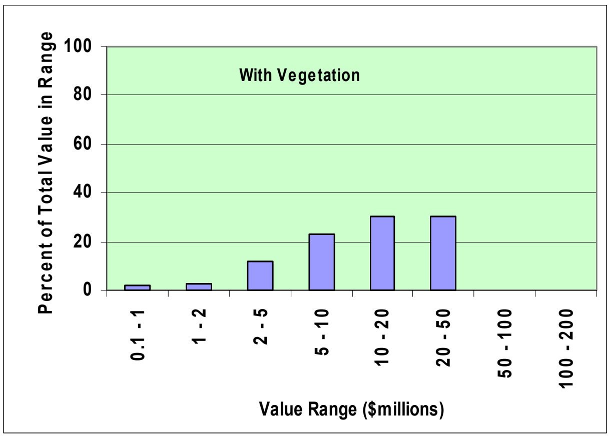
As a way of overcoming the above problem we propose the following. Firstly, for low wind speeds, when the dominant mechanisms for spread are direct contact, spontaneous ignition or piloted ignition, create buffers around buildings using the appropriate standard critical separation, and include vegetation using buffer width of 1m (equivalent to a critical separation of 2m). This applies for standard critical separations for buildings of up to 15m, which is the probable maximum for realistic widths of radiator in housing areas of a city.

Figure 3.6a shows the burn-zones developed for a 10m critical separation on buildings and 2m critical separation on vegetation compared to those developed for a 10m critical separation zone on buildings alone (Fig 3.6b). The addition of vegetation has reduced the number of burn-zones from 93 to 23. With vegetation included, the largest burn-zone contains 136 buildings with a combined value at $25.5 million. Without vegetation, the largest burn-zone contained 78 buildings with a combined value of $12.7 million. The distribution of value within the burn-zones for buildings and vegetation are summarised in Figure 3.7.

Figure 3.6a Burn-zones developed for critical separation of 10m on buildings and 2m on vegetation.

Figure 3.6b Burn-zones developed for critical separation of 10m on buildings alone.

Figure 3.7 Distribution of value amongst burn-zones generated with a 10 m separation on buildings and a 2 m separation on vegetation. Compare to Figure 3.4.



For critical separations greater than 15m, when branding is required for fire-spread, a similar procedure could be applied but with two separate buffer runs to create two separate "burn-zone" sets. The first would be for a 15m critical separation (no branding) and the other for a larger separation as appropriate to the wind conditions (branding required). Selection of a burn zone would then be made from one or other of the two sets according to the likelihood that branding would be possible. At one extreme, in winter when the vegetation is saturated and basically non-flammable the probability of ignition by branding would be essentially zero, and selection would be from the set of burn zones developed with a 15m critical separation. At the other extreme, when the vegetation is at its most flammable, the probability of successful brand ignition may be quite high, say for example 30%. Under these circumstances, selection of the "burn-zone" would be made from both sets with a probability of 70% that the selection would be made from the 15m set of zones and 30% that the selection would be made from the set defined with the larger critical separation.

3.7 Discussion

If not included in a fire-spread model, vegetation between buildings is likely to cause losses to be underestimated.

The inclusion of vegetation data, however, is not straight forward. There is no readily available source of vegetation data available at a suitable resolution. Even if such data were available at a reasonable cost, significant effort would be required to classify it in terms of species and flammability.

The pilot study in Karori suggests that, assuming all vegetation is flammable, estimates for loss from fire made without including vegetation may be 50% of estimates made with vegetation included.

4.0 RURAL FIRE-SPREAD

4.1 Introduction

The existing dynamic fire-spread model [12,13,14,42] has been tested in suburban Wellington and Napier (1932) [24]. A pilot study was proposed to test the possibility of using the modelling technique in a rural wildfire situation where fuel is a more continuous and heterogeneous feature.

4.2 Model techniques

The dynamic fire-spread model, described in full in Cousins et al. [12], uses a "cellular automaton" technique to model the spread of fire over time. ARC/INFO GIS is used to represent the environment as a regular lattice of cells, with each cell being assigned attributes representing the physical environment. Spread of fire from one cell to another (represented as a change of cell state) depends on the initial state of the cell, the attributes of the cell, and the spread rules.

Fire behaviour rules for vegetation fires are available, including methods to calculate the head and flank rate of spread and fire intensity for a limited number of New Zealand vegetation types, and the effect of wind and slope. Transporting these equations to a GIS-based fire model is however, not a straight forward process.

Numerous dynamic models for fire-spread have been developed overseas, particularly in North America. Most models fall into one of two types – cell-based [3,23,44] or ellipse-based [19, 46]. Both model types are claimed to be able to accommodate differing fuel types and fuel conditions, and the effect of wind and slope. Some are limited to modelling surface fires, whereas others include models for crown fires and branding.

Cell-based models simulate fire-spread as a process of spreading ignitions across a landscape composed of regularly sized cells. All are iterative models, and rely on predetermined reference time steps. At each iteration, the time for a fire to spread from a burning cell to all adjacent cells is calculated, and those cells with times equal or less than the reference time step are considered to be ignited in that iteration. These cells then become the sources for new ignitions at the next iteration. The existing GIS-based dynamic fire-spread model is of this type and, theoretically, should be easy to adapt.

Several fire-spread models have been developed using cell-based GIS (e.g., FIREMAP [3, 44], EMBYR [23]) and results of simulations published.

Vasconcelos [45],Vasconcelos et al [44], and Ball and Guertin [3] developed FIREMAP, based on Rothermel's [37, 38] thermodynamic model, for predicting fire-spread across a limited sized landscape. The FIREMAP model as described by Ball and Guertin [3] calculates the rate of spread, direction of maximum spread, and wind speed for every cell. With each iteration of the model, each non-burning cell is tested to determine if a neighbouring cell is burning, and if it is, what direction the fire is coming from and thus the type of fire (head, flank, or back). The rate of spread is adjusted[1] according to the flanking subroutine of BEHAVE [1]. The results were illustrated by a simulated fire in calm conditions and one with a 6 kph wind from the south. Hargrove et al [23] developed EMBYR, a large-scale cell-based probabilistic model. In EMBYR, each cell burns for a single time step of variable length, with spread to neighbouring cells being controlled by a probability. Factors affecting fire-spread include fuel type and moisture, wind direction and strength, and branding.

The ellipse-based models utilise a vector or wave approach to fire-spread. This method can be undertaken in a GIS, but uses a different set of processes to the existing dynamic fire model. Inclusion of this model type into the existing dynamic fire-spread model was not attempted because it would have involved a substantial amount of work. FARSITE is an ellipse-based GIS model developed by Finney [19]. The fire front is propagated as an expanding polygon, again at predetermined time steps, by using Huygen's principle as implemented by Richards [36], which assumes that each vertex on the polygon perimeter can serve as the source of independent elliptical expansion. The sizes of the ellipses at each new vertex are determined by the local fuel type, whereas the shape and orientation is determined by the direction of wind and slope. FARSITE includes models for crown fires and branding. Wallace [46] and several other authors have also developed techniques for calculating fire-spread based on Huygen's principle of wave propagation, though outside of the GIS environment.

The limited time available for this research was used to test a variety of cell-based techniques that appeared to have application to fire-spread modelling.

4.3 Results

ARC/INFO grid has an inbuilt PATHDISTANCE function that calculates, for each cell, the least-accumulative-cost distance over a cost surface from a source cell while accounting for surface distance and horizontal and vertical cost factors. An initial model was built using this function where the cost being accumulated was time. An elevation model allowed the true surface distance to be calculated, with wind being the horizontal cost factor and slope being the vertical cost factor. The horizontal and vertical cost factors were loaded as tables. For slope, a table of slopes from -90 to 90 degrees was populated using the equation of Cheney[9].

[1] The equation published by Ball and Guertin [3] contains an error.

As no similar equation was available for wind, a table for grass fires was developed from published ellipse length/width ratios for various wind speeds [35].

At each iteration of the model, the simulated fire was allowed to spread from burning cells to adjacent non-burning cells. The time of ignition was stored for each ignited cell. Once all cells had been ignited, the resulting grid could be queried to determine which cells were burning at any particular time and to illustrate the fire front at that time.

The results for calm conditions and a westerly breeze (Figure 4.1) were very similar to those illustrated by Ball and Guertin [3].

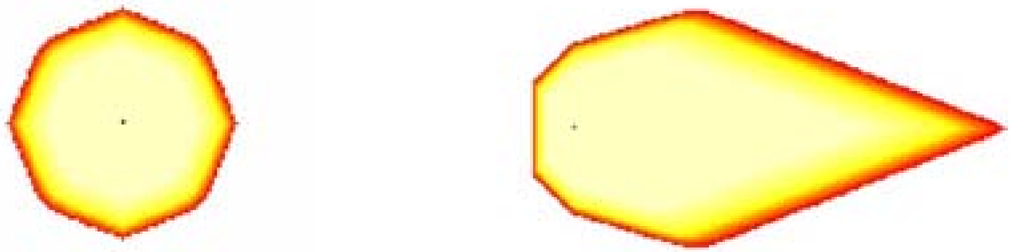


Figure 4.1 Simulation of fire-spread under calm conditions on zero slope, uniform fuel, and uniform moisture (left) and with westerly wind (right). Fire source is the dot.

Critics of the path distance technique have argued that it is limited by the function calculating the least path from the initial burning cell without reference to the states of any cells adjacent to the one under scrutiny. Further they argue that it is not possible to change parameters such as wind speed or direction during the running of the model. ARC/INFO PATHDISTANCE allows for a user-defined maximum cost to be specified. In the model, the cost being calculated is time, and a maximum time limit can be specified and multiple path distance calculations made. If a limit of 5 minutes is placed on each iteration of the model, at iteration 1, all flammable cells within 5 minutes fire-spread of the ignition point were deemed to be ignited, at iteration 2 all flammable cells within 5 minutes fire-spread of these newly ignited cells were deemed to be ignited. Thus the fire source is reset to the burning front every 5 minutes. Changes in wind strength or direction could be made at these times if required. Using the function in this way produced a burn pattern identical to that produced using a single path distance calculation with a limit equal to the total time, provided wind conditions remained constant.

The only disadvantage to using multiple path distance calculations is that cells with fuel that would require a longer time to burn out than the allocated time-step are never burned out. Alternative code was tested that calculated fire-spread only to adjacent cells with the ability to accumulate the fire-spread time without using the path distance function. Runtime was significantly longer than when using the path distance technique, and adjusting wind direction during the run could be achieved but not without further extending the run time. While not developed, additional code for use with the path distance function could have been written to account for partially burned cells.

Tests with the PATHDISTANCE function using different fuel types (with different rates of spread), wind strengths, directions, slope, and barriers (such as roads and waterways) were undertaken and could be accommodated in the model. Figure 4.2a shows a GIS representation of an area in Hawkes Bay with multiple vegetation types (pine, grass, and lucerne) and natural barriers (roads and drainage ditches). Figures 4.2b-4.2i shows predicted burn zone for several time steps for a fire starting with a westerly wind.

Figure 4.2a Digital representation of part of Hawkes Bay created in GIS from topographic data available from Land Information New Zealand. North is to the top of the page. Roads are in brown, drains and other water features in blue, shelter belts and blocks of trees in dark green, with individual trees shown as light green dots. The vegetation is dominantly grass, with a single lucerne crop shown in mid-green.

Figure 4.2b

Figure 4.2c

Figure 4.2d

Figure 4.2e

Figure 4.2f

Figure 4.2g

Figure 4.2h

Figure 4.2i

Figure 4.2b-i Simulated fire over flat terrain with varying fuel types and barriers for wind from west. The fire front is show in red with the burned are in yellow. Fig. 4.2b is shortly after ignition with the fire-spreading across grass. In Fig. 4.2c the flanking and backing fires have reached road barriers (north and west) but the head fire continues to spread east. In Fig. 4.2d the head fire hits a barrier (drainage ditch) but crosses at a single location. In Fig. 4.2e the head fire encounters another barrier (a road) but jumps this eventually. At the same time the flanking fire passes to the south of the barrier. The two fires merge (Fig. 4.2f, 4.2g). The head fire encounters a green lucerne crop (Fig. 4.2h) and slowly penetrates it with the main fire front passing to the south.

The barriers (roads and drains) in the model were able to be crossed by the fire depending on the barrier width, its orientation with respect to the wind direction, and a probability (assigned randomly, but which could be assigned on the basis of fuel type on both sides of the barrier). Additional runs were made with higher probabilities of barrier breaching, and a stronger wind which reduced the effectiveness of the barriers. Spread across the road to the north occurred at several locations under these circumstances.

The area selected for this trial was that of the 1991 Tikokino Fire [35]. The actual area burned and the area simulated in the model are shown in Figure 4.3. The location of fire suppression activity is not recorded by Rassmussen and Fogarty [35], but was probably concentrated in areas of buildings and will have altered the fire shape in those areas. The area burned in the simulation is also shown.

Figure 4.3 Area burned during simulation (red and orange) and during actual fire (orange and grey). In some simulations the fire jumped the road to the north. Fire suppression activity probably accounts for the shape of the southern boundary of actual burned area. No attempt was made to model suppression in the simulation.

The match between the simulated burn and actual burn is good in that barriers to the actual fire acted as barriers in the simulation. The failure of the fire to jump the road to the north in the simulation was the result of the orientation of the road with respect to the wind direction. Altering the wind direction towards the north, or adjusting its strength would allow the barrier to be breached. The location of the breach would be dependent on timing of such a change.

The wind direction recorded for the time of the fire was 270 ^{o} (i.e. from the west) at Napier Airport. Rasmussen and Fogarty [35] show an ellipse which represents the fire's size at the initial attack time which suggests a local wind direction of 289^{o} and record a change in wind strength and direction which resulted in the fire accelerating towards the northeast at sometime before the fire reached the first water barrier. Simulations with this wind change allowed the road to be breached in several locations.

A major problem noted with the path distance technique occurs when the direction of maximum spread diverges from one of the eight sub-cardinal directions (N, NE, E, SE, S, SW, W, NW). The cell-based model only allows travel in these eight directions. At any other angle, the fire front does not advance as far as would be expected in a given time. It appears that when the maximum spread direction is not a sub-cardinal direction the spread is partitioned between the adjacent sub-cardinal directions and the shape distorts unacceptably (Figure 4.4). The same could be expected for slopes, where fire-spread on those not aligned to a sub-cardinal direction would be under calculated.

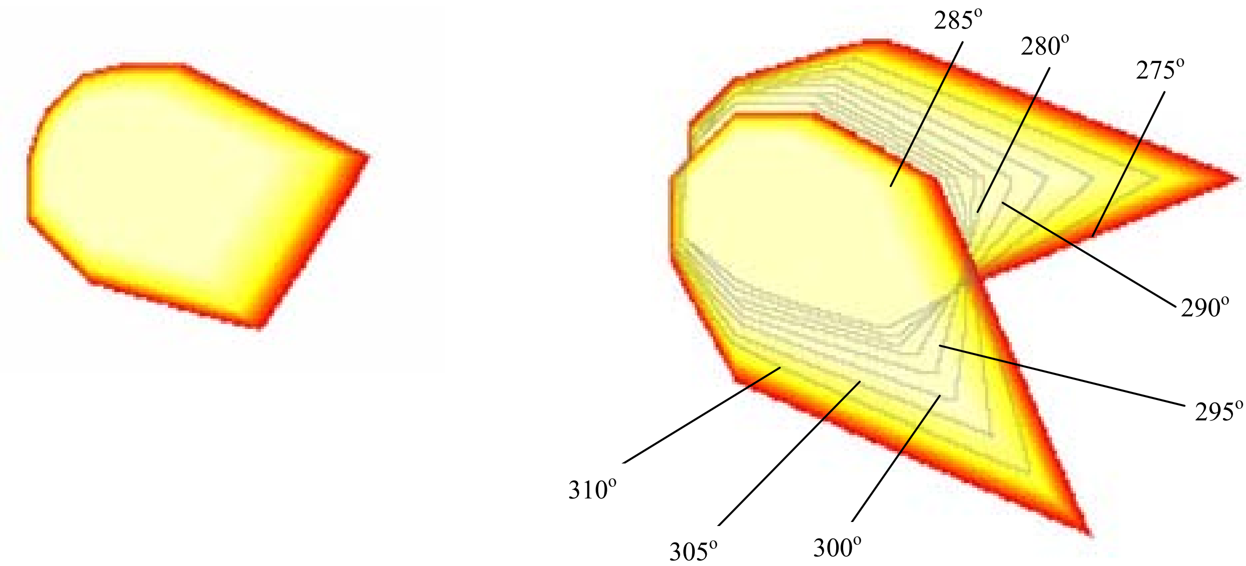


Figure 4.4 Simulation with wind blowing from 299° (left) compared to spread patterns for winds from 270° and 315° (right). The grey lines on the right are the perimeters of spread patterns calculated for winds at 5° intervals from 270° to 315°. The grid arrangement has resulted in the maximum spread for angles between these sub-cardinal directions being significantly less than would be expected, with the spread being partitioned between the two sub-cardinal directions.

This problem is not restricted to the PATHDISTANCE function but is inherent in the cell-based model where movement is only possible to adjacent neighbours. It is interesting to note that the illustrations published by Ball and Guertin [3] and Hargrove et al [23] all involve winds at one or other of the sub-cardinal directions.

It is likely this issue could be overcome by allowing the fire to spread beyond adjacent neighbours. If spread was allowed to two cells out, a wind angle resolution of 26 ° could be achieved. If spread was allowed to five cells out, a resolution of 11.3 ° could be achieved. This enhancement would require writing code to utilise the EUCLIDEAN DISTANCE and EUCLIDEAN DIRECTION functions rather than PATHDISTANCE and would require either making the assumption that cells in the intervening space have the same slope, wind and fuel characteristics as the tested cell, or testing the cells in the intervening space to calculate a more accurate arrival time. Testing to ensure the shortest travel time was obtained would be difficult and would make computation time lengthy.

4.4 Discussion

Whilst data on New Zealand vegetation fuel characteristics are far from complete, sufficient information was available here and overseas to allow the development and testing of a model.

Of the two techniques used overseas to model wildfire-spread, the cell-based approach was considered the easiest to interface with the existing dynamic model. While preliminary tests of the influence of vegetation fuel characteristics, wind strength, and presence of barriers could be effectively modelled, the cell-based technique could not reliably model the effect of wind or slope when the direction of maximum spread was not a sub-cardinal direction. As a consequence, the model as tested could not show the fire perimeter with any accuracy at a given time. Further more, while it was possible to allow for a change in wind direction and/or strength change during the model run, the inaccuracy of the fire perimeter at the time of the wind change would result in a poor estimate of the total fire area.

Whilst ellipse-based techniques appear not to be troubled by these problems, the techniques could not readily be included within the existing dynamic fire model. Further investigation of these ellipse-based systems is warranted. The source code for FARSITE, an ellipse-based system has been obtained and will be tested as time allows.

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