Predicting leapfrog rate of spot fires on severe bushfire days – A Theoretical approach

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Abstract

This paper articulates theories for bushfire spread based on observable phenomenon. It then uses data from documented severe bushfires to quantify the theories and convert them into prediction model for leading spot fires.
The model is then applied to two very severe bushfires and it is found to provide estimates of spread rate for leading spot fires that match observed spread rates within reasonable limits. The model is proposed as an interim measure for use by the fire control team until researchers develop a more accurate one.

Introduction

This paper has two aims. Firstly, it aims to articulate a better understanding of the duality of rates of spread in a severe bushfire - the rate of spread of an individual fire front and the leapfrog rate of leading spot fires. Secondly, it aims to provide a useful prediction tool for predicting leapfrog rate of spread of leading spot fires in a forest on a severe bushfire weather day. Thirdly, it aims to demonstrate the value of using a theory-based approach to provide a useful prediction tool for fire fighters. In this case, the prediction tool cannot be determined by the traditional empirical approach, because replication is impossible. The tool derives from theory, quantified by observations.

Definitions for terms in this paper:

Ember A burning fuel particle that is thrown upward or downwind from a burning source (active flame or smouldering surface)

Live ember Ember is alight when it lands and is capable of igniting a flammable fuel bed

Dead ember Ember has extinguished before it lands in a flammable fuel bed

Spot fire The fire that an ember ignites

Spotting The act of live embers igniting a fuel bed downwind of the ember source

Short distance spotting embers thrown from a few metres to 200 – 500m downwind of the source (head fire flame or smoulder flame)

Medium distance spotting embers thrown 1 – 5+ km downwind of flame source

Long distance spotting embers thrown 10 – 20+ km of flame source

Theory development

Theory of dual fire spread rates in severe bushfires

This theory derives from readily observable phenomena in any bushfire:

A bushfire in a forested landscape may have two types of spread, one due to the continuous run of a surface head fire (which includes short distance spotting – the head fire typically overruns short distance spotting), and the other due to the leap frogging mechanism of medium or long distance spotting.

1. In mild or low intensity fires, the surface fire runs at the predicted spread rate of the appropriate fuel bed type. Longer distance spotting is not supported by fire behaviour mechanisms.
2. In severe or high intensity fires, the surface fire of each given fire front runs at the predicted spread rate of the appropriate fuel bed type. In addition, each fire front can generate a longer distance spot fire, which in turn generates more long distance spotting, and so on This means the spread rate due to leading spot fires is distinctly greater than the surface fire rate.

Theory underlying the leapfrog prediction model

The leapfrog hypothesis is concerned with predicting maximum spotting distances. It is derived from the following theoretical sequence on a day of severe fire weather:

Initially, the head fire runs continuously along the forest floor at predicted rate of spread (ROS). It throws a live ember a maximum distance (Dt). Dt is far enough ahead to allow the spot fire to develop without influence from the head fire. As this spot fire develops in size, its convection column grows in strength. After a certain time (maturation time (Tm)), it throws a live ember the same maximum distance (Dt) as the original head fire. At this stage, the head fire of this spot fire at Tm also travels at ROS. This new spot fire develops in size and after time Tm, its head fire travels at ROS and it throws a live ember a distance of Dt. And so the cycle repeats.

The hypothesis applies to medium and long distance spotting. It excludes short distance spotting because the head fire usually overtakes it. It applies to forests that are capable of medium and long distance spotting, eg, long time since burnt.

The hypothesis is expressed mathematically as follows: **ROS(spot) = Dt / Tm**

Where

ROS(spot) is predicted maximum spread rate of the leading spot fire in kph.

Dt = Maximum expected spotting distance from head fire.

(Whether spotting is medium or long distance can be determined by throw distance range.). Dt is in km.

Tm = Time that a spot fire requires to build enough convection uplift to throw new spot fires a distance of Dt. Tm is in hours.

Assumptions:

(1) Leapfrog prediction rates apply from the time the fire enters a benchmark forest that has not been recently fuel reduced. When fire enters such forests on severe weather days, fire intensity increases dramatically and intensive spotting occurs.

(2) The initial head fire and subsequent spot fires move through similar forest type (eg, species mix, structure, fuel age) and undulating terrain (ie no steep hills).

(3) The benchmark forest is characterised as the MacArthur tall forest (refer Forest Fire Danger Meter). Whether it has litter bed only or shrub layers is irrelevant. What matters is the effect on wind speed at sub canopy level, eg, 1.5 to 2m, which is determined by density of canopy cover. The theory may not apply to a heavily thinned forest or in a shorter, more open forest because the same convective uplift may not be generated to produce long distance spotting.

Component theories in detail:

Maturation time theory

Theory: As the age of a spot fire increases, the longer is the spotting distance from that spot fire. When maturation time is reached, maximum distance spotting occurs.

(Assume constant forest fuel type, weather and topography)

Explanation: When spot fires develop, they throw short distance spot fires, but the originating spot fire overtakes these. As the spot fire grows, the components that determine convection uplift power also grow (ie, size of burn area, width of fire front and depth of fire front), and therefore spotting distance increases. As spot fires mature, their head fires throw medium distance spotting and as maturation time increases, they throw long distance spotting as well.

How long is maturation time (Tm)?

Based on observation and deduction, it is theorised that if a spot fire grows for ½ hour on a severe weather day, it is likely to be some 500m long by 100m width. A fire of these dimensions is likely to have sufficient convection uplift to throw medium distance spotting (eg, 1 – 5 km). Using similar logic, an hour old spot fire should be capable of long distance spotting (eg, 10+ km).

Throw distance theory
Theory: Maximum spotting distance in a given forest fuel is positively related to rate of spread of the initial head fire.

Explanation: Throw distance theory is based on calculations derived from McArthur's work, which relates spotting distance to rate of spread of the head fire as a linear relationship. Deductions from McArthur's Forest Fire Danger Meter led to this approximation: ***Dt = 3 x ROS.*** In the light of data analysis below, McArthur's multiplier comfortably applies to medium distance spotting.

Rationale: Conditions that generate a given rate of spread in a given forest also generate a predictable maximum spotting distance.

The following formula is theorised to apply to both medium and long distance spotting.
Maximum throw distance (Dt) = N x ROS

N = a multiplier determined by medium or long distance spotting. Nominally for medium distance spotting, N = 3 – 5 and for long distance spotting, N = 10+. These numbers can also be used as a tool by observers to identify whether medium or long distance spotting is occurring.

The leapfrog spotting prediction formula now becomes:
ROS(spot) = (N x ROS) / Tm

Where
ROS(spot) is predicted spread rate of the leading spot fire in kph.
Tm is spot fire maturation time in hours.
ROS = rate of spread of the initial head fire through the forest.
[Note: the maximum ROS is regarded as 1.5 kph. ROS is limited by wind speed at sub canopy level. If an active crown fire occurs, the head fire may spread up to 2 – 3 kph, but such an event is unlikely in the benchmark eucalypt forest on undulating terrain.]
N = a multiplier determined by medium or long distance spotting

Data Analysis - Quantification of this theory using documented bushfire data

Data from a range of recent severe bushfires is now analysed to quantify the spot fire prediction tool.
These definitions apply to the following fire analyses.
Leapfrog rates and distances are measured from START time and START location.
START = time the fire enters the (not fuel reduced) forest. If the fire begins in grassland, START time is different from time of origin.
Throw distance and lead spot fire distances were documented by observers, and this allowed calculation of ROS(spot).
ROS of head fires is estimated using prediction models.
Spotting sources are estimated using local vegetation knowledge. This allows throw distance estimates and using ROS figures, this allows calculation of N.

Fire 1 Daylesford 1962

McArthur (1967) documented the following leapfrogging forest fire at Daylesford, Victoria. ROS of head fire = 1.2 kph. He noted short distance spotting = 200m.
Conditions can be classified as **severe** bushfire weather – (35^0C, RH 34%, 45 kph).

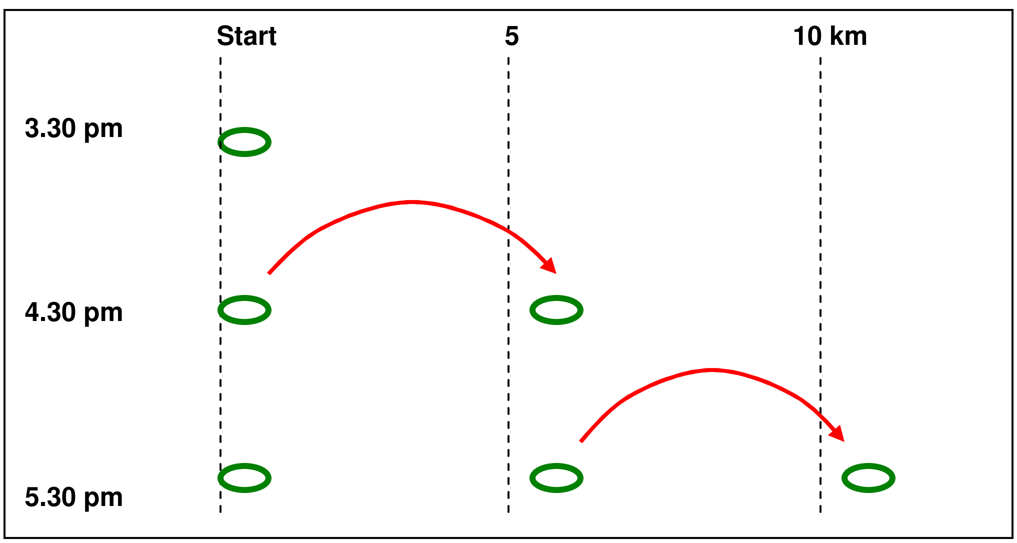
Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Mean spread rate of lead spot fire (= Dist from START / time since 3.30 pm)
3.30 pm = START			
4.30 pm / 1 hr	Spot fire at 6.4 km from start	4.8 km / N = 4 / near start	6.4 kph (= 6.4 / 1)
5.30 pm / 2 hr	Spot fire at 11km from start	5 km / N = 4 / previous spot fires	5.5 kph (= 11 / 2)

Summary of observations:
ROS(spot) = 5.5 – 6.4 kph, ROS = 1.2 kph, Dt = 4.8 – 5 km

What is N? N = 4 (Consistent with medium distance spotting)

What is mean Tm?
Maturation time seems to be approx 1 hour.
Mean Tm = Dt (mean) / mean ROS(spot)
When mean ROS(spot) = 5.5, Tm = [(4.8 + 5)/2] / 5.5 = 0.9 hours

Figure 1 Fire 1, Daylesford, 1962
(Green indicates head fire in forest, which generates more spotting)



The next fires occurred in conditions that can be classified as increasing categories of **very severe** bushfire weather.

Fire 2 Ash Wednesday 1983, Trentham
Conditions can be classified as very severe bushfire weather – (38^{0}C, RH 18%, 40 kph). Long distance spotting observed - 15 – 24 km. (from Rawson et al, 1983)
Author's estimate of ROS of head fire within forest = 1.5 kph on flat, 2 kph upslope

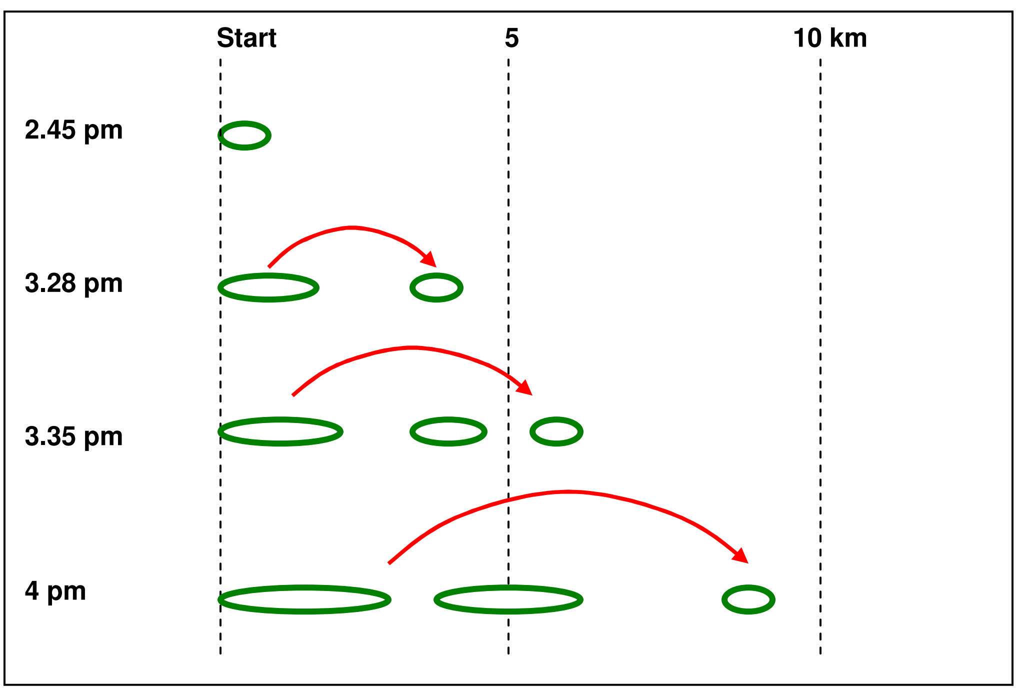
Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Mean spread rate of lead spot fire (= Dist from START / time after 2.45 pm)
2.45 pm = START	Fire enters forest (1.5 km from origin)		
3.28 pm / 0.75 hr	Spot fire at 3.5 km from start	3 km / N = 2 / near forest edge	4.7 kph (= 3.5 / 0.75)
3.35 pm / 0.8 hr	Spot fire at 5.5 km from start	Up to 5 km / max N = 3 / within forest	6.8 kph (= 5.5 / 0.8)
4 pm / 1.25 hr	Spot fire at 8.5 km from start	Up to 8 km / max N = 5 / within forest	6.8 kph (8.5 / 1.25)

Summary of observations:
ROS(spot) = 3.2 – 3.7 kph, ROS = 1.5 kph, Dt = 3 to maximum 8 km

What is N? Initially, N = 2. Thereafter, maximum N = 3 – 5
Consistent with medium distance spotting

What is mean Tm?
Maturation time seems to be approx 30 – 50 minutes

Figure 2 Fire 2, Trentham, 1983
(Green indicates head fire in forest, which generates more spotting)



Fire 3   Ash Wednesday 1983, Deans Marsh
(43^0C, RH 5%, 40-70 kph) (from Rawson et al, 1983, and Billing 1983)
Author's estimate of ROS of head fire in forest = 1.5 kph on flat, 2 kph upslope

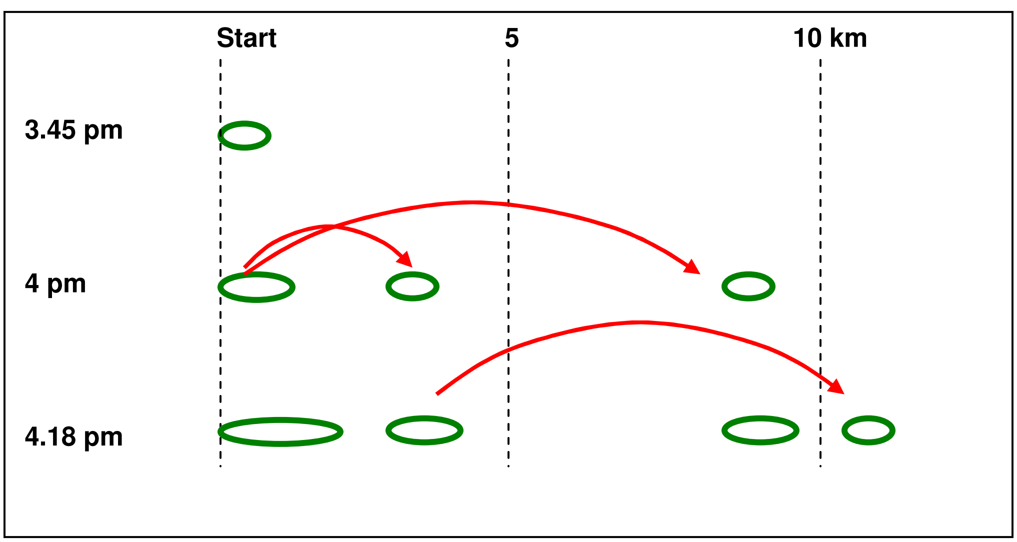
Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Mean spread rate of lead spot fire (= Dist from START / time after 3.45 pm)
3.45 pm = START	Fire enters forest, intensity increases		
4 pm / 0.25 hr	Fire near Benwerrin / 3 km	Up to 3 km / max N = 2 / near START	12 kph (3 / 0.25)
4 pm / 0.25 hr	Haines Ridge / 9 km	6 km / N = 4 / from near Benwerrin	36 kph (= 9 / 0.25)
4.18 / 0.5 hr	North Lorne / 11 km	8 km / N = 5 / from near Benwerrin	22 kph (= 11 / 0.5)

Summary of observations:
ROS(spot) = 12 - 36 kph, ROS = 1.5 kph, Dt = 6 - 8 km

What is N?   Initially, N = 2; later, N = 4 – 5. Consistent with medium distance spotting

What is mean Tm?
Maturation time seems to be approx 15 – 30 minutes

Figure 3   Fire 3, Deans Marsh, 1983
(Green indicates head fire in forest, which generates more spotting)



Fire 4 Black Saturday, 2009 Murrundindi
(41^0C, RH 10%, 35 - 45 kph) (from Royal Commission, 2010)
Author's estimate of ROS of head fire in forest = 1.5 kph on flat, 2 kph upslope

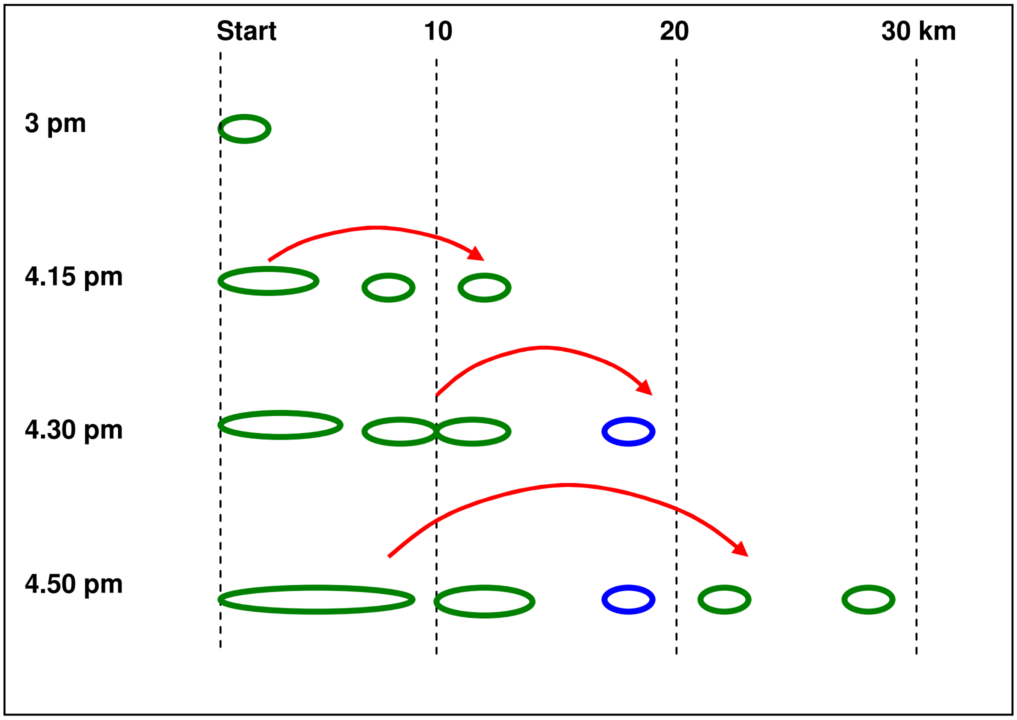
Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Spread rate of lead spot fire (= Dist from START / time after 3 pm)
3 pm = START	Fire enters forest / 0		
4.15 / 1.25	Leading fire front at Black Range ridge / 12 km	Indeterminate, probably multiple medium distance spotting rather than a single jump / estimate 3 jumps of 4 km	10 kph (= 12 / 1.25)
4.30 / 1.5	Spot fires at Narbethong / 19 km	5 km / N = 3 / from Black Range ridge	12.6 kph (=19 / 1.5)
4.50 / 1.8	Spot fire Mt Gordon / 21 km	9 km / N = 4 / from Black Range ridge	11.6 kph (= 21 / 1.8)
4.50 / 1.8	Spot fire at Mt Strickland / 28 km	16 km / N = 10 / from Black Range ridge	15.5 kph (= 28 / 1.8)

Summary of observations:
ROS(spot) = 12 - 15 kph, ROS = 1.5 kph, Dt = 5 - 16 km

What is N? N = 3 – 4 (consistent with medium distance spotting) and N = 10 (consistent with long distance spotting)

What is mean Tm for medium distance spotting phase?
If measurement commences from Black Range at approx 4pm, maturation time seems to be approx 30 minutes
What is mean Tm for long distance spotting phase?
If measurement commences from Black Range at approx 4pm, maturation time seems to be approx 50 minutes

Figure 4 **Fire 4, Murrundindi, 2009**
(Green indicates head fire in forest, which generates more spotting; blue indicates paddock or township, which produces no further spotting)



Fire 5 Black Saturday, 2009 East Kilmore
(40 - 42^{0}C, RH 9%, 55 - 65 kph) (Royal Commission, 2010)
Author's estimate of ROS of head fire in forest = 1.5 kph on flat, 2 kph upslope

Note: Between 3 and 3.30 pm, on 7 Feb, 2009, I observed the leading spot fire travel towards Mt Disappointment through tall forest at approx 1 - 1.5 kph. I observed a spot fire run up a windward upslope at maximum 2 kph. It ran sub canopy, and at the top of the ridge, spiked a tall flame, approx 1 – 2 x tree height. Such sub canopy fire spread has been described as trenching **(REF).**

Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Spread rate of lead spot fire (= Dist from START at Wandong / time after 2pm)
2pm = START	Fire enters forest near Wandong		
3pm / 1 hr	Spot fire at 9 km near Mt Disappointment / 9 km	9 km, assume 3 jumps of 3 km / N = 2 / within forest near Wandong	9 kph (= 9 / 1)
3 – 3.15 / 1.25 hr	Spot fires at Humevale and near Whittlesea / 20 km	12 km / N = 8 / from Mt Disappointment	16 kph (=20 / 1.25)

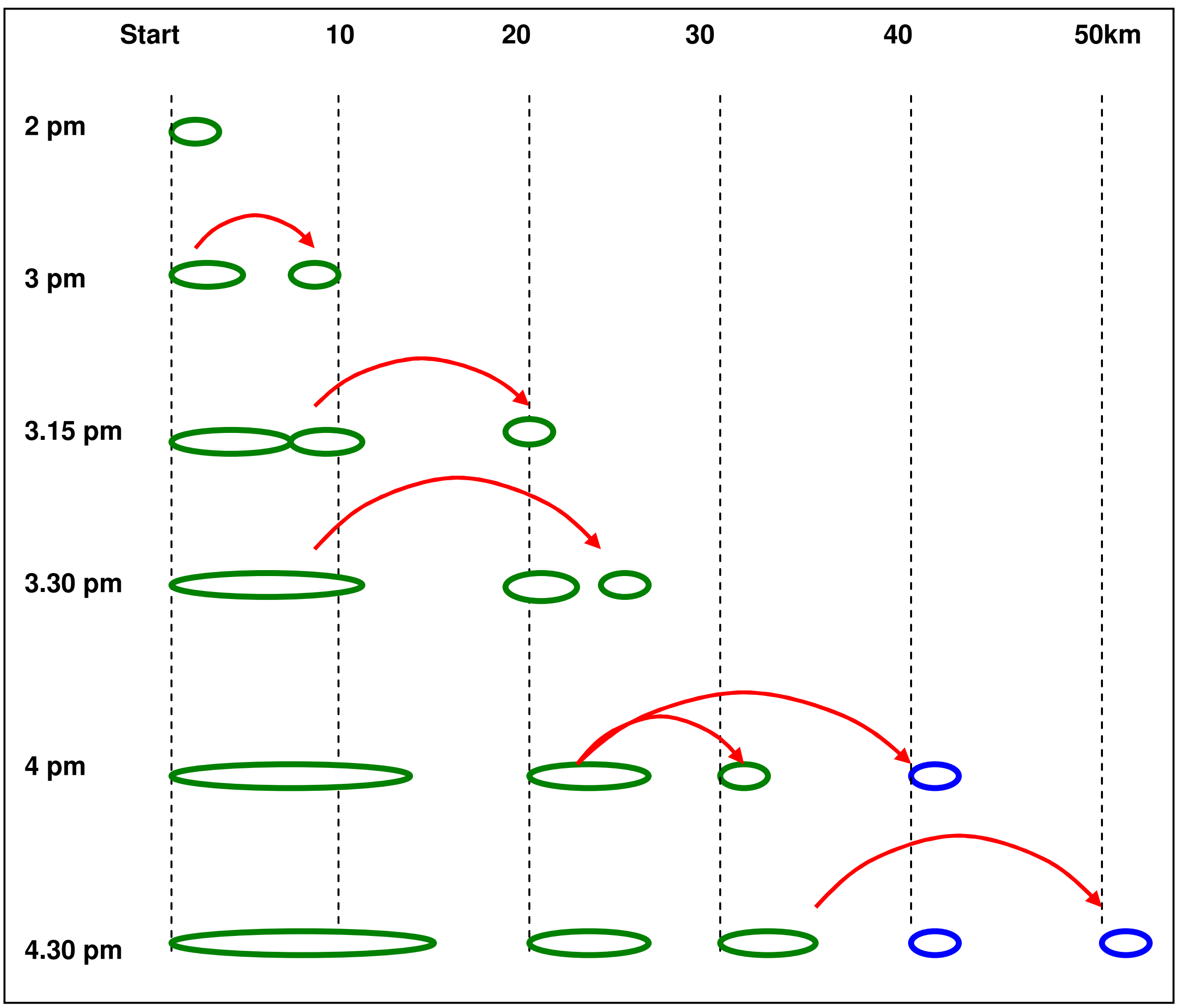
3.30 / 1.5	Spot fires at Strathewen / 25 km	15 km / N = 10 / from Mt Disappointment	16 kph (= 25 / 1.5)
4 pm / 2 hrs	Spot fires Heidelberg – Kinglake Rd area / 31 km	10 km / N = 7 / from Humevale area	15.5 kph (= 31 / 2)
4pm / 2 hrs	Spot fires in Yarra Glen / 41 km	20 km / N = 13 / from Humevale area	20.5 kph (= 41 / 2)
4.30 pm / 2.5	Spot fire Healesville / 52 km	16 km / N = 10 / from Heidelberg – Kinglake Rd area	20.8 kph (= 52 / 2.5)

Summary of observations:
ROS(spot) = 9 - 20 kph, ROS = 1.5 kph, Dt = 3 - 20 km

What is N? N = 2 (consistent with medium distance spotting) and N = 7 - 13 (consistent with long distance spotting)

What is mean Tm for long distance spotting phase?
If measurement commences from Humevale / Strathewen area at approx 3.15 – 3.30 pm, maturation time seems to be approx 30 - 45 minutes (10 and 20km jumps), and approx 30 min for the next 16 km jump. It is possible that the last jump may have originated from 25 km in an area that had been burning fiercely for an hour (dotted red arrow in Fig 5)

Figure 5 Fire 5, Kilmore East, 2009
(Green indicates head fire in forest, which generates more spotting; blue indicates paddock or township, which produces no further spotting)



Discussion

The theory-based approach allowed targeted data identification and consistency of analysis.

Maturation time: It is theorised that Tm for maximum medium distance spotting is ½ hr, and for maximum long distance spotting is 1 hour. Estimates for medium distance spotting from the above fires suggest a range of 15 – 30 min to 30 – 50 min for very severe weather fires and 1 hour for a severe weather fire. Estimates for long distance spotting from the above fires suggest a range of 30 - 45 min and 50 min for very severe weather fires. These figures provide preliminary support for these theorised figures. Subsequent research will be able to refine them.

Logistics of spotting: If upper winds are 60 kph, long distance spotting of 15 km requires 15 minutes minimum of flight time for the live ember. This suggests a spot fire incubation time of up to 45 minutes. ROS(spot) in these conditions is 15 kph.
Similarly for medium distance spotting under these conditions, a throw distance of 5 km requires a minimum ember flight time of 5 minutes, meaning a spot fire incubation time of up to 25 minutes. ROS(spot) in these conditions is 10 kph. Such long flight times require a productive source of large ember material, which means long unburnt forest. [Vesta (2007) found that jarrah (similar to messmate) bark samples of 5cm x 1.5 cm and up to 0.5 cm thick had an average burnout time of just over a minute (74 seconds). This suggests that much larger bark sizes are required for 5 minutes of flight time and considerably larger for 15 min flight time.]

Relevance of maturation theory to prediction: When applying maturation theory to a prediction perspective, the operator needs to determine whether medium or long distance spotting is likely by asking this simple question: is the patch of forest large enough to carry a high intensity fire for ½ hr, ie, will the fire burn long enough to generate medium or long distance spotting or both?

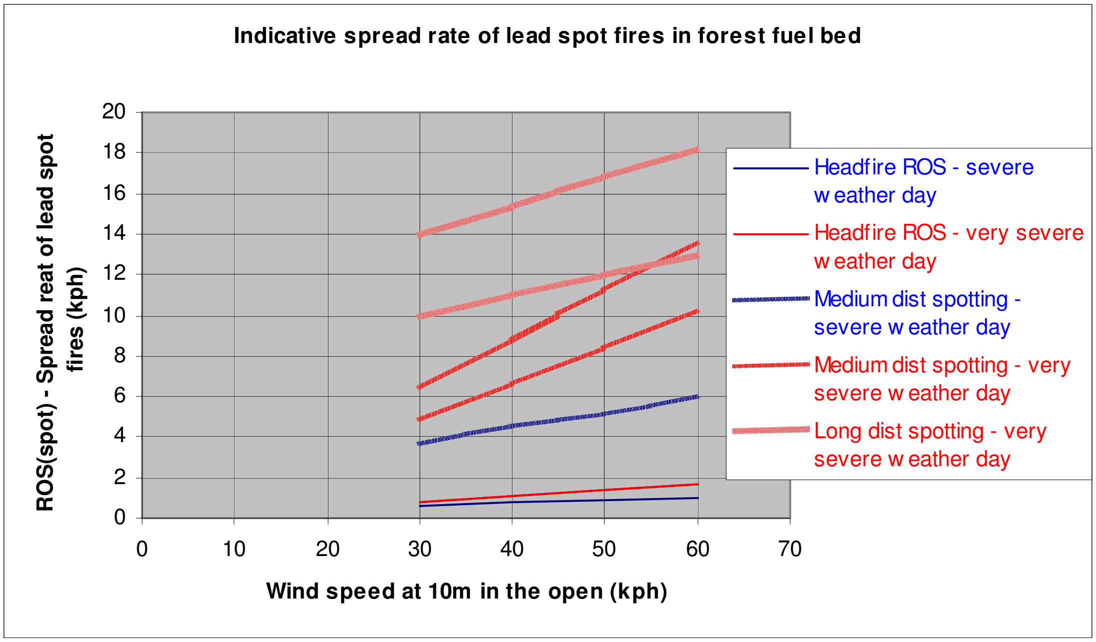
One contentious variable upon which agreement may be difficult is the author's designation of maximum ROS of the head fire in the forest. The difficulty arises because researchers and observers rarely distinguish the in-forest spread rate from the leapfrog rate of spread due to spotting. The author's deductions from McArthur's (1967) original work in litter bed fires and Burrow's (1999) work, find that ROS in a tall forest cannot rise above 1.5 kph, simply because wind speed at litter bed level is limited by tree cover (O'Bryan, 2005). This deduction is confirmed by the author's observation of the lead spot fire (with accompanying strong plume) travelling through forest approaching Mt Disappointment summit between 3 and 4pm, was a constant ROS of approx 1 kph, or at most 1.5 kph. It was checked by cross-referencing seen areas on Google Earth.

Note: it is conceivable that head fire ROS in a short forest or an open forest will be higher because wind speed is greater at ground level.

Development of the spot fire prediction model

The model applies to two categories of bushfire weather, severe and very severe. **Very** severe bushfire weather can be defined as close to, or worse than, 40^0C, 10%, 40 kph. Severe bushfire weather is a little milder than these conditions. Chart 1 represents the model. The x-axis uses wind speed at 10m as the independent variable. Wind speed predicts the dependent variable of ROS, which is the predicted head fire spread rate within a tall forest. Using ROS, the model then calculates throw distance for medium and long distance spotting, using ranges of 3x and 4x for severe and 10x to 14x for very severe weather. These values are divided by respective Tm, for medium distance, use Tm = 0.5 hrs and for long distance, use Tm = 1 hr. The model predicts the spread rate of leading spot fires, for both medium and long distance spotting. The prediction model applies to two categories of severe bushfire weather, severe and very severe. The Chart plots severe weather as blue and very severe as red.

Chart 1 Indicative spread rate of leading spot fires



The Chart envisages the following scenarios.
A head fire in a (non fuel reduced) forest spreads at a predicted rate according to wind speed at 10m. This is its surface spread rate, ROS.
Short distance spotting: The head fire generates massive short distance spotting - up to 200 - 500m ahead, but this will not add significantly to ROS.
Medium distance spotting: The head fire generates a steady rain of medium distance spotting. After maturation time of ½ hour, spotting occurs at a maximum distance of 3 - 5x ROS. As each of these spot fires grow, they also throw maximum distance of 3 - 5x ROS after maturation time of ½ hour.
Long distance spotting: The head fire generates a sporadic rain of long distance spotting. After maturation time of 1 hour, spotting occurs at a maximum distance of 10 - 14x ROS. As each of these spot fires grow, they also throw maximum distance of 10 - 14x ROS after maturation time of 1 hour.

Application Notes:
This Chart applies to the benchmark forest that meets two prerequisites - firstly, the forest has the capability to produce medium and long distance spotting, characterised as long unburnt forest, and secondly, the fuel bed in the forest where the live ember lands downwind is flammable and also capable of generating medium and long distance spotting. These conditions were not met at some locations on Black Saturday, which explains why there were fires that did not produce significant medium or long distance spotting. Eg, the maximum ROS recorded for grass fires at Horsham was 10 kph and at Redesdale 10 kph (Royal Commission, 2010). These fires also burnt through patches of trees, which would have also generated spotting downwind, but presumably it was short distance and rapidly overtaken by the grass fire. Similarly, the first 40 min of the Kilmore East fire was in grass with scattered tree patches and a young eucalypt plantation. It ran the first 3.5 km at a modest 5 kph.

Prediction tool in action
The prediction model provides a structured format to estimate spread rate of the leading spot fires. This may assist command teams to plan for community protection downwind and avoid the possibility of being taken by surprise by the leapfrog effect of spotting.

(A) Beechworth fire
It is useful for the controller to know the rate of spread of the lead spot fires and the location of the lead spot fires at the time of the wind change.

Beechworth fire narrative:
6 pm The fire began in **very severe** conditions, wind averaging 35 kph, gusting to 57. Weather gradually became milder over the next few hours. The fire ran through recent fuel reduced area until 9 – 9.30, after which fire intensity and spotting activity increased dramatically. Initially, the fire spread through fuel reduced forest with flame height 10m, and spotting at 500m. ROS was estimated at 2.3 kph (Royal Commission), but this rate would have included assistance by some medium distance spotting.
At 9.30 pm, the Royal Commission reported a dramatic increase in fire intensity, spotting up to 9 km ahead.
Wind change forecast for 12.30AM
Further details of Beechworth fire appear in Appendix 1.

The following two scenarios are useful for the controller to know.

(1) Predict ROS(spot)
Using 35 kph wind speed, predicted ROS(spot) for medium distance in very severe weather = 6 – 8 kph, and for long distance spotting = 10-14 kph
It may be reasonable to use lower numbers because fire is in late evening, when weather conditions tend to become less severe.

[Comparison: Actual long term ROS(spot) was 7.4 kph]

(2) Location of lead spot fires at time of expected wind change
Change is expected at 0.30 AM
START is approx 6 km from origin.
START time = 9.00pm.
Allow ½ hr for maturation time, commence prediction from 9.30 pm.

(a) Estimate for medium distance spotting Estimated ROS(spot) = 6 kph
Change expected at 0.30 AM = a 3 hours run from 9.30.
Leapfrog distance due to medium distance spotting - 3 hrs at 6 kph = 18 km
Add 6 km, total = 24 km from origin
Predicted length of fire's run before wind change if only medium distance spotting occurred is 24 km.

(b) Estimate for long distance spotting - ROS(spot) = 10 kph
Change expected at 0.30 AM = a 3 hours run from 9.30.
Leapfrog distance due to long distance spotting = 3 hours at 10 kph = 30 km
Add 6 km, total = 36 km from origin
Predicted length of fire's run before wind change if long distance spotting occurred is 36 km.

[Comparison: Actual length of fire's run before wind change was 32 km.]

(B) Hindsight application of the tool to Kilmore East Fire

Estimate of spread rate of lead spot fires		
Medium distance rate = 12 kph		
Long distance rate = 18 kph		
Start measuring from east Wandong, 10 km from origin. Start measurement from 2.30 pm, when fire has been in forest for up to ½ hour. Location of lead spot fire up to 5.30 pm:		
	Medium distance spotting	Long distance spotting
Prediction for 3.30 pm	12 km from east Wandong (22 km from origin)	18 km from east Wandong (28 km from origin)
Prediction for 4.30 pm	24 km from east Wandong (34 km from origin)	36 km from east Wandong (46 km from origin)
Prediction for 5.30 pm	36 km from east Wandong (46 km from origin)	54 km from east Wandong (64 km from origin)

Comparison:
3.30pm lead spot fires at 25 km from origin
4pm lead spot fires at 41 km from origin
4.30pm lead spot fires at 52 km from origin
The lead spot fires recorded at after 4 – 4.30 were in paddocks, which meant that they could not generate further distance spotting.
The SW wind change arrived at 5.30pm.

Conclusion

The paper has articulated theories for bushfire spread based on observable phenomenon. It then used data from documented severe bushfires to quantify the theories and converted them into prediction model for leading spot fires.

The model was then applied to two very severe bushfires and it was found to provide estimates of spread rate for leading spot fires that reasonably matched observed spread rates. The model is proposed as an interim measure for use by the fire control team until researchers develop a better one.

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Vesta 2007 Project Vesta - Fire in Dry Eucalypt Forest CSIRO, Australia

Appendix 1 Beechworth fire narrative continues in tabular form:

(Source – witness statements from Royal Commission)

Time / time since START	Event / distance from START	Throw distance (Dt) / N (= Dt / ROS) / Probable origin of spotting	Spread rate of lead spot fire (= Dist from START / time after 9.30 pm)
8.30 pm	Leading fire front in Musgrove area, 6 km from origin		
9.00 pm = START	Fire enters non fuel reduced forest some 6 - 8 km from fire origin		
9.50 pm / 0.9 hrs	Spot fires at Mudgegonga / 9 km	9 km / N = 6 / from Musgrove area	10 kph (= 9 / 0.9)
Midnight / 3 hrs	Spot fire south of Carrols Rd / 16 km	EITHER 5 km / N = 3 / from Mudgegonga area OR 12 km / N = 10 / from Musgrove area	5.3 kph (= 16 / 3)
Approx 12.30 am / 3.5 hrs	Spot fires at Havila / 26 km	Probably 10 km / N = 10 / from Carrols Road area	7.4 kph (= 26 / 3.5)

Summary of observations:
ROS(spot) = 6 - 22 kph, ROS = 1 - 1.5 kph, Dt = 5 - 12 km

What is N? If N = 3 (consistent with medium distance spotting). If N = 6 - 10 (consistent with long distance spotting)

What is mean Tm for long distance spotting phase?
If measurement commences from Mudgegonga area, maturation time seems to be up to 2 hours (12km jump). The next 10km jump seems to have a maturation time of ½ hr.

Figure 6 **Beechworth Fire 2009**
(Green indicates head fire in forest, which generates more spotting)