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Modelling self-evacuation archetypes to improve wildfire evacuation traffic simulations: A regional case study

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Abstract: Wildfires are a serious threat in many regions of the world, including Australia. The risk of these fires is expected to continue to increase due to climate change, putting more people and communities in harm's way. One approach to reducing the risk to lives in such fires is to plan and prepare for community evacuations. Researchers have been exploring the use of self-evacuation archetypes, clustering self-reported individual behaviours in past fires, to gain insights into who evacuates, why they do so, and when. Self-evacuation archetypes encompass a range of factors, including demographic characteristics, risk perception, social networks, and prior experience. By understanding these factors, researchers can create more realistic models of decision-making during a wildfire event.

In Australia, evacuations are not mandatory, and while the understanding of the decision to leave or shelter in place has advanced, much less is understood about how these decisions play out as traffic on the transport network. For instance, intermediate trips, which are trips to destinations other than the evacuation place, can constitute a significant proportion of trips following an evacuation recommendation, and can lead to different outcomes compared to those of a coordinated evacuation. Therefore, modelling the diversity of decisions and their contribution to traffic is vital to understanding local evacuation concerns and planning safe community evacuations.

In this work, we present an agent-based decision-making model and scenario for the town of Castlemaine, located in the state of Victoria, Australia. Our model is based on self-evacuation archetypes, applied to a synthetic population representing the demographics of residents of the region. The model provides a framework for understanding how different individuals are likely to respond during a wildfire event, and allows exploration of the potential impact of different interventions. We believe that our approach provides a more realistic and nuanced picture of traffic during a wildfire event and can help emergency services plan more effective response strategies.

Keywords: *Wildfire evacuation, Population synthesis, Agent-based modelling, Belief-Desire-Intention agents, Self-evacuation archetypes*

1 INTRODUCTION

Wildfires pose a serious threat to life, property, and the natural environment. The extreme temperatures produced by radiant or convective heat represent the most significant risk to human life. Additionally, delayed evacuations can result in fatalities [Handmer et al., 2019] including severe road accidents [Blanchi et al., 2014]. Adequate planning and preparation for such catastrophic events is therefore essential to minimise the potential loss of lives and property. Over the past few decades, extensive research has been conducted with two main perspectives, namely the engineering perspective and the behavioural perspective. The engineering perspective involves addressing the issue of large-scale evacuation through traffic flow modelling, which provides information on expected network congestion and anticipated timing of evacuation [Even et al., 2014, 2015].

A behavioural perspective considers individual protective responses to wildfire threats, including remaining to defend the property, delaying the decision to leave until it is deemed necessary, and leaving immediately after the threat is perceived. These responses are generalisable to jurisdictions that apply mandatory evacuation orders (North America) and those that do not (Australia) [McLennan et al., 2019]. Three key factors influencing evacuation decisions in the literature are risk perception, represented by likely impact, receipt of official warnings and perception of evacuation as protective of personal safety [Strahan et al., 2019]. Planning, preparation and equipping actions influence the perception of evacuation as a safe response to wildfire threats [Strahan and Watson, 2018]. Other important factors identified in the literature are: residents not at their property, when becoming aware of a fire may attempt to return rather than immediately proceed to a safer location; households with dependants, including children and people with special needs, or companion animals and/or livestock will experience more challenging, delayed evacuation [McLennan et al., 2019]; residents of farms and other agribusinesses are more likely to stay and defend their properties while residents of amenity dwellings are more likely to leave [Strahan et al., 2018]; mandatory evacuation orders are likely to result in higher rates of compliance and fewer residents delaying evacuation [McLennan et al., 2019; Reininger et al., 2013].

These critical elements of human behaviour are not incorporated into computer models [Folk et al., 2019] due to the lack of a systematic modelling framework of household perceptions and responses to bushfires [Russo and Chilà, 2014]. In this context, an agent-based model of householder decision-making was developed using the behavioural insights of the self-evacuation archetypes [Strahan et al., 2019, 2018]. Some archetypes will 'leave early' (Considered Evacuator), delay (Responsibility Denier) or remain (Experienced Independent), influencing the type and timing of their protective response.

These response behaviours are integrated into the Simulations of Emergency Evacuations for Knowledge, Education and Response (SEEKER) tool [Singh et al., 2022] along with other inputs such as fires from Phoenix RapidFire simulator [Tolhurst and Chong, 2011]. Individuals are assigned an archetype based on their demographic representation in the community. In the simulation, they make decisions based on personal circumstances, their knowledge of the bushfire event, and their risk perception. Outputs from SEEKER include individuals' decisions and vehicle movements, and provide a simulated account of community response to the bushfire event. SEEKER is supporting Victorian emergency services with scenario-based planning to identify potential traffic management issues and to test potential solutions; assessing the implications of evacuation decisions on community safety outcomes; and as an adjunct to community engagement activities.

2 CASE STUDY: MODELLING EVACUATION BEHAVIOURS FOR CASTLEMAINE REGION

In this study, our goal was to see how self-evacuation archetypes [Strahan et al., 2018], which were originally developed from bushfire experiences of residents of Perth and Adelaide hills but have since been shown to be robust more widely across Victoria [Strahan and Gilbert, 2021], could be applied to a new community to better represent the variability in residents' behaviours and resulting local traffic during evacuations. To this end, we describe in this section the process of developing an evacuation scenario using behaviour personas modelled on self-evacuation archetypes, applied to the target community of Castlemaine in Victoria, Australia.

The overall idea was to build a virtual or *synthetic* population for the new region, and assign to each individual in this population one of the seven self-evacuation archetype personas, summarised in Table 1. The synthetic population was then used in agent-based simulations of bushfire evacuation scenarios, where, based on assigned archetypes, synthetic agents reacted to the situation according to their assigned personas and individual circumstance. Taken together, this provided a more nuanced view of decisions during bushfire events, and gave a more realistic picture of likely traffic in such events. Learnings from these scenarios are able to then inform emergency planning, training, and community education programs.

Several design decisions and modelling assumptions were made in achieving this goal. First, and after analysing Strahan's original phone survey data on which self-archetypes were created [Strahan et al., 2018], as well as the available data and method [Wickramasinghe et al., 2020] on which a representative resident

Table 1: Strahan et al. [2018]'s self-evacuation archetypes.

Archetype	Key characteristics	Evacuate or Remain
Responsibility Denier	Believe they are not responsible for their personal safety or for their property	Highly committed evacuators but expect others to direct and assist
Dependent Evacuator	Expect the emergency services to protect them and their property because they are incapable of taking responsibility for themselves	Highly committed evacuators but expect others to direct and assist
Considered Evacuator	Having carefully considered evacuation, are committed to it as soon as they are aware of a bushfire threat	Committed to self-directed evacuation
Community Guided	Seek guidance from neighbours, media and members of the community who they see as knowledgeable, well-informed and providing reliable advice	Committed to evacuation on community advice
Worried Waverer	Prepare and equip their property and train to defend it but worry they lack practical experience to fight bushfire putting their personal safety at risk	Wavering between evacuating and remaining
Threat Denier	Do not believe that their personal safety or property is threatened by bushfire	Committed to remain as perceived lack of threat makes evacuation unnecessary
Experienced Independent	Are highly knowledgeable, competent and experienced and are responsible and self-reliant fighting bushfire	Highly committed to remaining because they are highly experienced and well prepared

population for the target area of Castlemaine could be constructed, it was decided that the most feasible option for assigning self-evacuation archetypes to the target population was using a demographic matching function. In other words, the likelihood of assigning a self-evacuation archetype to a target individual of a certain age, gender, and household type (whether they have dependants) would be based on the calculated distribution of archetypes in the source data for that age, gender, and household type.

Next, it was agreed that the synthetic population thus created would be injected into an existing agent-based bushfire evacuation simulator available to the authors [Singh et al., 2022]. The question then was: in what ways should the assigned self-evacuation archetypes influence the behaviour of agents? The simulator already included complex decision making agents coded using the belief-desire-intention (BDI) paradigm [Rao and Georgeff, 1995]. In the BDI world-view, an agent has *beliefs* about the world, whether factual or otherwise, and acts according to those beliefs; it has *desires*, or goals, it wants to achieve in the world; and has been supplied (by the programmer or domain expert) with a set of plan options for achieving those goals; a committed, or selected, plan being known as an active *intention*. Each plan is effectively a recipe, or sequence of steps, where each step can either be an action that the agent takes in its environment, or is itself a complex task–a sub-goal–with its own set of plan options in a hierarchical manner as shown in Figure 1. Notably, an agent must successfully complete every sub-goal in sequence for a plan to succeed, whereas it only needs to complete one from all available plan options for a goal or sub-goal to succeed. Finally, which plan options are suitable choices at any given time depends on the situation the agent finds itself in at the time; a plan option being *applicable* at the time if its *context condition*, or pre-condition typically evaluated using current beliefs, holds. Figure 1 shows the behaviour goal-plan tree of a synthetic agent in the simulation. A high level goal (`Response`) is triggered when perception of risk from external stimuli–such as smoke or emergency warnings–reaches a threshold (see Table 2), activating a plan of action (`FullResponse`). In the initial response step (`InitialResp`), the agent visits the location of a dependant, driving directly to there if nearby (`DepsNear`) or via home if that is closer (`DepsFar`), and either waits at the destination or returns home afterwards (`Go(h)`). If the agent has no dependants (`NoDeps`) it either continues doing what it is doing or goes home. In the final response step (`FinalResp`), the agent decides to either stay in place (`Defend`), or leave (`Leave`) for the evacuation place or an alternate destination (`Go(e|*)`). Here `Go` is a parameterised goal (achieved by plan `Goto` not shown for brevity) that takes a destination input (`h` is home location, `d` is dependants location, and `e` is evacuation location). Dashed goals are optionally executed with some probability.

Since the key difference between archetypes is effectively their *attitude* towards a bushfire threat, after discussion it was settled that assigned self-evacuation personas should therefore modify agents' *beliefs* in different ways, for instance, in how much value agents put on the sight of smoke in the neighbourhood or an evacuation message received from the emergency service. The agents would still have similar goals and plans of action in the BDI sense (as per Figure 1), but would differ in if/when they get triggered depending on their archetype. The task was then to decide how archetypes should differ from each other in their beliefs. This was done by

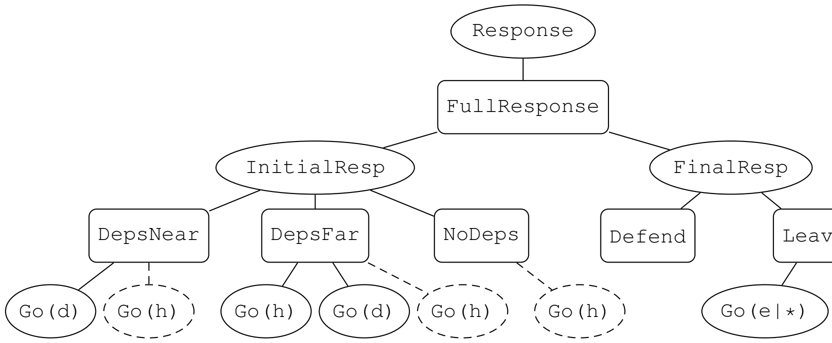


Figure 1: A self-evacuating archetype agent's BDI behaviour goal-plan tree. A goal (ellipse) is achieved by any one of its children plans. Each plan (box) is a sequence of goal actions from left to right.

constructing a table listing possible beliefs in rows, and self-evacuation archetypes in columns (Table 2). Then over several meetings and discussions, typical values (such as the mean of a normal distribution if the belief held a numerical value) were assigned to each belief for each archetype. In doing so, our aim was not so much to find representative, or absolute, belief values for archetypes (we had no basis for such an assignment), but rather to assign values to belief rows in such a way as to highlight the relative difference in values of that belief across the archetypes. Once this table was constructed, each agent in the synthetic population was assigned belief values by drawing from the corresponding column for that archetype.

Table 2: Archetypes behaviour attitudes.

Attitude	CE	CG	TD	WW	RD	DE	EI
VisibleSmoke	0.3	0.2	0.0	0.1	0.0	0.2	0.0
VisibleEmbers	0.5	0.4	0.2	0.4	0.2	0.4	0.3
VisibleFire	0.6	0.5	0.5	0.5	0.3	0.5	0.4
Advice	0.25	0.20	0.00	0.20	0.00	0.25	0.00
WatchAndAct	0.25	0.20	0.00	0.20	0.00	0.25	0.00
EmergencyWarning	0.30	0.30	0.00	0.30	0.00	0.30	0.00
EvacuateNow	0.40	0.40	0.00	0.35	0.20	0.50	0.10
ThresholdInitial	0.3	0.3	0.6	0.3	0.4	0.3	0.4
ThresholdFinal	0.3	0.5	0.8	0.7	0.5	0.3	0.9

Initial beliefs thus assigned to the population impacted its behaviour in two ways. First, different archetype agents put different values to observed events in simulation, which changed *when* they started responding to the unfolding fire situation. For instance, consider two agents in the simulation that were to become aware of the fire based on how close they are to the progressing front. If the agents were at different distances (spatially) to the fire, they would already react at different times (temporally). With the addition of archetypes, now it was also possible for two agents at the same distance to the fire to react at different times, given their archetype. Second, the decision to react was also now dependent on the archetype. Even if two agents were to observe the same sequence of events, it was possible for them to come to different conclusions about whether to react or not, depending on whether they deemed the situation serious enough for action given their archetype.

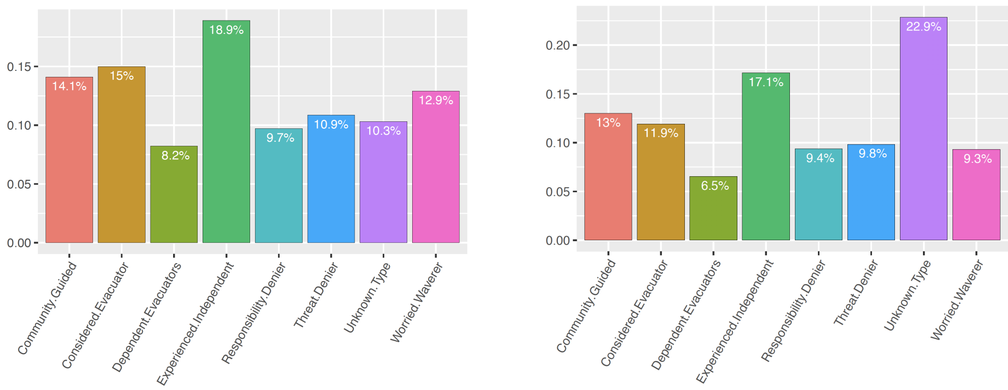
3 Evaluation

With the self-evacuation archetype behaviour personas attached to agents, we experimented with the model to determine how this modification influenced evacuation consequences for the modelled community. We developed a wildfire evacuation simulation for the Castlemaine region to the northwest (120 kms) of Melbourne, consisting of the Castlemaine and Castlemaine Region SA2[1] statistical areas. We generated 16,489 individuals in 6,273 households assigned to valid street addresses in the area, using our population generation algorithm [Wickramasinghe et al., 2020], based on Australian census 2016 data.

To evaluate how well the synthetic population distributions match with the census distributions, we conducted Freeman-Tukey's Goodness of Fit (FT) [Freeman and Tukey, 1950] and Standardised Absolute Error (SAE) [Voas and Williamson, 2001] tests. The FT test compares the similarity between a known (census) and a sample (synthesised) distribution, with the null hypothesis being that the distributions are similar. At household-level,

[1]The Australian Statistical Geography Standard (ASGS) Edition 3 defines Statistical Areas Level 2 (SA2s) as medium-sized general purpose areas representing a community that interacts together socially and economically with an average population of 10,000 people.

the generated and census distributions match perfectly, since the population algorithm uses census household-level distributions as a reference. At person-level, the FT test gave p-values close to 1.0 ($P > 0.05$) for both SA2 areas, therefore we accept the null hypothesis concluding that the comparison distributions are similar at the significance level of 0.05. The errors from the SAE test were also very small (0.004 and 0.007 for Castlemaine and Castlemaine Region respectively), confirming that the two distributions match well.



(a) Assigned archetypes (estimate)

(b) Strahan et al. archetypes (actual)

Figure 2: Archetypes distributions of the Castlemaine region vs the original data from Strahan et al. [2018]. The Unknown Type individuals have demographic profiles that do not have an archetype assigned in the Strahan et. al data.

Figure 2 shows the distribution of archetypes we generated using demographic profile matching (as explained in Section 2) for the Castlemaine region (left), compared to the initial distribution (right) [Strahan et al., 2018] for Adelaide and Perth hills communities. The predicted percentages of the seven archetypes (Table 1) differ slightly (up to 4%) compared to Strahan et al. [2018]. These predictions can be useful. For instance, community education programs can be organised for the biggest predicted group Experienced Independent. From the synthetic population, for simulation purposes, we removed all Unknown Type persons[2], leaving 10,867 archetype persons in the final population. We note that our archetype assignment function based on demographic profile matching is not validated. To this end, we are currently analysing a newer data set obtained from post-season telephone surveys for the larger Bendigo SA4 region that includes the Castlemaine region. Our intention is to generate the archetypal population for the larger Bendigo region, compare it against the archetypal makeup derived from the new surveys, and then further revise our model as needed.

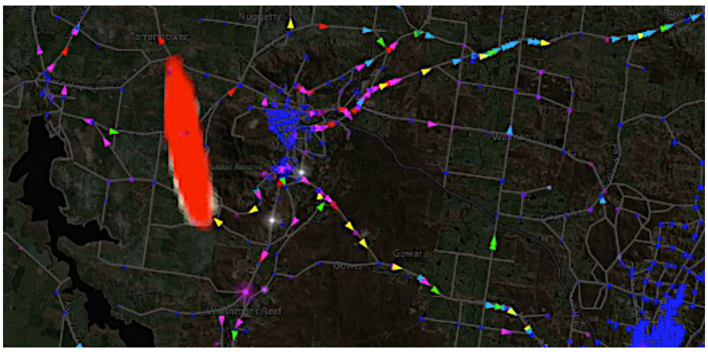


Figure 3: A snapshot of the wildfire evacuation simulation for Castlemaine region.

Figure 3 depicts a screenshot of the modelled scenario. Synthetic agents become aware of the fire (red) in two ways; by ”seeing” fire/embers based on their proximity to the threat, and by receiving any official warnings issued to the spatial zone they are located in. Whether they will respond to the threat or not depends on their perceived personal risk and whether it has reached a threshold. Different events, such as the sight of the fire or the reception of an official warning, will increase an individual’s perception of risk level by different amounts based on their archetype. In addition, the threshold at which a response is triggered is also determined by their archetype. Residents that respond to the fire threat will do so by engaging in various activities, such

[2]Synthetic persons with no matching demographic profile in Strahan et al. [2018] data were removed. Road capacities were accordingly scaled down in the model to negate the affect on traffic flows from the removed population.

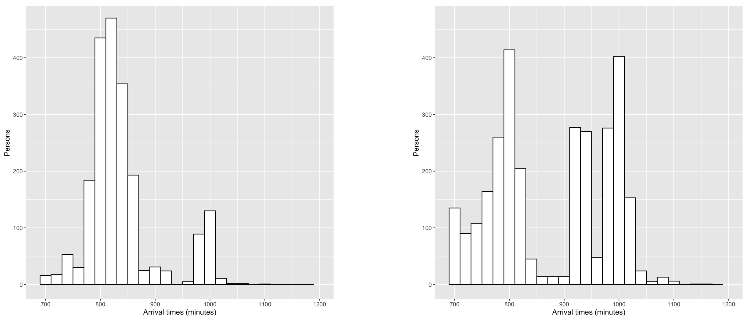
as preparing/waiting at home (dark blue), picking up dependants even if it requires driving towards the fire (white) and deliberating their next action (pink glow). The triangles are the vehicles on roads with different archetype persons: Worried Waverer (light blue), Community Guided (green), Considered Evacuator (yellow), Responsibility Denier (pink), Threat Denier (orange), and Experienced Independent (red).

While validating the behaviours and traffic generated from them is not possible for a hypothetical event, we nevertheless were interested in verifying that individuals behaved in a manner consistent with their archetype. To this end, we focused on sampling individuals in the simulation, examining their decisions and vehicle routes, and comparing this against the knowledge of local emergency experts and anecdotal accounts of people's behaviours reported in previous wildfire surveys (e.g., [Matthews et al., 2015]). A mixture of random sampling and targeted sampling of trajectories deemed interesting was used. We also compared such virtual anecdotal accounts with Strahan et al's understanding of likely behaviours for the different archetypes. In cases where inconsistencies were found, we resolved them by refining the attitudes assignment (Table 2) either to fix a cell error, or adjust rows to amplify the relative differences between archetypes. This process was completed manually in three 2-hour meetings between authors.

In general, the archetype behaviours exhibited in the simulation met the expectations of the domain experts and the researchers. For example, Considered Evacuator and Community Guided individuals evacuated in the early hours of the event, by picking up their dependants (if any), and then returning home or driving immediately to the evacuation centre. Only a handful of Experienced Independent and Threat Denier persons were on the roads in the early phases of the evacuation. The majority of them remained at home till late and started driving after perceiving increased risk due to seeing embers/fire in close vicinity. Some of the Considered Evacuator and Community Guided residents, who are likely to leave early, did not evacuate till late since they did not receive official warnings. Such scenarios may provide insights into how such archetypes might respond in reality if they do not receive warnings, as they deliberately assess the fire threat and respond when the firefront comes in close proximity due to a change in wind direction. We also found unlikely behaviours that require further revision. For instance, a Responsibility Denier decides to pick its dependant residing close to the fire zone only after the highest level of warnings are received. It is expected that this pickup happens much earlier, knowing that the person's dependant is in a danger zone. Overall, the simulation demonstrated a range of known behaviours during wildfires such as picking up dependants, waiting and seeing at home or at the dependant's place and eventually evacuating to the designated evacuation centre.

3.1 Comparison of Archetypes vs Non-archetype Scenarios

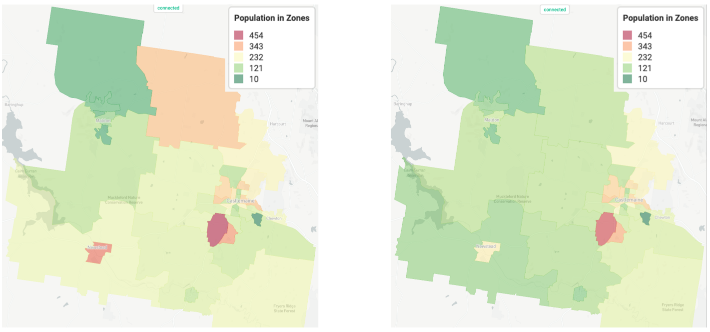
We conducted a sensitivity analysis experiment to examine how inclusion of an archetypal population affects simulation outcomes. We compared two scenarios: the Castlemaine scenario with a population of self-evacuation archetypes as discussed above (`SEAS`); and one with a generic population having attitude values (in the range [0,1]) averaged across all archetypes (`GAS`). To ensure a fair comparison, both scenarios had the same number of persons in the population, the same proportion with dependants to attend to (locations for dependants were randomly selected within 5km of a person's origin in both scenarios), and evacuating to the same destination.



(a) `GAS` (Generic Archetype)   (b) `SEAS` (Self-evacuation Archetypes)

Figure 4: Arrival times distributions of the comparison scenarios.

Figure 4 shows the destination arrival time distributions for the two scenarios. As can be seen, the time distributions differ substantially. The number of evacuees reaching the evacuation centre is 2074 (19%) and 2924 (29%) in `GAS` and `SEAS` respectively. Importantly, about 1489 persons (51% of arrived persons) arrive after 900 minutes in `SEAS`, compared to 278 evacuees in `GAS`. The key difference between the scenarios is the attitude levels in the population, which determine evacuee behaviour. These levels influence if and when a person responds to the threat. Taken together, individual choices cause varying traffic and congestion levels, resulting in significant differences in evacuation outcomes between scenarios. We tested for the statistical significance of the difference in the distributions using Wilcoxon signed rank test [Wilcoxon, 1945] and concluded that the distributions were significantly different ($p < 0.05$) at the significance level of 0.05.



(a) GAS (b) SEAS

Figure 5: Person counts in different SA1 zones of the Castlemaine region at 1pm in the comparison scenarios.

The test shows that the inclusion of self-evacuation archetype behaviours can significantly influence evacuation simulation outcomes, and suggests that a more robust understanding of human behaviour in rapid-onset fire events is crucial when planning for safe egress under time constraints.

4 Discussion

We presented an evacuation model in which community behaviours were based on Strahan et al's self-evacuation archetypes [Strahan et al., 2018], and showed that the inclusion of differences in the perception of risk based on self-evacuation archetypes can make a significant difference to evacuation simulation outcomes. This was true even when the goals and plans of residents were assumed to be similar in terms of their actions. The difference could be attributed to individuals with different risk perceptions acting (if at all) at different times and locations, leading to different traffic conditions and clearance times. Our early findings reveal that inclusion of self-evacuation archetypes in modelling can inform a more robust understanding of bushfire evacuation behaviour for at-risk communities.

Our model is able to capture diversity in behaviour of residents of a community and how that can impact evacuation, such as through increased congestion from additional intermediate trips [Murray-Tuite and Wolshon, 2013] to destinations other than the evacuation place. However, lack of data on bushfire evacuation behaviours remains a key challenge [Kuligowski, 2021] for validating evacuation models. Our own efforts were limited to verification of simulated behaviour with domain experts.

Where traffic modelling is being considered to inform evacuation decisions in rapid-onset events particularly, our findings suggest that improving assumptions about evacuation behaviour, such as through the modelling of self-evacuation archetypes, is vital for avoiding over-optimism in estimation of evacuation times [Bulumulla et al., 2017]. On the topic of self-evacuation archetypes, new research is also needed, to extend the description from individuals to households and resident to visitors, in the continued effort to improve our understanding of bushfire evacuation behaviour.

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