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Supporting Hazard Analysis for Wildfire Response Using fmdtools and MIKA

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In addition, thanks to Guillaume Brat for his input and guidance on the development of fmdtools and MIKA as well as on this report. Thanks to Ganesh Pai and Irfan Sljivo for their input and discussions on hazard analysis, which helped refine several of the concepts in the report. Special thanks to Joseph Coughlan who lent his expertise in wildfire fighting to help us mature our vision for data sources for MIKA.

This report is available in electronic form at

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Executive Summary

The System Wide Safety (SWS) Safety Demonstrator (SD) Series drives development of an increasingly capable In-Time Aviation Safety Management System (IASMS) focusing on humanitarian applications, starting with wildfire response (SD-1). The goals of this report are to (1) provide an early hazard analysis and mitigation evaluation of wildfire response to support these efforts and (2) provide a demonstration of capabilities of the Fault Model Design Tools (fmdtools) and Manager for Intelligent Knowledge Access (MIKA) tools. fmdtools provides a modeling, simulation, and resiliency analysis framework in which a wildfire response model, the System Modeling and Analysis of Resiliency in Scalable Traffic Management for Emergency Response Operations (SMARt-STEReO), is built. MIKA is an intelligent knowledge manager with several capabilities, including assisting in hazard analysis by extracting and analyzing hazards from historical incident reports. The following topics are covered in the report:

- *Understanding Wildfire Hazard Dynamics*. We provide a description and simulated examples of how hazards occur in the SMARt-STEReO model of wildfire response and their effect on its outcome. This provides a common mental model and focuses the analysis presented in the remainder of the report.
- *Wildfire Hazard Identification.* MIKA identifies wildfire hazards from three relevant datasets: the ICS-209-PLUS, SAFECOM, and SAFENET. Hazards are manually organized into a taxonomy and MIKA analyzes each hazard's effects, likelihood, severity, and risk.
- *Evaluating Mitigation Strategies.* The SMARt-STEReO wildfire response model built in fmdtools evaluates a subset of identified hazards. Specifically, we simulate the effect of communications faults and equipment faults on operator safety, the effect of changing winds and flammability, and a scenario with multiple ignition points and heavy smoke.
- *Tool Limitations and Usage Considerations.* We provide a discussion of appropriate tool use cases as well as limitations and considerations for usage.

The tool findings are used to synthesize recommendations for wildfire response operations, which can be captured as part of an IASMS. Key recommendations are as follows:

- Hazards are identified from a broad spectrum of sources including aircraft subsystems, operational sources, and ground crew operations. Highest risk operational environment hazards identified are Evacuations. The highest risk manned aerial operations hazard categorized is Jumper Operations Mishap. Ground crew hazards that are highest risk are Burns, Cargo Operations Overhead, Dehydration, Entrapment, Falling Objects, Heart Attacks, Heat Exhaustion, Inadequate Training or Certification, Vehicle Breakdown, and Vehicle Collision.
- Modelled containment failures arise from a mismatch between the difficulty of the firefighting scenario and the capacity (e.g., speed, effectiveness, awareness) of the response. In firefighting scenarios where containment is possible (e.g., because the fire does not spread too quickly), these mismatches can occur because of a change in environmental conditions (e.g., wind, flammability, etc) or because of planning, equipment, or communications faults.
- Improvements to communications increase the capacity of the firefighting response by reducing the time needed to respond to the fire. While surveillance does not increase this capacity by itself, it increases operator safety by increasing state awareness,

enabling firefighters to evade approaching fires. Increasing both has a synergistic effect. In general, these performance and resilience increases generalize over fault scenarios as well as unforeseen changes to circumstances (i.e., wind, aridity, etc.). However, these improvements need to be designed so as not to make the system prone to persistent large-scale communications outages, which can reduce performance.

Introduction

Emerging wildfire response operations will require new approaches for safety management. Ensuring safe firefighting operations is difficult because of the inherently hazardous nature of containing a wildfire—operators often need to be put into risky situations to actively mitigate the impact of the fire as it unfolds. New technologies, such as unmanned aircraft systems (UAS), have the potential to reduce risks to operators and enable a more effective wildfire response. However, integrating these technologies within a firefighting environment presents additional challenges because of the ad-hoc, person-to-person nature of wildfire management communications [1]. It has thus been proposed in the in the Scalable Traffic Management for Emergency Response Operations (STEReO) [1] project that the introduction of UAS and other technologies in wildfire response should be complemented by new paradigms for airspace control, such as UAS Traffic Management (UTM) [2].

For these technologies to fulfill their requirements, they need to improve operator safety and firefighting effectiveness. Thus, it is important to identify potential hazards and mitigation strategies while conceptualizing these technologies to ensure they will meet these requirements. This process is called hazard analysis and is an essential part of any Safety Management System (SMS) (e.g., the FAA SMS framework for Part 121 air carriers [3]). NASA General Safety Program Requirements define a hazard as “a state or a set of conditions, internal or external to a system that has the potential to cause harm” [4]. Possible malfunctions and degraded operations should be considered as well as fault management strategies [5]. Wildfire response provides additional challenges to traditional hazard analysis methods, because, unlike traditional aviation environments, firefighting is an uncontrolled and inherently hazardous setting with (1) a large set of potential hazardous events and consequences and (2) trade-offs between operator risk and operational effectiveness (i.e., when fire-mitigating operations put operators in harm’s way).

To extend and supplement existing hazard analysis approaches to the wildfire response scenario, the Manager for Intelligent Knowledge Access (MIKA) [6] and Fault Model Design Tools (fmdtools) [7] toolsets being developed for hazard identification and analysis are applied to the firefighting use-case. The MIKA tool under development at NASA Ames Research Center provides a means to extract, search, and analyze hazards from repositories of incident reports, which complements expert identification of hazards through conventional means via an intelligent assistant. MIKA assists in the generation of an initial listing and analysis of hazards [8, 9], which can then be modeled and simulated using the fmdtools framework. The System Modeling and Analysis of Resiliency in STEReO (SMARt-STEReO) model [10], built using fmdtools, is used to understand the hazard dynamics of wildfires, quantify the resilience of the response to fault modes and hazardous operating circumstances, and compare alternative configurations [11]. Ongoing work (shown here) has been using MIKA and fmdtools to identify new hazards and better understand resilience in wildfire response. While previous work has demonstrated the development of these tools, the scope of analysis has been limited to demonstrating the tools rather than providing a comprehensive analysis.

The goal of this report is to provide an initial hazard analysis suitable for informing new paradigms for safety management of wildfire response while showcasing the features of the fmdtools and MIKA toolsets being developed for this purpose. This report provides an early hazard analysis (which can be extended over time) that (1) develops a model of wildfire hazards to inform the high-level understanding of potential hazards and mitigations, (2) identifies the “present state” hazards in wildfire response based on analysis of incident report datasets, and

(3) explore and evaluate potential technologically enabled mitigation strategies which could increase the safety of wildfire response to defined hazardous scenarios. As an early hazard analysis, the focus of this report is on high-level hazards and mitigation strategies—it should be noted that this analysis process should continue and evolve over the system's life cycle as concepts become more detailed and advanced. Additionally, as a high-level assessment, this report is meant to cover hazards across a variety of scenarios, rather than any particular scenario—thus, analyzing a specific wildfire event (and how to mitigate it) may require more specialized analyses to ensure accuracy in that specific scenario.

Wildfire Response System Definition

In previous work, the SMARt-STEReO project defined an early concept of operations (ConOps) of technology-enabled wildfire response to guide modelling and analysis [12]. In this report, we adopt the SMARt-STEReO ConOps of wildfire response to define the scope of the analysis. A wildfire response operation is a complex system. For the purposes of this report, we define the wildfire response operation as the top-level system, with subsystems being ground operations (including ground crew personnel), aerial operations (including aircraft and pilots), and incident management teams. UAS operations are a subset of aerial operations. The overall goal of the operation is fire containment via the formation of fire lines. Within the overall wildfire containment activity, actors may perform individual ground crew and aircraft missions, such as reconnaissance, water/retardant drops, and fireline construction. These activities must be coordinated with respect to the overall firefighting strategy.

The wildfire containment activity is itself a hazardous activity that relies on several lower-level hazardous activities including reconnaissance, water drops, and fireline construction. Hazards in wildfire response may originate from a variety of internal and external sources [13]. Some hazards affect single assets and may have subsequent impacts and cascading effects on the system (e.g., an aircraft component malfunctions and requires an emergency landing, which puts the pilot at risk of entrapment or requires a dangerous evacuation mission). Other hazards, such as broad-reaching communications issues or visibility challenges, may affect multiple assets or operators. Safety of ground personnel as well as pilots and the public must be considered. Firefighting activities have the additional goal of protecting assets such as natural and cultural resources as well as property, while trading these goals off against risk to operators. Typical decision-making surrounding risks and goals is described by Calkin et al [14].

This report focuses on the response to an active wildfire. Pre- and post-fire activities, while essential, are beyond the scope of this report. While the focus of this project broadly is aviation safety, due to the coordination required for and dependencies between aerial and ground operations, it is important to identify hazards and consequences for both in tandem. Finally, since MIKA extracts hazards from existing incident reports, it does not identify hazards unique to emerging operational concepts – i.e., new use cases for UAS that are not yet being flown regularly. However, the fmdtools modeling and simulation portion of this report accounts for possible scenarios involving future operational concepts using identified hazards and detailed simulations.

Understanding Wildfire Hazard Dynamics

As an emergency response operation, wildfire response is an inherently hazardous

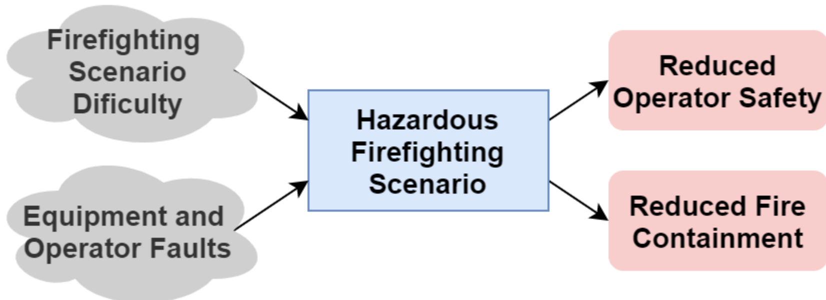


Figure 1: Sources and Effects of Hazards in Wildland Firefighting.

environment. As a result, there are two types of hazard sources and effects considered in our modelling work, as shown in Figure 1—those associated with the fire (e.g., hazardous operating conditions and fire containment), and those associated with the operators (e.g., operator mistakes/faults and operator safety effects). Note that while effects are considered completely distinct model results, causes are considered conceptually distinct but interacting, since hazardous conditions may raise the rates of initiating events. Given the rapidly changing and partially unknown state of the fire, trades are often made between the risk to operators and the risk of reduced fire containment. While operator safety is considered a top priority, pilots and ground crews often take on significant risk (e.g., difficult aircraft maneuvers in legacy aircraft or operation of equipment close to a rapidly evolving fire) to contain the fire and thus reduce risks to civilians and property. This can be contrasted with a more traditional safety/hazard analysis scenario, where the singular concern is pilot/passenger safety and hazards are nearly often eliminated—operator hazards can and should be reduced, yet it is important to ensure that this does not come at significant cost to fire containment.

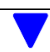
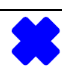
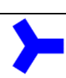
In this section we illustrate at a high level how hazardous outcomes (to both safety and containment) can arise in firefighting from the operational environment. This is accomplished using the SMARt-STEReO model, which simulates the propagation of the fire, planning of containment actions, and ground/aerial operations in an integrated simulation. This model further enables the simulation of a variety of firefighting scenarios as well as the injection of fault modes to determine the dynamic effects of unforeseen environmental and operational effects over time. While presenting the model in full is out of the scope of this work, further details can be found in previous work [10] (although it should be noted that development is ongoing).

SMARt-STEReO Model Description

The System Modelling and Analysis of Resiliency in Scalable Traffic management for Emergency Response Operations (SMARt-STEReO) model was developed to better understand the complex behavioral dynamics involved in wildfire suppression. The SMARt-STEReO model simulates a basic firefighting training exercise, with a 2000x2000 meter grid environment with flat grass/shrubland fuel properties over eight hours with a time-step of eight minutes, during which a wide variety of operations can be performed (fire area surveillance and communications, fireline construction, water drops, etc.). While this simulation may be run for the full 60 timesteps, by default it is terminated based on two end conditions: fire containment (meaning a fireline has totally encircled the fire) and fireline breach (meaning the fire has breached the perimeter of the grid), which often terminate the simulation much earlier. These fireline breaches, along with injuries (which occur when assets get too close to the fire), constitute the hazards considered by the model.

The SMARt-STEReO model captures three major parts of wildfire response--the propagation of the fire over time, the planning of firelines and other response efforts, and the actions of ground and air-based assets which execute these efforts. These assets and their behaviors were implemented as functions in fmdtools, with the roles and behaviors described in Table 1. In general, the monitoring of the fire occurs in the Surveillance and Aerial Commander functions, which is then used by Incident Commander and Aerial Commander to plan response operations based on proximity of the fire to gaps in the fireline. These operations are then undertaken-- Ground and Engine Crews create firelines around the perimeter of the map to contain the fire while Tankers/Helicopters drop retardant to slow the spread of the fire towards these firelines. The properties and spread of the fire are simulated with the FireSpread function in terms of flammability (spread rate), fuel (burn time), and fuel type (which determines heat/injuries). The modelling of these asset behaviors derive from conversations with the STEReO team and have been checked against existing fire models—we consider it to be valid for understanding wildfire response at a high level, but not necessarily for providing a quantitative prediction of any particular fire scenario.

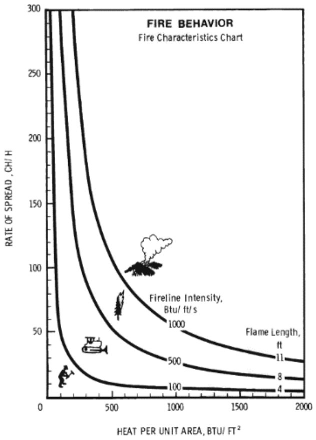
Table 1. Functions in the SMARt-STEReO model and their corresponding behaviors.

Function/Asset	Symbol(s)	Abbr.	Description/Role in the model
IncidentCommander		IC	Uses ground information sent from AC and S to identify most-threatened gaps in the fireline based on the proximity of the fire to valued locations, assigns GCs and ECs to close these gaps, and relays threats to the AC.
AerialCommander		AC	Conducts surveillance (1 quadrant/timestep), determines drop locations based on threats from IC and relays these to Tankers and Helicopters.
Surveillance		S	Surveils the map grid (1 quadrant/timestep) to update the ground information perceived by the IC and other assets.
Tanker		T	Drops retardant in drop locations specified by the AC
Helicopter		H	Delivers GCs to and from their fireline locations, conducts drops in locations specified by the AC, delivers supplies to GCs and ECs.
UAV		UAV	Delivers supplies to GCs and ECs.
GroundCrew		GC	Creates firelines (1-2 pixel/timestep) in places specified by the IC. Must be delivered by tankers.
EngineCrew		EC	Creates firelines (1-2 pixel/timestep) in places specified by the IC. Can travel to firelines directly (when accessible).
FireSpread			Determines the propagation and properties (ignition, flame length, etc.) of the fire based on

Function/Asset	Symbol(s)	Abbr.	Description/Role in the model
	timesteps fire spent fuel fireline		the flammability (timesteps to ignition), fuel (timesteps to burn-out), and fuel type (determines flame length) distributions for the map as well as environmental parameters such as windspeed and direction.
SmokeSpread			Determines the spread of smoke based on the location of burning pixels in the fire and environmental parameters such as windspeed and direction. Only used when using “smoke” model option.

Depending on the scope of the analysis, the SMARt-STEReO model can additionally be run in different configurations and/or sets of parameters specifying the type of scenario, the characteristics of the fire, the type of response, and the faults to be injected. Both the characteristics of the fire (e.g., map property distributions, wind speed, place locations, sides to protect) and the response (e.g., communication delays, the degree of state awareness, the quantity of each asset, the size of tanker drops, etc.) can be adjusted as parameters prior to simulation. In particular, the distributions of map properties (i.e., the fuel and flammability for each pixel in the grid) may be given as uniform or procedurally generated from random distributions, enabling us to consider the stochastic nature of fire propagation a deterministic model. As will be illustrated in the next sections, changing these parameters (and injecting faults) enable us to determine the resilience of the overall response to hazardous and/or unexpected changes in conditions (i.e., Fire Difficulty) as well as faults occurring in the assets.

Hazards Arising from Fire Difficulty



Flame length		Fireline intensity		Interpretation
ft	m	Btu/ft/s	kJ/m/s	
< 4	< 1.2	< 100	<350	• Fires can generally be attacked at the head or flanks by persons using hand tools. • Hand line should hold the fire.
4 – 8	1.2 – 2.4	100 – 500	350 – 1700	• Fires are too intense for direct attack on the head by persons using hand tools. • Hand line cannot be relied on to hold the fire. • Equipment such as dozers, pumpers, and retardant aircraft can be effective.
8 – 11	2.4 – 3.4	500 – 1000	1700 – 3500	• Fires may present serious control problems—torching out, crowning, and spotting. • Control efforts at the fire head will probably be ineffective
> 11	> 3.4	> 1000	> 3500	• Crowning, spotting, and major fire runs are probable. • Control efforts at head of fire are ineffective.

Figure 2: Firefighting strategies by fire difficulty. Note that above a certain intensity, fires become difficult or impossible to fight effectively. From [28].

The major environmental hazard in wildland firefighting can be summed up as the difficulty of the firefighting scenario. Fire difficulty arises from a number of factors—including windspeed, ease of access, fuel type, terrain, and aridity/dryness—which make the fire propagate faster and limit firefighters' ability to effectively fight the fire. Many of these factors are variable over time and not fully characterized, making it difficult to plan mitigation actions to both strategically prevent adverse fire spread and protect operators. As shown in Figure 2, fire difficulty is a severe limitation on firefighting, with fires above a certain threshold of intensity and windspeed being essentially impossible to contain or control. There is thus a narrow band of fire difficulty where firefighting is an effective activity. Above this band, fires are impossible to control and can jump firelines, while below this band, fires put themselves out. Within this band, a faster fire requires more effective equipment and resources to contain effectively [15]. Hazards can thus result when the firefighting operation lacks the sufficient capacity to match the difficulty of the fire. Firefighting capacity is the ability of the response to quickly slow and contain the propagation of the fire via surveillance, planning, and coordination, conducting aerial drops of retardant to slow the fire, and creating firelines to contain the fire. It is thus a result of a number of factors, including information accuracy, strategy, drop effectiveness, number of tankers, fireline construction speed, and number of ground crews.

To illustrate how inadequate firefighting capacity can lead to hazards, Figure 3 shows how aerial retardant drop effectiveness (the number of time-steps a tanker drop slows down a fire) changes whether a fireline ends up completed or breached over a number of different fire spread rates. These (deterministic) simulations take place in otherwise identical scenarios with four ground crews but result in significantly different simulation results. As shown at t=16, the increased drop effectiveness results in less fire spread at a given over time across all levels of flammability, slowing the eventual spread of the fire. However, as shown at the end of the simulation, faster fires (flammability=3) evade the fireline regardless of effectiveness while slower fires (flammability=5) can be contained regardless of effectiveness. However, at flammability=4, the level of drop effectiveness makes the difference between a fireline breach (<20 drop effectiveness) and completion (≥20 drop effectiveness). While the results here show the effect on fire containment, we can also see that this drop effectiveness has a safety effect for ground crews. In scenarios where the fireline is breached (or about to be breached), ground crews that are in the process of constructing the fireline are put in direct danger from the fire itself and must take evasive actions (which may not always be available) to avoid injuries. These situations additionally become likely in cases where the fireline is just barely completed before the fire reaches it, since ground crews may still be brought close to the fire. Thus, increased drop effectiveness, as an increase in *firefighting capacity*, can both increase the ability to contain the fire and increase ground crew safety by slowing the fire down as it propagates.

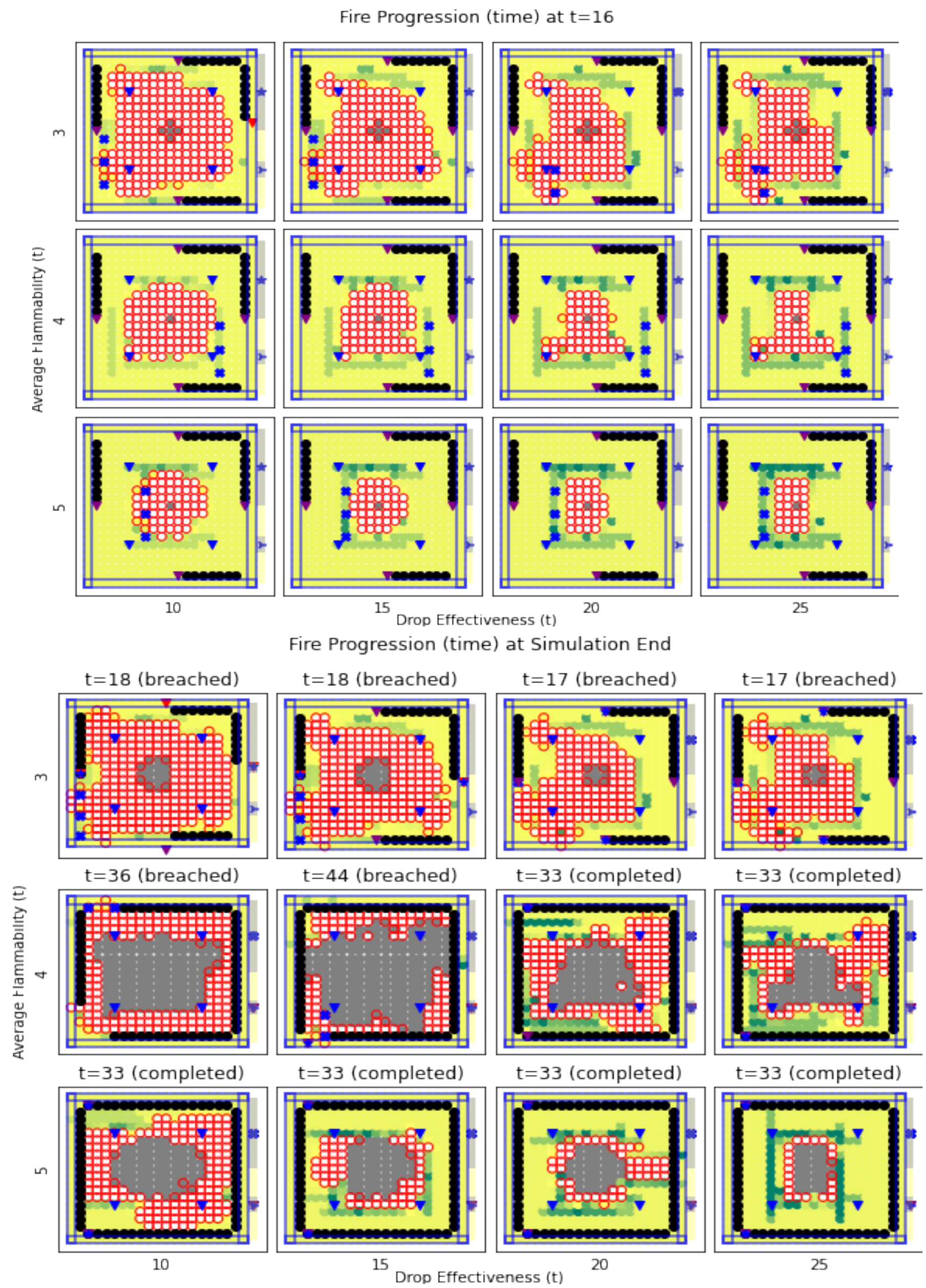


Figure 3: Effect of Drop Effectiveness over Grid Flammability (a) at t=16 and (b) at simulation end.

A similar result is shown in Figure 4, which compares the effect of changing the number of ground crews on fire containment. As shown, at t=15, the responses with more ground crews have made more progress completing the fireline than the responses with fewer ground crews. This is further reflected in the results for fireline completions and breaches, where (at flammability=4 and above), increasing the number of ground crews from three to five makes the difference between a breach and a fireline completion and above five ground crews, each additional crew reduces the amount of time required to complete the fireline. As a result, an

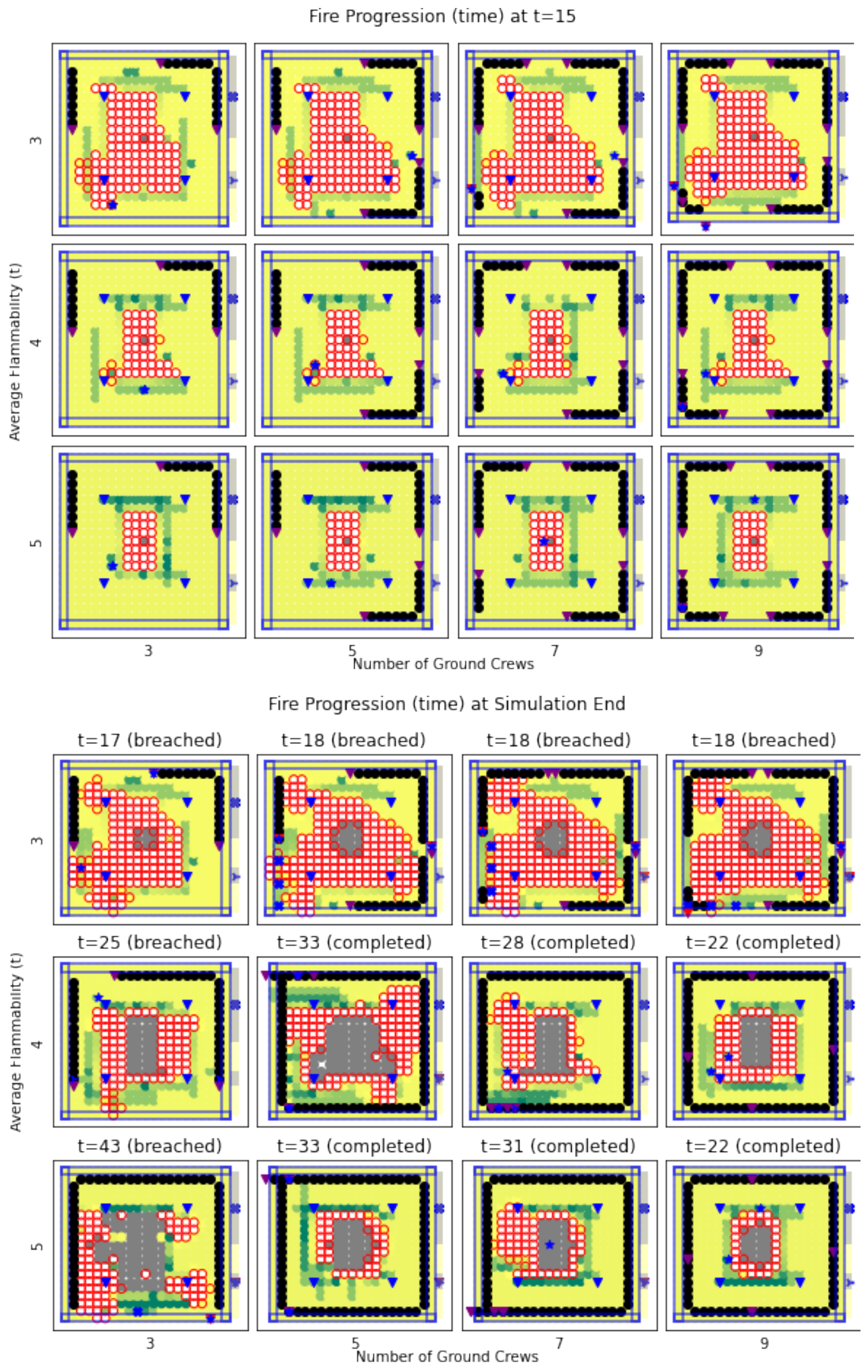


Figure 4: Effect of Ground Crews over varying Grid Flammability at t=15 timeteps (top) and at simulation end (bottom).

increase in capacity via the number of crews can both increase the ability of the response to contain the fire and increase overall safety by completing the fireline faster so that ground crews have more time to evacuate. However, this approach can have pitfalls if conditions change (consider, for example, Example 2 in "Evaluating Mitigation Strategies") and the fire spreads more quickly, because it puts more ground crews at risk.

These examples show the relationship between *fire difficulty*, *firefighting capacity*, and hazardous outcomes. If the capacity of the firefighting response is inadequate to the difficulty of the fire, it can pose risks to both fire containment and operator safety. Additionally, increasing firefighting capacity beyond what is required for containment can increase firefighter safety by increasing the time buffer between ground crews completing and evacuating firelines. It also provides margin against changing conditions (e.g., increased windspeed or aridity) or fault scenarios (e.g., ground crews or aircraft being taken out of commission) which could otherwise cause a loss of fire containment due to lack of redundancy. This relationship is admittedly not linear, since the major gains in safety happen right at the line between fire containment and fireline breaches—beyond that point, the main effect is creating margin which improves the situation in unforeseen scenarios. Thus, hazards resulting from fire difficulty can be addressed via an increase in firefighting capacity. Since capacity is not limited to speed or resources, but also extends to information availability and planning effectiveness, one major consideration for technological infusion in wildland firefighting is whether and how much these technologies increase this capacity—if it increases it a significant amount, it may provide significant impacts not just to operational effectiveness, but safety.

Hazards Arising from Faults

In addition to the operational environment, operator and equipment faults can result in significant hazards, both to operational safety and to fire containment. While a much fuller analysis of these faults/accidents (in terms of types, prevalence, and severity) is provided in the "Wildfire Hazard Identification" section, this section shows examples of how these events can lead to hazardous consequences in simulation to give an overall understanding of the types of risks that they pose and how they might be mitigated.

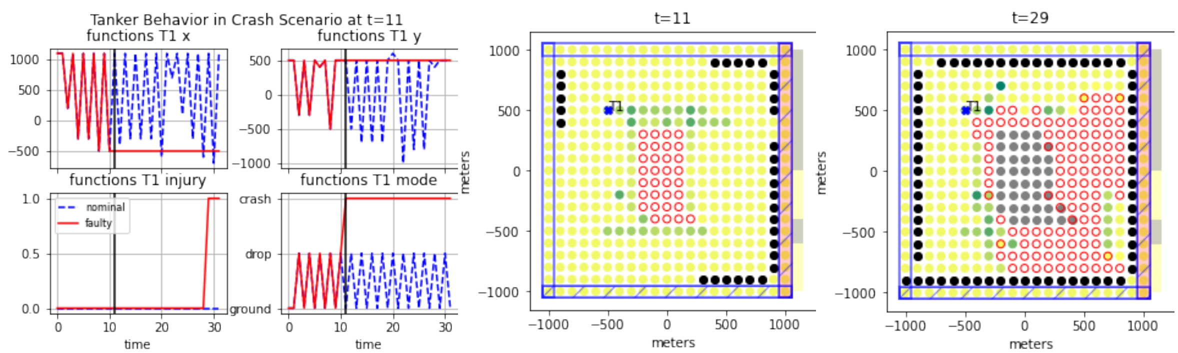


Figure 5. Effect of Tanker Crash at t=11. The tanker is immobilized at its drop location, causing further injuries when the fire approaches the crashed aircraft at t=29.

To illustrate how aircraft faults can lead to hazards, Figure 5 shows the results of an aircraft crash on the aircraft and response as a whole. Crashes like this can occur in fire response in part because of the variability of conditions, age of the aircraft, and difficulty of maneuvers. As shown, when there is a crash, the tanker (and pilot) is immobilized in a location not far from the fire. In many cases, the crash itself could lead to injuries or death of the pilot. However, even when the pilot survives (e.g., because of proper use of emergency procedures), there can be additional injuries or death from heat or burning because the location of the crash may be difficult to access and in the path of the fire. This is the case in this simulation, where pilot injury occurs due to proximity of the pilot and the fire. Note that in this situation the loss of the tanker does not significantly affect fire containment, which still occurs as expected, in part because of the capacity of the response.

To illustrate how ground crew faults can lead to hazards, Figure 6 shows a scenario where an engine-based ground crew has a vehicle breakdown, leaving them stranded in an entrapment scenario and unable to complete firelines. While the fault does not (as modelled) have an immediate safety impact, the engine crews are eventually injured when the fire approaches their location at time t=25. This shows how equipment faults can lead to safety effects—while they can directly cause hazardous outcomes (e.g., by injuring the operator of the equipment), they also put operators at greater risk of being stranded and thus running out of supplies or being unable to evade the fire as it approaches.

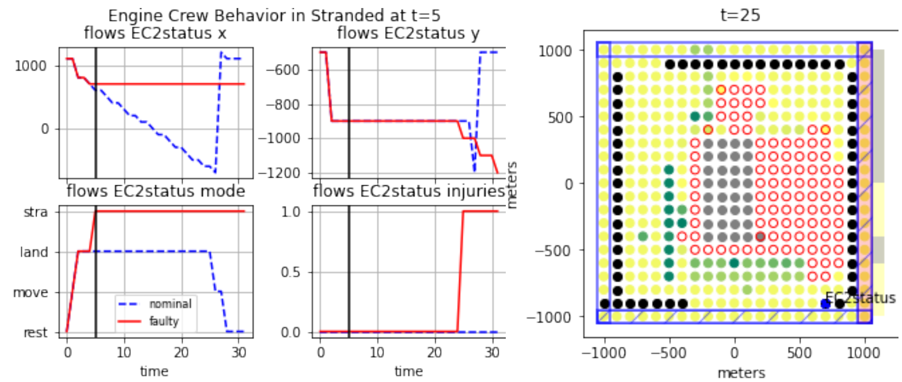


Figure 6. Effect of Engine Crew Being Stranded at t=5. The crew is immobilized and eventually injured when the fire approaches.

The primary hazardous effects of singular (single-asset) faults like this are on the safety of the respective operators themselves. When there is adequate *firefighting capacity*, operators often have enough buffer time to contain the fire even when single assets are taken out of commission. However, when there is little buffer in firefighting capacity, these faults can additionally affect the ability of the response to contain the fire, as illustrated in Figure 7. As shown here, when there are two engine crews and three ground crews, a poorly timed tool break fault[1] in an Engine Crew at t=15 causes the crew to be unable to complete the fireline in time, resulting in a breach at time t=39 when it would have otherwise completed the fireline at t=31. This essentially turns the five ground-crew response (see Figure 4) that barely contains the fire into a four ground-crew response which cannot contain the fire in time. Based on this and other model results, we surmise that single fault modes of this type predominantly cause a breach of the fireline when:

1. the response is performing with little or no extra firefighting capacity above what is required by the difficulty of the fire,
2. there are also unforeseen changes in conditions,
3. the operation was critical and singular to the asset (e.g., the sole tanker or helicopter was destroyed), or
4. the fault is systemic (propagating through multiple assets) and/or effects multiple assets at the same time.

[1] Tool break faults cause ground/engine crews to be unable to build fireline until the fault is fixed.

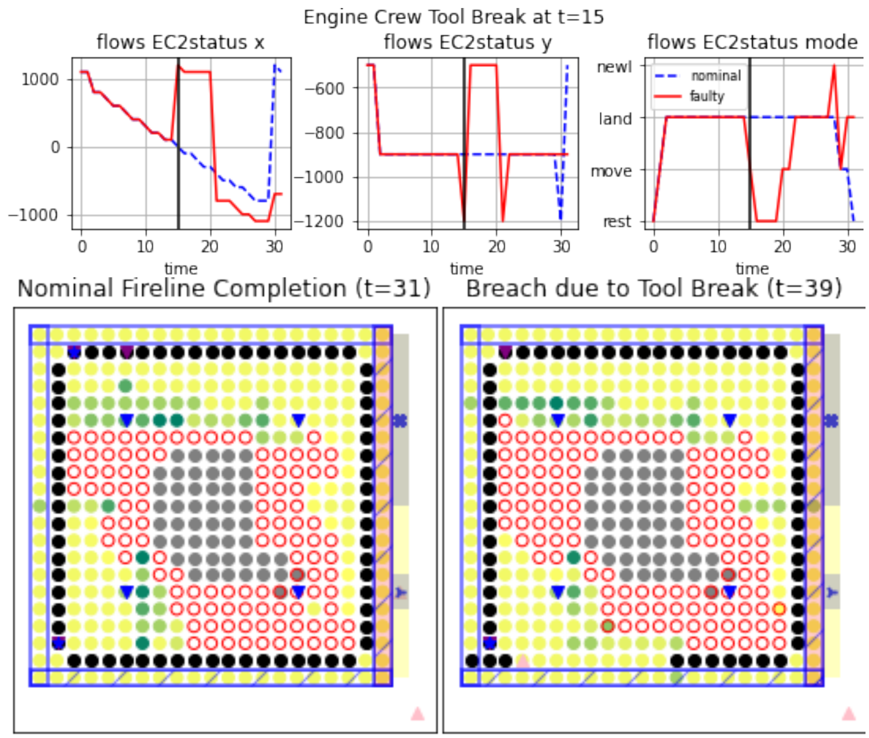


Figure 7. Effect of tool break fault on crew behavior at t=15 (top) and comparison between final end-state (at t=31) of nominal end-state and tool break scenario at t=39. (2 ECs, 3 GCs)

Thus, the most likely effects of single-asset fault modes are on the safety of the operators. Technological infusion has the potential to increase pilot safety in these situations by putting fewer operators in harm's way. For example, automating prescribed aerial ignitions operations transfers the risk of pilot injuries onto an automated system, where the risks to operators are much lower. However, these benefits need to be weighed against potential introduced hazardous modes and performance effects, if, for example an automated aerial ignitions drone is less effective or malfunctions more (e.g., mechanism for releasing flammable balls is jammed). In particular, consideration needs to be given to systemic or common-mode errors potentially introduced by new technologies—such as errors in communications infrastructure or errors affecting the awareness, planning, and/or management functions of the Aerial Supervisor or Incident Commander—since these errors have the ability to severely effect not just the safety of a pilot or ground crews, but cause a loss of containment, even when there is otherwise excess firefighting capacity. Existing system hazards must also be considered in the context of technology-enabled mitigations. To evaluate system hazards, it is first necessary to identify them. In the next section, we identify hazards using the MIKA tool.

Wildfire Hazard Identification

MIKA provides a suite of natural language processing techniques to support hazard analysis from natural language-based reports. In this section, we use MIKA's knowledge discovery toolkit to extract and document hazards from incident reports in natural language format [6, 8, 9, 16, 17]. Hazards extracted using these methods are driven by their occurrence and documentation in practice, rather than derived from theory or ontology. In other words, MIKA results are descriptive in the sense that they describe hazards present in the data, rather than normative, i.e., defining how hazards in the system should be organized or detailed.

Hazard Extraction Method and Data

MIKA uses two natural language processing techniques to extract hazards: Latent Dirichlet Allocation (LDA) topic modeling [8, 9] and a custom named-entity recognition (NER) model [16]. The Hazard Extraction and Analysis of Trends (HEAT) [8, 9] framework is used to extract hazards with topic modeling. Hazards are identified by first applying a topic model to the text, then manually interpreting the resulting topics. Next, hazard extraction precision is evaluated by randomly selecting documents with each hazard and manually verifying the correct hazard is present. Hazards are extracted from three datasets: the ICS-209-PLUS, SAFECOM, and SAFENET. Together, the three datasets provide multiple views of hazards in wildfire response, from the operational environment to aerial operations and ground operations. This relevance is considered when choosing the datasets as well as the quality of the reports and available metadata.

ICS-209-PLUS

Large and complex wildfires are managed according to the Incident Command System (ICS), which assigns an incident commander to manage the response. Incident commanders document a suppression response as it unfolds through situation reports filed using form ICS-209. Situation reports contain quantitative meta data, including acres burned and number of personnel, alongside multiple narrative text fields, such as “major problems”, “remarks”, and “significant events”. At the end of an incident, commanders complete a summary report using a separate version of form ICS-209. Summary reports document the final damaged caused by the fire, in terms of acres burned, injuries, fatalities, and structures destroyed. While ICS-209 forms are available to the public, they are typically published in difficult to analyze formats, such as portable document formats (pdfs). Recently, a group of researchers composed a dataset compiling all ICS-209 forms from 1999 to 2014, named the ICS-209-PLUS dataset [18]. After filtering out reports missing data and duplicates, the set of reports used for hazard extraction consisted of 44,363 situation reports from 8,991 incidents ranging from 2006 to 2014. Hazard extraction is performed on the combined narrative data from situation reports.

SAFECOM

The Aviation Safety Communique, known as SAFECOM, is a voluntary aviation safety reporting system hosted by the Department of the Interior and the United States Forest Service (USFS) [19]. The Aviation Safety Communique, known as SAFECOM, is a voluntary aviation safety reporting system hosted by the Department of the Interior and the United States Forest Service (USFS) [19]. A variety of operations are documented in the SAFECOM system, including research flights, search and rescue, and wildfire aerial operations. Reports date from 1995 to the present and can be accessed publicly[2]. In total, there are 15,111 unique reports on aerial wildfire response mishaps through 2020. SAFECOM reports are reviewed by analysts as they are submitted, in addition to quarterly and annual reviews by the DOI. The goal of the SAFECOM system is to foster safety through learning from reported incidents. Each report consists of a mixture of categorical meta-data (i.e., aircraft type, model, region, etc.), alongside qualitative text fields for “Narrative” and “Corrective Actions”. Hazards are extracted from the

[2] https://www.safecom.gov/search

combined text fields, and meta-data can be used to understand the effects and severity of hazards.

SAFENET

The Wildland Fire Safety and Health Network, or SAFENET, is a voluntary, confidential firefighter safety reporting system operated by the National Interagency Fire Center (NIFC). This system is the ground crew-oriented counterpart of the SAFECOM system and is intended to identify near-misses, unsafe conditions, and incidents. While most reports are from wildland fire operations, personnel can also submit reports from training exercises and other disasters, such as floods. Personnel are encouraged to submit SAFENET forms to their supervisor or incident commanders, who are then responsible for corrective action. All SAFENET reports are compiled and stored by the NIFC, and administrators immediately review reports prior to public publication[3]. Reports are composed of two text fields: "Narrative" and "Immediate Action Taken". The reports also contain meta data on contributing factors, type of response, and resources involved. Hazards are extracted from the "Narrative" text section of 2,375 reports from 1999 to 2021.

Hazard Analysis Method

Following identification, hazards are further analyzed to define system and subsystem level hazard effects, hazard likelihood, hazard severity, and overall risk. Qualitative hazard effects are determined either manually by an expert, or automatically using a custom named-entity recognition model [16]. For manual effects analysis, experts examine reports with the hazard and consider the ramifications to the wildfire response operation should the hazard occur. A Safety Management System for aerial wildfire response operations has been defined by the U.S. Forest Service [13], alongside an operational risk management guide [20]. Thus, both hazard likelihood and severity are calculated in accordance with the U.S. Forest Service guidelines [13, 20]. Hazards are assigned one of five likelihood categories (frequent, probable, occasional, remote, improbable) [13] according to how often the hazard occurs in terms of years, as defined in Table 2. Similarly, for each hazard, one of four severity categories (catastrophic, critical, marginal, negligible) is assigned according to the presence of damages, injuries, and fatalities defined in Table 3 [13]. The exact severity calculation varies by data set because each data set has different information on severity. For example, severity for ICS-209-PLUS reports is calculated using structures destroyed, structures damaged, fatalities, and injuries [9], while severity for SAFECOM reports is calculated based on the number of passengers on board, damages, injuries, and hazardous materials [8, 16]. Within SAFECOM reports, the severity of manned and unmanned aircraft are calculated differently, with hazard severity for manned operations defined in Equation (1), and hazard severity for unmanned operations defined in Equation (2). SAFENET reports do not have any clear measure of severity, so categories are manually assigned according to hazard effects in terms of injuries, damages, and fatalities described in Equation (3). Risk is then defined by the combination of likelihood and severity, with each hazard assigned one of four risk levels (high, serious, medium, low) according to the risk matrix in Figure 8 [21]. In this analysis, only static risk constant throughout an operation is considered due to the descriptive rather than predictive

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[3] https://safenet.nifc.gov/

nature of the current state MIKA capabilities. However, it is important to note that risk changes throughout an operation, across different actions, and between different stakeholders. Different risk matrices, such as the one defined in FAA Order 8040.4B [21] may be applicable for different stakeholders.

Table 2: Likelihood categories and definitions

Likelihood Category	Description	Formal Definition	Dataset
Frequent	Expected to occur routinely or continuously experienced	Occurs more than 1000 times per year	ICS-209-PLUS
		Occurs more than 100 times per year	SAFECOM, SAFENET
Probable	Will occur several times, expected to occur often	Occurs between 100 and 1000 times per year	ICS-209-PLUS
		Occurs between 10 and 100 times per year	SAFECOM, SAFENET
Occasional	Likely to occur sometime or several times	Occurs between 10 and 100 times per year	ICS-209-PLUS
		Occurs between 1 and 10 times per year	SAFECOM, SAFENET
Remote	Unlikely to occur, but can reasonably be expected to occur	Occurs between 1 and 10 times per year	ICS-209-PLUS
		Occurs one time every 1 to 10 years	SAFECOM, SAFENET
Improbable	Unlikely to occur, but not impossible	Occurs one time every 1 to 10 years	ICS-209-PLUS
		Occurs less than one time every 10 years	SAFECOM, SAFENET

$$S_{manned} = P(I + D) \quad (1)$$

$$S_{unmanned} = I + D + H \quad (2)$$

$$S_{SAFENET} = I_s + D + F_s \quad (3)$$

Where:

$$P = \#\ of\ passengers$$

$$I = \begin{cases} 1\ if\ injuries = True \\ 0\ if\ injuries = False \end{cases}$$

$$D = \begin{cases} 1\ if\ damages = True \\ 0\ if\ damages = False \end{cases}$$

$$H = \begin{cases} 1\ if\ hazardous\ materials = True \\ 0\ if\ hazardous\ materials = False \end{cases}$$

$$I_s = \#\ of\ expected\ Injuries$$

$$F_s = \#\ of\ expected\ fatalities$$

Table 3: Severity categories and definitions for each dataset.

Severity Category	Description	Formal Definition	Dataset
Negligible	Less than minor injury and/or less than minor system damage	Injuries = 0 Fatalities = 0 Structures Damaged = 0 Structures Destroyed = 0	ICS-209-PLUS
		S ≤ 0.1	SAFECOM
		S ≤ 1.0	SAFENET
Marginal	Minor injury and/or minor system damage	Injuries ≤ 2 Fatalities = 0 Structures Damaged ≤ 10 Structures Destroyed ≤ 10	ICS-209-PLUS
		0.1 < S ≤ 1.0	SAFECOM
		1.0 < S ≤ 2.0	SAFENET
Critical	Severe injury and/or major system damage	Injuries > 2 Fatalities ≤ 2 Structures Damaged > 10 Structures Destroyed > 10	ICS-209-PLUS
		1.0 < S ≤ 2.0	SAFECOM
		2.0 < S ≤ 4.0	SAFENET
Catastrophic	Results in fatalities and/or loss of the system	Injuries > 2 Fatalities > 2 Structures Damaged > 10 Structures Destroyed > 10	ICS-209-PLUS
		S > 2.0	SAFECOM
		S > 4.0	SAFENET

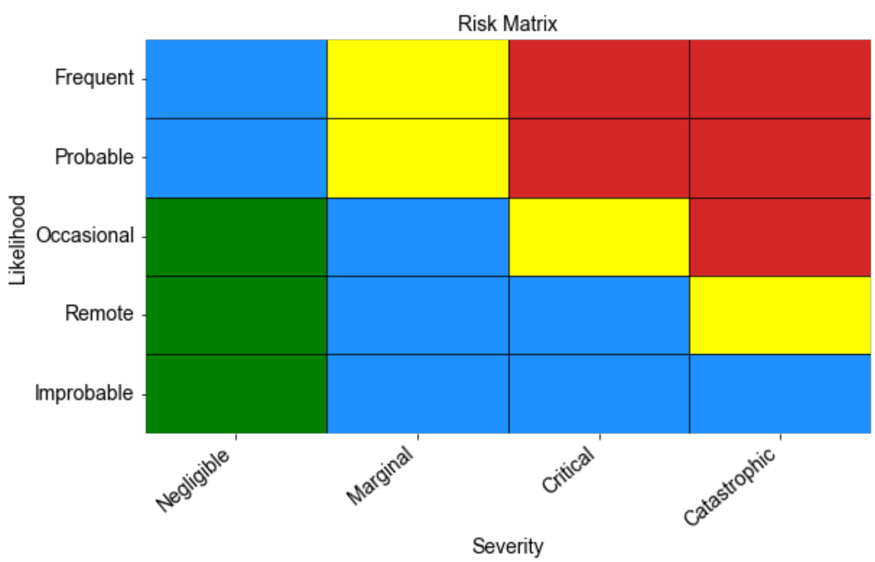


Figure 8: Risk matrix showing how risk levels are assigned according to likelihood and severity. Low risk is green, medium risk is blue, serious risk is yellow, and high risk is red.

Wildfire Response Taxonomy Formulation

After extracting hazards using MIKA, we apply two approaches to assemble hazards into a final taxonomy: a top-down and a bottom-up approach. The results presented in Table 4 represent a fusion of the two techniques. For the top-down approach, we consider the source of the hazard (i.e., the dataset from which it was extracted) and the scope of that source. For the bottom-up approach, we consider the hazards individually and how they might be logically grouped, split, and merged. The categories primarily encompass hazards extracted from their respective datasets with minimal exceptions noted. Duplicate or near-duplicate hazards, including multiple versions of weather-related hazards, are reorganized during the bottom-up approach. The choice of datasets used to extract hazards determines the scope of hazards extracted. Note that, while datasets were chosen for their relevance to the project, MIKA results are descriptive of the dataset used and how the hazards are discussed in the reports and require expert analysis to translate into a formal and complete hazard analysis.

Table 4 provides an organized overview of the hazards extracted using MIKA, which describe three broad categories of hazards in wildfire response: those originating from the operational environment, those originating from aerial operations (both conventional and unmanned), and those originating from ground crew operations. Note that these hazard categories are not necessarily mutually exclusive, and some hazards may fall under multiple categories (e.g., communications breakdowns can occur in both aerial and group operations). The hazard taxonomy is a descriptive, rather than normative, review of hazards found in the datasets studied and, broadly, their sources. Broadly, operational environment hazards tend to be found in the ICS-209-PLUS, aerial operations hazards in SAFECOM, and ground crew operations hazards in SAFENET. Where hazards are cross-cutting, their position in the taxonomy is chosen based on the primary entity involved in the hazards or, for truly cross-cutting hazards, the operational environment category is appropriate. Each overall category and the individual hazards are described in the following subsections and in Tables 5-8.

Table 4: Hazards extracted from SAFECOM, ICS-209-PLUS, and SAFENET.

Category		Sub-Category	Hazard	Source
Operational Environment		Environment	Dangerous terrain/landing site Dry weather Ecological resources threatened High wind Rain Smoke Thunderstorms	ICS-209-PLUS, SAFECOM
		Mission	Aerial groundings Command transitions Evacuations in place Hazardous or closed roads Inaccurate mapping Resource shortages	ICS-209-PLUS, SAFECOM
		Wildland Urban Interface	Cultural resources threatened Infrastructure threatened Livestock in area Law violations or looting Military base in area	ICS-209-PLUS
Aerial Operations	Manned Aircraft	Airspace	Airspace control In-flight collision with object or terrain Intrusion (UAS)	SAFECOM
		Communications	Jumper operations mishaps Radio malfunction	
		Maintenance	Avionics failure Control surface damage Door failure Engine failure Fuel system malfunction Hydraulic Fluid Leaks Landing gear failure Oil system malfunction On-board caution light illuminates Tanker loading issue	
		Mission Equipment	Bucket drop failure Cargo letdown failure Helitorch operations failure	

Category		Sub-Category	Hazard	Source
		Policy Deviation	Inadequate personal protective equipment Load limits exceeded Medivac Personnel duty hours exceeded	
	Unmanned Aircraft	Airspace	Fight Plan Error Intrusion (Manned Aircraft) UAS separation issue	
		Communications	Communications breakdown	
		Loss of Link	Loss of Flight Navigation Software Loss of GCS Loss of GPS	
		Maintenance	Battery degradation Casing dislodged Engine failure Landing gear failure Loss of control Motor mount failure Motor failure Propeller arm failure	
		Mission Equipment	Hang fire in PSD operations Parachute failure	
		Pilot Action	Hazardous landing site Loss of line-of-sight Pilot error	
		Policy Deviation	Employee uses personal drone Hobbyist offers drone usage	
Ground Crew Operations		Communications	Air to ground communication issue Bandwidth Cargo operations overhead Communications disruption Inaccurate weather data Red flag warning Technical infrastructure outage	SAFENET
		Decision Making	Food supply issues Inadequate training or certification Insufficient breaks	
		Environment	Entrapment Falling objects Insect stings Poison oak	
		Equipment	Fuel leak, spill, or spray Insufficient personal protective equipment (PPE) Reckless driving Vehicle breakdown Vehicle collision or accident Vehicle damage	
		Medical	Burn Dehydration Drug use Fatigue Heart attack Heat exhaustion Illness Unsanitary bathrooms Water contamination	

Operational Environment Hazards

Operational environment hazards, listed in Table 5, are system-level hazards which result from the unique, complex nature of wildfire response operations and are related to the fire difficulty level previously discussed. These hazards are inherent and generally unavoidable in wildfire response, with each scenario having an elevated risk for different hazards. For example, some fires may have only small amounts of smoke which does not affect operations, whereas other fires will have denser smoke due to fuel, causing hazardous operations and aerial groundings. Hazards listed in Table 5 are extracted from the ICS-209-PLUS dataset, which is a complete record of form ICS-209 situation and summary reports. Hazards are extracted from the text data of situation reports filed from 2006-2014. Operational environment hazards tend to be cross-cutting, with hazard effects involving personnel, aircraft, and civilians.

Table 5: Wildfire operation environment hazard descriptions, effects, and risk.

Hazard	Description	Effects	Likelihood	Severity	Risk
Environment					
Dangerous Terrain	Steep, inaccessible, and generally hazardous terrain	Slow response time, ground crew injuries	Probable	Marginal	Serious
Dry Weather	Unusually dry weather or drought conditions	Health risk to firefighters, increased flammability of fuels, quicker fire spread	Probable	Marginal	Serious
Ecological Resources Threatened	Threat to endangered species habitat of both plants and animal, fire located in sensitive area, including national parks and wilderness	Reduced firefighting ability and accessibility to area, some tactics (e.g., prescribed burn) may not be used to prevent damage to ecological resources	Occasional	Marginal	Medium
High Wind	Extreme wind patterns in terms of variability, speed, and direction	Hazardous flight conditions, increased fire spread	Probable	Marginal	Serious
Rain	Any degree of precipitation, typically in the form of rain or showers	May benefit containment efforts by reducing fire spread, can cause slippery and dangerous conditions for personnel, potential for flooding	Probable	Marginal	Serious
Smoke	Excessive smoke, likely due to vegetation conditions	Loss of visibility, health risk for firefighters, suspension of aerial operations	Probable	Marginal	Serious
Thunderstorms	Lighting and thunderstorms in fire area	Lighting may ignite new fires, cause unsafe conditions for personnel	Probable	Marginal	Serious
Mission					
Aerial Groundings	Temporary suspension of aerial suppression operations. May be due to smoke or wind conditions	Decreased situational awareness of fire location, limited suppression capabilities	Occasional	Critical	Serious
Command Transitions	Transitioning between different incident type levels or between incident commanders	May impact the group and response dynamic, may miss sharing pertinent information, transitioning to a less severe incident type will decrease amount of assets	Probable	Marginal	Serious
Evacuations in place	Community evacuations currently in place or at a warning level	Unevacuated civilians at risk, evacuations may pull resources from fire attack	Probable	Critical	High
Hazardous or closed roads	Roads closed to public or emergency response, or roads narrow and difficult for operations	Slow response time, greater possibility for entrapments, increased traffic on operational roads	Probable	Marginal	Serious
Inaccurate Mapping	Over estimation or under estimation of fire area	Crews deployed to wrong location, fire takes longer to contain, or unanticipated fire spread	Probable	Marginal	Serious
Resource shortages	Shortages of resources for suppression response or shared resources between multiple incidents	Difficulty containing the fire, increased damages	Probable	Marginal	Serious
Wildland Urban Interface					
Cultural Resources Threatened	Includes valuable areas, such as nature reserves, historical landmarks, etc., that are threatened by a fire	May increase political pressure on response. Some tactics (e.g., prescribed burn) may not be used to prevent damage to cultural resources	Occasional	Marginal	Medium
Infrastructure threatened	Fire threatening or damaging infrastructure,	Loss of communications, loss of infrastructure, long term	Occasional	Critical	Serious

Hazard	Description	Effects	Likelihood	Severity	Risk
	including powerlines and watersheds	effects to water quality and impact on civilian life			
Law Violations and Looting	Illegal activity caused a fire or during a fire, including looting and trespassing	Loss of firefighter equipment and belongings, risk to trespassers, loss of civilian property	Occasional	Marginal	Medium
Livestock in Area	Livestock in fire path creates a huge logistical issue when coupled with evacuations	Loss of livestock, danger to firefighters, logistical issues when coupled with evacuations	Occasional	Marginal	Medium
Military Base in Area	Military base operations may be affected and may be a hazmat risk if fire burns within the base	Disruption of military operations, HAZMAT risk, unexploded ordinance may impact operations	Remote	Critical	Medium

Aerial Operations Hazards

Aerial operation hazards, listed in Table 6, are hazards originating from aerial operations and are subsystem level hazards within the wildfire response operation. These hazards are specific to manned aircraft mishaps and extracted from SAFECOM data. In Table 7, unmanned aerial operations hazards are listed. These are also sourced from SAFECOM data. While there is some overlap between the hazard names (e.g., engine fault occurs in both manned and unmanned aircraft), we document these separately because they may have different likelihood and effect (i.e., an onboard fault of a manned aircraft is more likely to put a person, in this case the pilot, at risk). In this analysis, aerial operations hazard effects are focused primarily on impacts to the aircraft, operators, and designated mission; however, these hazards may also affect the wildfire response operation as a whole.

Table 6: Manned aviation operations hazard descriptions, effects, and risk.

Hazard	Description	Effects	Likelihood	Severity	Risk
Airspace					
Airspace Control	Restricted airspaces, lack of adherence to air traffic controller commands, violations, runway obstructions	Near miss events, delays, shutdowns, hazardous landings and take-offs	Occasional	Marginal	Medium
In-flight Collision	Usually with powerlines, trees, or terrain	Injury to operator, damage to or loss of aircraft	Occasional	Marginal	Medium
Intrusion (UAS)	Unintentional or intentional airspace intrusion by non-mission unmanned aircraft	May lead to NMAC, grounding of aircrafts. Affects both mission and non-mission drones.	Probable	Negligible	Medium
Communications					
Jumper Operations Mishaps	Accidents involving both smoke jumpers and spotters. May include issues with parachutes or harnessing	Injury to firefighters, delay in aircraft mission	Occasional	Catastrophic	High
Radio Malfunction	Unreadable transmissions or interference	Communications loss may delay mission or increase likelihood of collision	Probable	Negligible	Medium
Maintenance					
Avionics Failure	Electrical failures involving circuits and loose or broken wiring	Aircraft mission abort, repairs required	Probable	Negligible	Medium
Control Surface Damage	Cracks or other abnormalities in control surfaces	May lead to uncontrolled pitch, yaw, roll, or hard landing	Probable	Marginal	Serious
Door Failure	Door latches failing to secure or stay secure, broken seal or cracks on door windows	Aircraft mission abort, repairs required	Probable	Marginal	Serious

Hazard	Description	Effects	Likelihood	Severity	Risk
Engine Failure	Transmission, spark plugs, and chip light warnings from engines	Aircraft mission abort, repairs required	Probable	Marginal	Serious
Fuel System Malfunction	Fuel leaks, spills during refill, cap configuration issues, and filter replacements	Delay in aircraft mission, repairs required	Probable	Marginal	Serious
Hydraulic Fluid Leak	Leaks may originate from any hydraulic system onboard	Aircraft mission abort, repairs required	Probable	Marginal	Serious
Landing Gear Failure	Failure of landing gear to retract, remain locked, or extend	Injury to operator, damage to or loss of aircraft	Probable	Marginal	Serious
Oil System Malfunction	Includes leaks, pressure gauge malfunctions, temperature issues	Aircraft mission abort	Probable	Marginal	Serious
On-Board Caution Light Illuminates	Includes master caution light and warning light	Precautionary landing	Probable	Negligible	Medium
Tanker Loading Failure	Premature jettison of retardant or water drop loads	Delay of aircraft mission, dropped load may impact ground crews	Probable	Marginal	Serious
Mission Equipment					
Bucket Drop Failure	Failure, degradation, or breakage of drop equipment. Can occur mid-air, during drop, during refill, or during landing.	Delays in controlling spread of fire, drop equipment may impact ground crews	Probable	Marginal	Serious
Cargo Letdown Failure	Includes premature release of external loads,	Delays in controlling spread of fire, cargo equipment may impact ground crews	Probable	Marginal	Serious
Helitorch Operations Failure	Lack of notification prior to operations, inadvertent release of helitorch, unapproved equipment, torch collision with obstacle	Delay in aircraft mission, spilled ignition gel, dropped load, damage to torch equipment	Occasional	Marginal	Medium
Policy Deviation					
Inadequate Personal Protective Equipment	Missing protective gear such as helmets, gloves, flight suits, and boots	Injury to operators	Occasional	Negligible	Low
Load Limits Exceeded	Excessive load weight due to incorrect calculations or negligence	Damage to or loss of aircraft, delay in aircraft mission	Occasional	Negligible	Low
Medivac	Medivac required for personnel or civilians	Emergency transportation aircraft may require reserved airspace corridors	Occasional	Catastrophic	High
Personnel Duty Hours Exceeded	Pilots and personnel exceeding predefined duty day requirements	Health risk to operators	Occasional	Negligible	Low

Table 7: Unmanned aviation hazard descriptions, effects, and risk.

Hazard	Description	Effects	Likelihood	Severity	Risk
Airspace					
Fight Plan Error	UAS abruptly and without manual command changes angle of attack or flight plan	UAS may crash land and sustain damage	Occasional	Marginal	Medium
Intrusion (Manned Aircraft)	Non-mission aircraft or unaware mission aircraft may enter the UAS operating area	Termination or postponement of UAS operations	Occasional	Negligible	Low
UAS Separation Issue	Close proximity to other aircraft	Operations may be temporarily halted	Occasional	Negligible	Low
Communications					

Hazard	Description	Effects	Likelihood	Severity	Risk
Communications Breakdown	Lack of information and communication between operators and other personnel	Premature UAS or manned aircraft mission abort	Remote	Negligible	Low
Environment					
High wind	Wind gusts may push UAS off-course	Collision with obstacle, damage to casings, damage to propellors	Remote	Marginal	Medium
Loss of Link					
Loss of Flight Navigation Software	Flight navigation software freezes	Delay due to restarting GCS, potential loss of control, return to home	Remote	Negligible	Low
Loss of GCS	Errors, signal loss, and inability to respond to feedback	UAS may initial return to home mode incorrectly, may crash land and sustain damage	Occasional	Marginal	Medium
Loss of GPS on UAS	Loss of GPS connection and location services	Manual control with LOS may be required. UAS may initial return to home mode incorrectly, may crash land and sustain damage	Occasional	Marginal	Medium
Maintenance					
Battery Degradation	Rapid loss of battery power, inconsistent or inaccurate readings	Can cause collision with obstacles, rapid altitude loss	Remote	Marginal	Medium
Casing Dislodged	Cowling and covers on various components may become lose or dislodged	May impact propellor arms on the aircraft or fall on other aircraft	Remote	Negligible	Low
Engine Failure	Failure from piston rendering engine unusable	UAS may crash land and sustain damage	Occasional	Marginal	Medium
Landing Gear Failure	Landing gear fails to raise on one or more sides	UAS mission abort via immediate landing; could lead to loss of UAS	Improbable	Negligible	Low
Loss of Control	Sticking of surfaces, lack of response, or uncommanded actions	UAS may collide with obstacle, crash land, and sustain damage	Occasional	Marginal	Medium
Motor Mount Failure	Motor mount separation in flight or crack during transport	UAS may lose control and crash land, or be inoperable	Occasional	Marginal	Medium
Motor Failure	Overheating, failure to response	May damage/melt UAS components and result in loss of control	Occasional	Marginal	Medium
Propellor Arm Failure	Sheared bolt heads may cause propellor disconnection or arm may snap from	May result in damage and hard landing	Occasional	Marginal	Medium
Mission Equipment					
Hang Fire in PSD Operations	Incendiary balls or material is caught in the hatch	In-flight fire on-board UAS	Improbable	Negligible	Low
Parachute Landing Failure	Failure to completely deploy parachute or pack properly	May cause hard landing	Improbable	Marginal	Medium
Pilot Action					
Dangerous Landing Site	Uneven ground under landing pad	UAS may tip over and sustain damage	Improbable	Marginal	Medium
Loss of Line-of-Sight	Low visibility conditions, including nighttime or bright lights	UAS may collide with obstacle, crash land, and sustain damage	Improbable	Marginal	Medium
Pilot Error	Incorrect sequence of commands for landing or take off	UAS may tip over and fall, experience hard landing, or sustain damage	Occasional	Marginal	Medium
Policy Deviation					
Employee Uses Personal Drone	Personnel may volunteer to fly non-certified drones	Personnel may be fined for violating the law, other aerial operations may be at risk	Remote	Negligible	Low

Hazard	Description	Effects	Likelihood	Severity	Risk
Hobbyist Offers Drone Services	Non-mission personnel volunteer their drones for mission use	Personnel may be fined for violating the law, other aerial operations may be at risk	Improbable	Negligible	Low

Ground Crew Operations Hazards

Ground crew operations hazards, listed in Table 8, may result in close calls, injuries, or fatalities to ground personnel. These hazards are extracted from SAFENET reports, which detail mishaps resulting in ground crew harm. Ground crew operations hazards effects are defined primarily at the subsystem level in terms of impact to crew personnel. Although, some ground crew hazards also impact the entire wildfire response operation system and effects are described accordingly.

Table 8: Ground crew hazard descriptions, effects, and risk.

Hazard	Description	Effects	Likelihood	Severity	Risk
Communications					
Air to Ground Communication	Degradation of air to ground communications due to equipment issues or human factors	Critical information is delayed or not communicated, loss of contact between personnel	Occasional	Marginal	Medium
Bandwidth	Narrow bandwidth issues and wide bandwidth issues	Missed transmissions, static transmissions, interference	Occasional	Marginal	Medium
Cargo operations overhead	Drop operations or cargo transportation overhead	Water or retardant drops onto personnel, falling tree snags knocked onto personnel	Occasional	Catastrophic	High
Communication Disruption	Disruption due to radio malfunction, channel issues, configuration issues, or lack of cell service	Critical information is delayed or not communicated, loss of contact between personnel, could lead to injuries	Probable	Marginal	Serious
Inaccurate Weather Data	Outage of weather station, weather station with inaccurate predictions, or distant weather station	Hamper suppression activities, decreased situational awareness	Occasional	Marginal	Medium
Red Flag Warning	Red flag warning in effect usually for high winds and dry weather	Increased fire activity, unpredictable and fast spread	Occasional	Negligible	Low
Technical Infrastructure Outage	Outage in computers, networks, and other technical infrastructure	Loss of internet access, communications, or other data	Occasional	Marginal	Medium
Decision Making					
Food Supply Issues	Distribution issues, expired, rotten, undercooked, or small portions of food	Illness, decreased energy, allergic reactions, and malnutrition	Occasional	Marginal	Medium
Inadequate Training or Certification	Unsupervised trainees, missing certifications/ qualifications, untrained personnel, and falsified certifications	Increased risk for both individuals and crews, inadequate safety zone designations	Probable	Catastrophic	High
Insufficient Breaks	Violation of work-rest ration during incident of transport to incident	Increased fatigue	Occasional	Marginal	Medium
Environment					
Entrapment	Personnel trapped within fire	Loss of vehicle, injuries, loss of life	Occasional	Catastrophic	High
Falling Objects	Falling trees, rocks, and limbs over personnel	Severe bodily injury (fractures, concussions) or fatality, damage to equipment	Occasional	Catastrophic	High
Insect Stings	Stings and bite from bees and other insects, may cause anaphylaxis	Minor irritation, allergic reaction, hospitalization	Probable	Marginal	Serious

Hazard	Description	Effects	Likelihood	Severity	Risk
Poison Oak	Contact with poison oak or inhalation of poison oak smoke	Rash, allergic reaction, respiratory symptoms	Occasional	Marginal	Medium
Equipment					
Fuel Leak	Leak from chainsaw fuel or vehicle	Fuel may spray personnel in the face or drip on clothing increasing risk of burns	Occasional	Marginal	Medium
Insufficient PPE	Missing, torn, worn down, or inadequate personnel protective equipment	Increased susceptibility to injuries and burns	Occasional	Marginal	Medium
Reckless Driving	Speeding, swerving, and irresponsible driving, usually to and from incident locations	Near-miss accident with other vehicles and objects	Occasional	Marginal	Medium
Vehicle Breakdown	Vehicle breakdown during incident or in transport to incident due to mechanical issues	Risk of entrapment, damage to vehicle, loss of vehicle	Occasional	Catastrophic	High
Vehicle Collision or Accident	Vehicle collision, accident, or near miss during incident or in transport to incident	Damage or loss of vehicle, injuries to on-board personnel	Occasional	Catastrophic	High
Vehicle Damage	Tire damage, break damage, and other mechanical wear on vehicle	Vehicle out-of-service for repairs	Occasional	Marginal	Medium
Medical					
Burn	First, second, or third degree burn to personnel	Hospitalization, medivac, potential long-term injury	Occasional	Catastrophic	High
Dehydration	Dehydration in fire personnel	Exhaustion, collapse, dizziness, hospitalization, inability to work on fireline	Probable	Catastrophic	High
Drug use	Illegal drug use and intoxication by personnel	Potential for injury to intoxicated individual and those around them	Occasional	Marginal	Medium
Fatigue	Extreme fatigue in personnel, may be due to sleep deprivation, long fire response, or insufficient breaks	Impaired vehicle operators leading to accidents, susceptibility to illness	Occasional	Marginal	Medium
Heart Attack	Personnel heart attack, civilian heart attack emergency during incident	Hospital transport, medical evacuation, fatality	Occasional	Catastrophic	High
Heat Exhaustion	Extreme heat may cause heat exhaustion or heat stroke in personnel	Exhaustion, collapse, dizziness, hospitalization, fatality	Occasional	Catastrophic	High
Illness	Viral or bacterial illnesses such as COVID-19, flu, or hepatitis, toxic exposure related illness, nausea, headaches	Super spreader events, decreased crew effectiveness, decrease available crew members	Occasional	Marginal	Medium
Unsanitary Bathrooms	Infrequent cleanings, limited number of bathrooms, lack of hand wash stations	Illness in personnel, unsanitary conditions, low moral	Occasional	Marginal	Medium
Water Contamination	Contaminated drinking water or bucket drop water	Exposure to personnel may cause illness, contaminated drinking water may cause dehydration	Occasional	Marginal	Medium

The Flight Safety Foundation (FSF) previously identified UAS-related hazards in humanitarian scenarios, including wildfire response [22]. Many of their identified hazards overlap with those extracted from SAFECOM, especially those related to communications faults, weather, human error, and out-of-date data. In addition, FSF identifies cybersecurity attacks as a possible hazard as well as physical interference from the ground, with the given example of rocks being thrown at the UAS. Hazards identified via MIKA are intended to augment human expert and traditional analysis, and therefore these additional hazards could be added to Table 4. As UAS are a relatively recent addition to wildfire response, it is possible there will be future relevant incidents that are captured in these datasets. This highlights the importance of regularly running MIKA as datasets are updated, as well as the value of supporting regular identification of hazards in an evolving wildfire response environment.

Evaluating Mitigation Strategies

As seen in the "Hazard Identification" section, there is a large, heterogenous space of hazards in wildfire response arising from the operational environment, aircraft, and ground crew suppression efforts. Both faults and fire scenario difficulty can lead to hazardous operating scenarios, which may impact fire containment and operator safety. While MIKA yields a thorough set of hazards, their effects, and risk levels in the existing system, hazards identified from MIKA cannot be easily assessed in the context of emerging operational concepts because they are identified from historical datasets. Instead, identified hazards and their behaviors can be modeled and simulated in the SMARt-STEReO model to understand how hazards and potential mitigations interact. In this section, advanced technology-based mitigation strategies are evaluated in three examples including MIKA-identified hazards. The first example focuses on faults in mission equipment and communications infrastructure, both for aerial resources and ground resources. The remaining two examples are centered on operational environment hazards, with the second example modeling variable wind and flammability scenarios and the third example modeling scenarios with multiple ignition points and smoke.

As identified in the "Hazard Dynamics" section, hazards to fire containment and operator safety can arise from both from fire difficulty, from operator/equipment faults, and their interactions. Advanced technology provides an opportunity to mitigate hazardous scenarios by increasing firefighting capacity across all scenarios. Thus, the next sections will examine the effects of both operating circumstances as well as faults in a variety of baseline scenarios. The goal of this analysis will be to show whether the proposed mitigation strategies reduce current firefighting hazards without introducing significantly more risks (due to, e.g., new fault modes). Two technology-enabled mitigation strategies – increased communications throughput and UAS for surveillance with advanced sensors – are proposed and evaluated across the three examples. The parameters used to define the scenarios are described in Table 9, where descriptions for assets, such as "GC" can be found in Table 1. While UAS are currently used in some present-day wildfire response operations, the UAS in operation do not have advanced sensor capabilities and cannot safely fly simultaneously with manned aircraft [12]. These mitigations are consistent with the STEReO project and utilize emerging technology [1]. Proposed increased communications may be implemented through a UTM-like system previously developed by NASA [2], while surveillance UAS may provide enhanced situation awareness and fire monitoring through advanced sensor technology developed by NASA's Earth Science Division (ESD) [23, 24]. This results in a 2 (increased communications versus default) x 2 (UAS versus no UAS) experiment resulting in four distinct design scenarios:

- *Default:* represents a present-day wildfire response system (with no UAS), including a communications lag due to information being relayed manually between the aerial commander and the incident commander and no UAS for surveillance.
    - parameters: comms_delay=1, numS=0
    - labeled as: "present"

- *Increased Communications:* represents the implementation of advanced communications infrastructure allowing instantaneous communication between any assets, meaning that fire and aircraft location information relayed to the incident commander by the aerial supervisor and other surveillance assets is always current (i.e., a UTM-like system).
    - Parameters: comms_delay=0, numS=0
    - Labelled as: “-lag”
- *Increased Surveillance:* represents the implementation of surveillance UAS with advanced sensing technologies (i.e., can detect fire through smoke; these sensors have been developed by the Earth Sciences Division). This provides the incident commander more complete information about the entire map and position of the fire, rather than just a certain quadrant
    - Parameters: comms_delay=1, numS=3
    - Labelled as “+surv”
- *Increased Communications + Surveillance*: Represents the implementation of surveillance UAS with an advanced communications infrastructure, meaning that the incident commander always has a current view of the fire and aircraft location
    - Parameters: comms_delay=0, numS=3
    - Labelled as: “+surv -lag”

Table 9: Parameter and variable values for the SMARt-STEReO model used in the presented examples.

Constant Parameters		
Parameter	*Value*	*Description*
NumGC	3	Number of groundcrews who require helicopter transport
NumEC	3	Number of groundcrews with engine transport
NumH	2	Number of helicopters
NumT	3	Number of tankers
Avg_time	5	Average time to ignition for grid points (i.e., flammability)
Enginesides	[r,d]	The grid sides accessible to engine crews (right, down)
Stateinfo	‘all’	The amount of information sent to the incident commander
Mitigation Variables		
NumS	0 or 3	Number of surveillance UAS is 0 or 3
Comms_delay	0 or 1	Length of communications delay is 0 or 1 timestep
Independent Variables for Examples		
Example 1		
Equipment Faults	Assets, times, modes	Equipment fault mode (minor, major, tool break), injection time (0-30), and asset (AC, T, H, S, GC, EC).
Immobilization Faults	Assets, times, modes	Fault injection time (0-30), and asset (AC, T, H, S, GC, EC).
Comms Faults	# of Joint faults, disruption time	Number of joint fault modes and the length of the disruption
Example 2		
Flammability {timestep: avg_time}	Increasing: {0: 5, 10: -0.3, 30: -0.5} Decreasing: {0: 5, 10: 0.8, 30: 0.6}	Represented by the average time it takes for a grid point to ignite. The initial value is decreased by 30% and then by an additional 50% when flammability increases. The initial value is increased by 80% and then by 60% at t=10 and 30, respectively when flammability decreases

Wind: Speed {timestep: speed}, Direction {timestep: heading angle}	Changing Wind: {0: 1}, {0: 0, 10: 80}, Wind + Flammability: {0: 0, 8: 1, 28: 4.5}, {0: 0, 8: 45, 28: 160}	Represented by wind speed and direction in m/s and degrees, respectively. For changing wind scenario, the speed is maintained at 1 m/s while the wind direction is changed from 0 to 80 degrees at t=10. For the changing wind + flammability scenario, wind speed and direction are changed at t=8 and 28 to the values shown here.
Example 3		
Smoke	(True, False)	Whether or not smoke has an impact, can be True to use smoke or False to ignore smoke
Initspark	[(0,0)], [(0,0), (100,100), (-100, -100)]	The initial start location of the fire can be either (0,0) for a single ignition scenario, or can be at (0,0), (100,100), and (-100, -100) for a multiple ignition scenario with three spark points

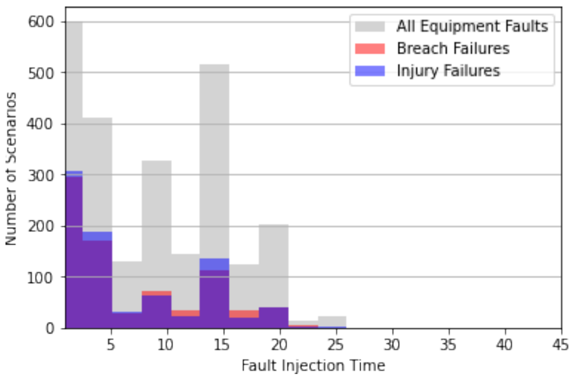
Example 1: Simulation of Communication Errors and Equipment Faults Effect on Operator Safety

An important consideration for the adoption of new technologies in wildfire response is how these technologies affect the resilience of the response to potential equipment faults and accidents. In wildfire response, resilience can be thought of both as the mitigation of an ongoing fire scenario (the "disaster resilience" definition—see [25]) and the mitigation of fault scenarios within this scenario (the "engineering resilience" definition—see [26]). To consider both these aspects of resilience, we use the nested resilience analysis approach developed in [11] to evaluate the effect of the mitigation strategies (in terms of fire containment and operator safety) across both firefighting scenarios and fault events. Since it is desirable for the technologies to improve the performance of the response during hazardous scenarios while not introducing further hazards, this section studies the effect of these technologies on the resilience of the response to three high-level types of fault scenarios—equipment faults, asset immobilization (e.g., crashes), and communications faults. While studying equipment faults and asset immobilization faults evaluate how mitigations affect resilience to common high-level fault events, communications faults evaluate potential hazards which may be introduced with new communications technologies.

Given the assumptions embedded in the model, it is expected that the effect of increased communications and surveillance will increase the capacity of the response such that it is better situated to handle fault events. In this situation, fault events may still affect containment—even at the same levels—but that the effects will not erase the performance improvements seen in the baseline case. Additionally, it is further expected that increased surveillance will result in fewer injuries, since ground crews will more readily receive information about an approaching fire head. This evaluation will be performed over the parameters given in Table 9 over 30 randomly-generated maps. By performing this evaluation, we can both evaluate potential risks presented by these technologies (e.g., to the communications infrastructure) while also evaluating potential improved resilience (and thus, reduced risks) of the system to other external fault scenarios.

Equipment Faults

To better understand the resilience of these design improvements, we first examine their effect on the system's response to equipment faults. Equipment faults take a given asset out of commission for a defined length of time which varies depending on the type of asset and fault mode. Aerial assets have two major equipment faults in the simulation—major and minor mechanical faults. Major mechanical faults cause emergency landing in a safe location and take the asset out of commission for the duration of the simulation, while minor mechanical faults are resolved after 2 timesteps. For ground assets, the single simulation fault mode is “tool break,” which takes the asset out of commission for 10 timesteps (or until repaired at base). Note that these faults do not (as modelled) cause injuries by themselves unless the fire gets too close to the assets. The assumptions for these behaviors were developed during the development of the simulation scenario, where minor faults were considered to take ~15 minutes to resolve and major faults were considered to take ~80 minutes to resolve.



	injury %	completion %	breach %
AerialCommander	73.3	26.1	73.9
Tanker	50.6	51.7	48.3
Helicopter	29.8	77.2	22.8
nominal	20.0	76.7	23.3
Surveillance	19.4	77.2	22.8
GroundCrew	19.3	75.2	24.8
EngineCrew	18.9	78.5	21.5

Figure 9. Relative Impact of Equipment Faults Over Simulation Time (left) and Asset Type (Right)

The relative impact of these faults over time is shown Figure 9. As shown on the left, these faults are generally injected before the 18th time-step, to represent the operational interval of the response, since simulations typically end between the 20th and 30th timestep. As shown, a higher ratio of faults injected at the beginning of the simulation result in failures (in terms of breaches and injuries) than later in the simulation. This is because (1) firefighting operations are more critical early in the simulation, when the fire is small and the firelines are just beginning to be constructed and (2) faults injected early in the simulation that are unable to be repaired (e.g., major mechanical faults) are present in the simulation longer and thus have a greater cumulative impact. However, most equipment faults still do not result in fireline breaches or injuries directly. This is more apparent from the table of faults on the right of Figure 9. As shown, the equipment faults with the most cumulative impact are first Aerial Commander and Tanker faults, which result in injuries and breaches 73% and 51% of the time, respectively, because of the direct impact the loss of these assets has on the spread of the fire (and the loss of the asset throughout the simulation in major fault modes). Other faults have less of an impact because (1) there are sufficient redundancies between the assets (for Helicopters, Surveillance, and the Aerial Commander) and (2) GroundCrew faults are more easily resolved by returning to the base (since they are transported by helicopters).

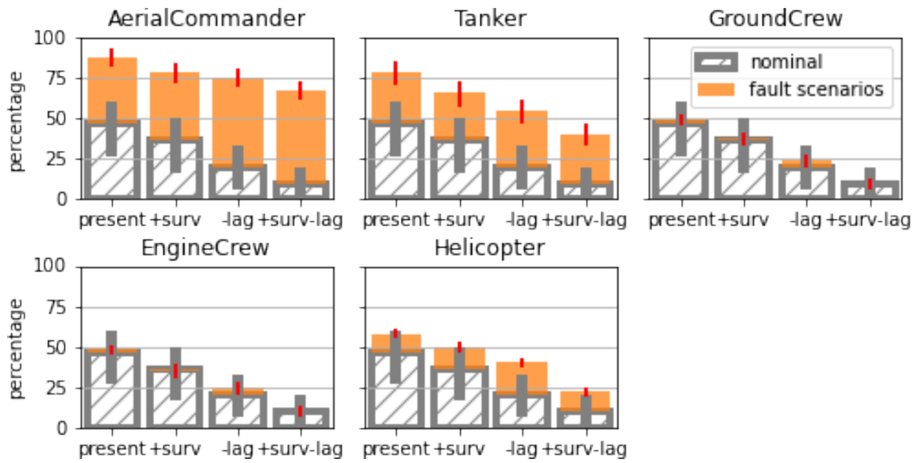


Figure 10. Effect of Equipment Faults on Injuries Over Designs.

The effects of these designs on these faults are shown in Figure 10 (for injuries) and Figure 11 (for fire containment). As shown, most faults have a very small effect, thus, the dominant improvement given by the designs (increased surveillance and reduced lag) is the improvement given in the nominal scenario (with a very small change for each fault). However, tanker and aerial commancer faults, which have substantial impact, do significantly affect the designs' ability to mitigate the fire—as shown, the fireline completion and injury metrics for the (individual) increased surveillance and decreased lag designs is the same or above the present-state design without these faults. This essentially means that if these designs were to cause these fault modes with regularity (a highly conservative assumption), there may not be improvement over the default design. However, given the prevalence of these faults is not affected, there is still a visible improvement in hazard metrics over these fault scenarios. This shows how the performance improvements given by increased surveillance and decreased communications lag generalize over equipment faults.

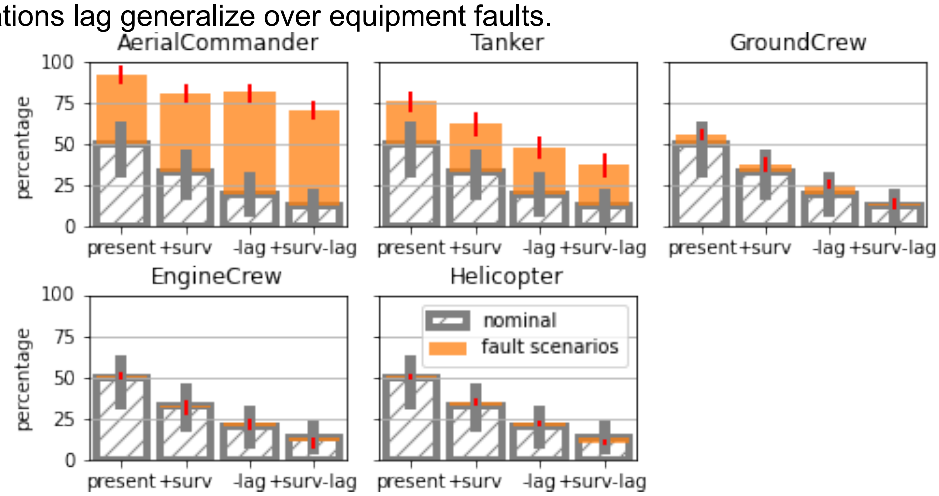


Figure 11. Effect of Equipment Faults on Fireline Breaches Over Designs.

Immobilization Faults

To further understand the resilience of these design improvements, we additionally study the effect of immobilization faults, which have a higher potential severity and safety impact than normal equipment faults. Immobilization faults, like equipment faults, place assets out of commission for a defined duration of time. For aerial assets, these faults result in crashes at the given location (and thus have their own independent safety impact) while for ground assets, they result in the asset being stranded at a given location. Thus, these faults are more likely to cause injuries because of (1) the direct safety impact of the fault (i.e., crashing in and of itself can cause flight injuries) and (2) the increased chance that the asset will come in contact with the wildfire. Direct injuries are not included in the model (since they are given), but Figure 12 shows the effect of these faults over the designs. As shown, the effects of these faults are similar to the equipment faults (see Figure 10 and Figure 11), but more pronounced. This is because immobilization has a higher impact both on the ability of the asset to perform its role (since it takes the asset out of commission) and a more direct impact on asset safety (since the asset is more likely to be vulnerable). In particular, tanker crashes occur during drops, which are very close to the fire, and stranded ground/enginecrews are unable to evade the fire when it approaches their location on the fireline.

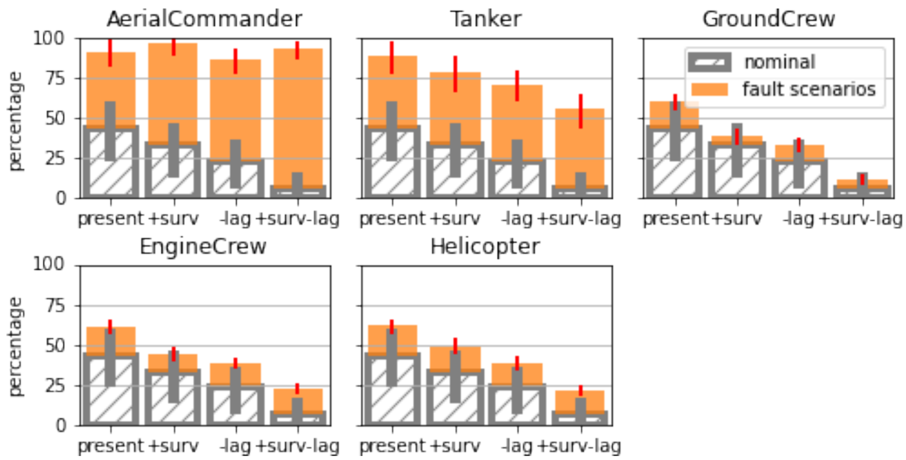


Figure 12. Effect of immobilization faults on injuries over designs.

However, as shown in Figure 12 and Figure 13, the increased surveillance and decreased communications lag designs (both individually and in combination) still generally increase performance over these fault scenarios as similar to the nominal scenario. Similar to Tanker equipment faults, Tanker immobilization faults still have a significant impact on the rate of injuries and breaches over all designs, which reflects the severity of the fault and the lack of ability to mitigate it by any design. Nevertheless, increased surveillance and decreased lag still decreases the number of injuries and fireline breaches in these scenarios, even if the improvement is less pronounced. This shows how these performance gains are robust to externally-driven hazardous fault modes.

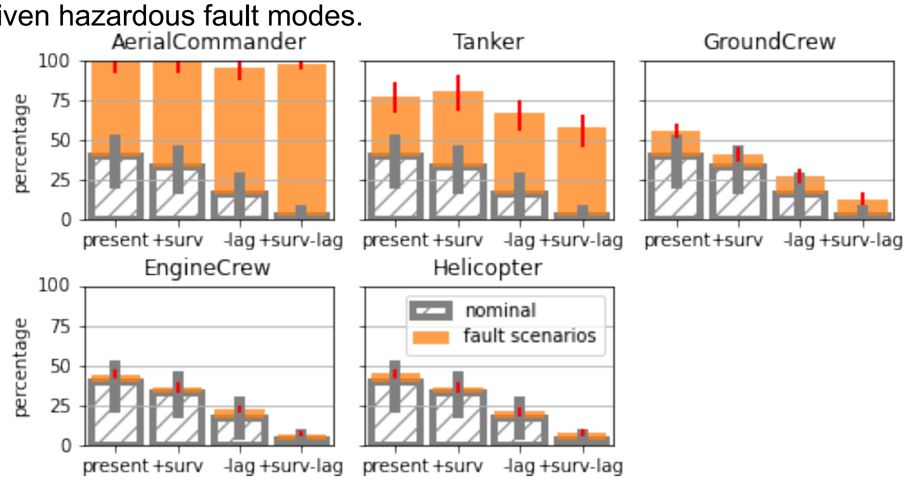
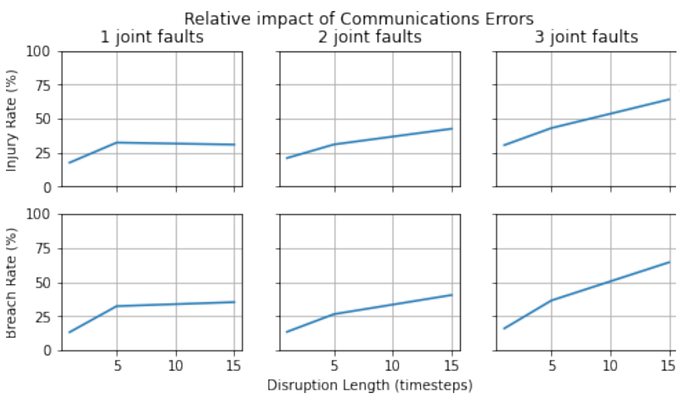


Figure 13. Effect of immobilization faults on fireline breaches over designs.

Communications

Finally, to understand both the resiliencies added and potential risks posed by the studied technological improvements, we examine their impact on the system response to communications faults. Communications faults prevent the transfer of information between assets, the aerial commander, and the incident commander. This information includes (1) fireline locations (2) locations for fire breaks (3) Requests to go/leave a location. Unlike mechanical faults, communications errors may be likely to occur in multiple assets simultaneously because common cause errors arising from the variable and remote environment (e.g., terrain, weather, etc), in which there may not be reliable existing communications infrastructure and ad hoc response infrastructure (depending on the technology used) may encounter setup and interference difficulties. As a result, faults with more than one affected asset may be likely to occur. There may also be substantial variability in the length of communications loss, with some faults likely to be resolved quickly (i.e., a few minutes) and others lasting throughout the simulation. To investigate the effect of communications faults, this section first studies how loss of communications affects fireline breaches and injuries across asset types and scenario impact (disruption length and number of joint faults). It then examines the resilience of each design to communications faults at different levels of scenario impact.



	injuries	comptime	breachtime
AerialCommander	0.400000	0.700000	0.300000
IncidentCommander	0.363636	0.727273	0.272727
GroundCrew	0.222222	0.888889	0.111111
Tanker	0.166667	0.833333	0.166667
Helicopter	0.000000	1.000000	0.000000
nominal	0.000000	1.000000	0.000000

Figure 14. Relative effect of communications faults over differing levels of impact (left) and asset types (right)

To investigate the effects of different types of communications faults, Figure 14 shows the effect of communications faults on injury and breach rates across asset types (right) as well as the average effect of multiple fault scenarios and disruption length on injury and breach rates (left). As shown, Faults in the AerialCommander and IncidentCommander have the biggest impact, followed by Ground Crews and Tankers, with Tankers having a more significant impact on breaches and Ground Crews having a more significant impact on injuries. This is because Aerial Commander and Incident Commander faults have a much wider impact—affecting multiple asset communications at the same time—to the other assets, which only effects their own communications. Additionally, tanker communications errors have a more significant impact on completion because tankers (nominally) slow the fire down (meaning, a loss of functionality results in a faster-spreading fire that can more readily evade firelines), while ground crew errors have a more significant impact on injuries because crews operate closer to the fire (meaning, a loss of communication is more likely to put them at risk.). As modelled, Helicopter communications faults have very little impact. This is for two reasons: (1) Helicopter roles as support (drop/surveillance/supply) aircraft are tertiary, meaning the missions they perform in the model have a low impact if lost and (2) Critical roles for Helicopters (transporting ground crews) are intermittent, making it easy for a single redundant helicopter to take up the slack when communications are lost. Figure 14 (right) further shows how the number of joint faults and disruption length can increase the impact of fault modes. Note that while this trend holds for fault length, it does not hold universally for number of joint faults (See Figure 14 breach rates at ½ joint fault modes, which is further reflected in Figure 16)—while the set of joint fault modes often has more impact than the set of single modes, it can sometimes have less impact. This is because the set of these joint scenarios is formed by taking the intersection of intervals when modes could occur, meaning that some joint fault modes may not occur when individual fault modes have the most impact, since there is not interlap in the interval. Nevertheless, it is important to evaluate these levels of impact to ensure a response isn't particularly prone to joint fault modes.

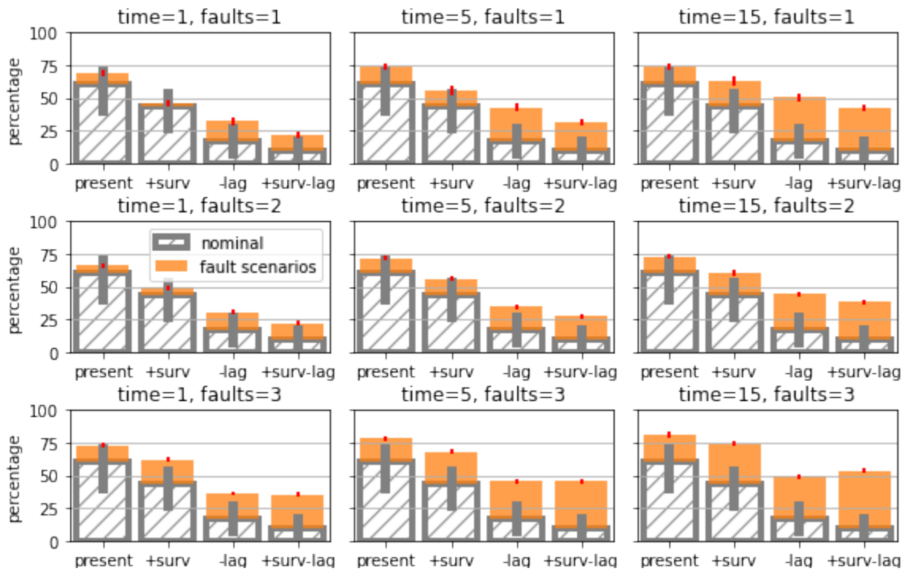


Figure 15. Effect of Communications Faults (at varying levels of impact) on injuries over designs.

Figure 15 and Figure 16 show the effects of increased surveillance and decreased communications lag on the resilience of the response to communications faults in terms of operator injuries and fireline breaches in nominal and faulty scenarios. As shown, surveillance and decreased lag makes the response more able to handle communications errors at all levels of impact. Additionally, the reduction of injury rate between the combined design and the "present" design is robust to all types of communications errors—meaning that even if this design had persistent communications errors (as modelled), on average the design would still lower the injury rate due to the increase in state awareness. While the effect on breaches is similarly positive, it should be noted that, for high-faults (i.e.., >15 time-step communications faults in >3 assets), the generality of this effect is lost, meaning that the faulty scenario performance in the improved design becomes worse than the nominal performance of the "present state" design. This is an important consideration for the design of new technologies—while new communications technologies can (in theory) increase information throughput (see: [1]), they need to be reliable enough to avoid introducing high-impact communications errors, which could negate their performance advantages.

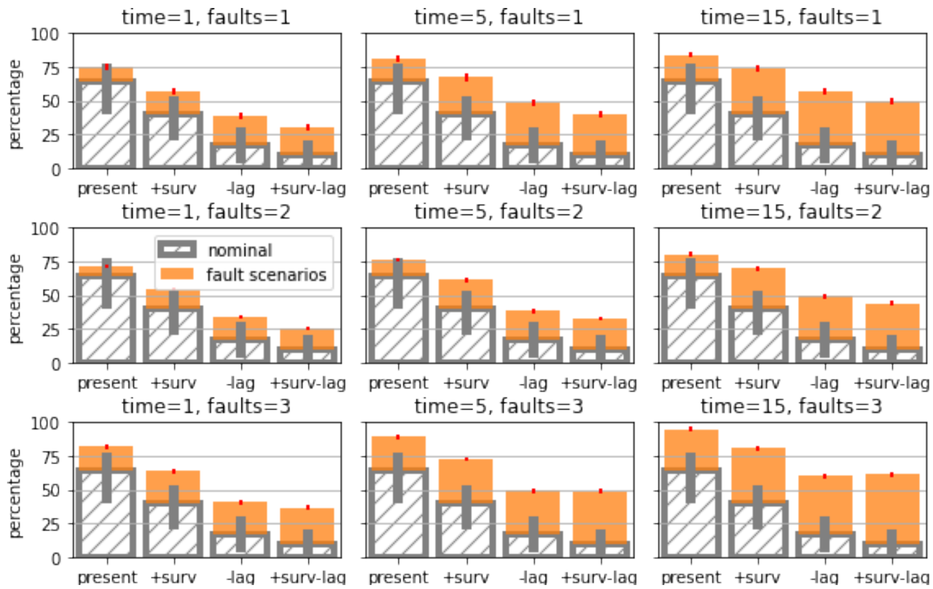


Figure 16. Effect of communications faults (at varying levels of impact) on fireline breaches over designs.

Example 2: Changing Winds and Flammability

The wind conditions and the flammability can play significant role in fire difficulty and the resulting response. These conditions continue to change during a fire depending on the fire conditions and weather. Wildland fires can have their own micro weather, which needs to be accounted for in the fire response. Thus, it is important to consider these factors in the resilience modeling of wildland fire response. In this example, we explore how changing wind conditions and flammability affect the fire response with and without the proposed technological improvements. Specifically, we study 5 scenarios involving changes to the wind conditions and flammability using the SMARt-STEReO model without any technological mitigations and with increased surveillance and communication throughput.

1. *Nominal:* This is the default scenario that will be used as a benchmark. In the SMARt-STEReO model, flammability is captured by a parameter that dictates the average time it takes for the fire to transition to the next grid point in the map. In this scenario, it is maintained at five timesteps while the wind is set to zero.
2. *Increasing Flammability:* During fires, the flammability can increase due to reasons such as dry weather spells. This scenario aims to capture such instances. In this scenario, no wind is present, the average time for a grid point to ignite (flammability) is set to 5 timesteps at the beginning and decreased by 30% and by an additional 50% at t=10 and t=30, respectively.
3. *Decreasing Flammability:* This scenario aims to capture instances where factors like rain cause the flammability to decrease during a fire. No wind is present, and the flammability (average time for a grid point to ignite) is set to 5 timesteps at the beginning of the fire, and the average time is increased by 80% and then by another additional 60% at t=10 and t=30, respectively, resulting in decreasing flammability.
4. *Change in Wind Direction:* Wind conditions continue to change during fires due to micro and macro weather conditions. This scenario aims to capture a scenario where the wind direction changes from 0 degrees to 80 degrees at t=10 while the wind speed stays constant at 1 m/s. Flammability is maintained at a constant 5 timesteps.
5. *Changing Wind and Flammability:* Wind and flammability are highly dependent. For example, a dry wind spell can increase flammability, while a rainstorm can decrease it. As a result, it is important to study their combined effects and how the technological

mitigations affect the fire response in such scenarios. This scenario aims to capture a rain scenario where the wind speed and direction change while the flammability decreases. At t=0, the wind is set to 0 m/s heading 0 degrees, at t=8, the wind is set to 1 m/s heading 45 degrees, and at t=28, the wind is set to 4.5 m/s heading 160 degrees. Flammability starts at 5 timesteps and decreases like in scenario 3.

While the fmdtools toolkit can represent more detailed dynamic wind and flammability models and their dependencies (e.g., dry wind increasing flammability), the representation in this assessment uses a simple model of discrete changes in these conditions. Since the goal here is to understand the resilience of wildland firefighting with the proposed technological advancements (increased surveillance and communications throughput) in general and not individual fire responses, the computational costs of detailed models may outweigh the benefits of insights gained. Also, the wind speeds are chosen to be low because higher values would result in a breach in very little time because the area of the grid is small (4 square kilometers), leaving no room to study how these conditions evolve over time. In general, the values for the flammability and wind variables were chosen in a way to make sure that they will have a noticeable (and reasonable) impact on the simulation results (given the grid size and model setup), while representing the natural phenomenon that cause the changes at a low fidelity. Using this experimental setup, we examine the fire responses using each technological mitigation strategy in each operational scenario over hundred randomly generated fuel distributions (referred to as replicates). We aim to understand if the technological advancements have improved the fire response in the operational scenarios studied when compared to no technological advancements and nominal operations.

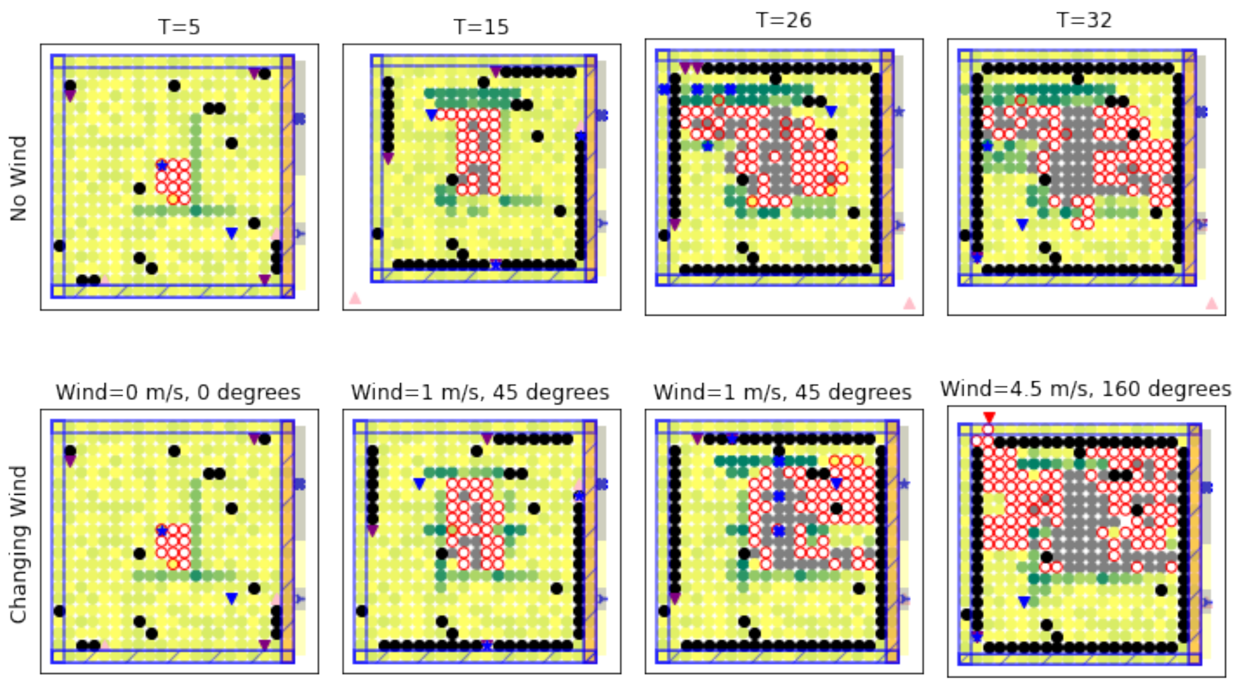


Figure 17: Fire progression at t = 5, 15, 26, and 32 for fires occurring on identical grids with no wind and changing wind conditions.

An example fire progression on identical maps with and without wind is shown in Figure 17. As shown, the fire progression is similar until the wind conditions change. In this example, the fire difficulty increases with the changing wind conditions, resulting in a breach (as shown at t =32), while the fireline is completed when there is no wind. Also, the differences in fire spread direction (it spreads more to the west with no wind and towards northeast and then towards northwest with changing wind) and the resulting response (differences in retardant drops and asset locations as seen with the *dark green* and *blue* markings in the map) are evident at t = 15, 26, and 32. While the change in wind conditions increased the fire difficulty in this example, at times, it may affect the fire response positively given the right conditions. In fact, for scenario 3 (where the wind direction changes at t=10), the changing wind improved the response (i.e., simulations that resulted in breaches with no wind but resulted in completed firelines with changing wind conditions) on 7 of the 100 randomly generated replicates (fuel distributions) while it had a negative impact on 42 replicates.

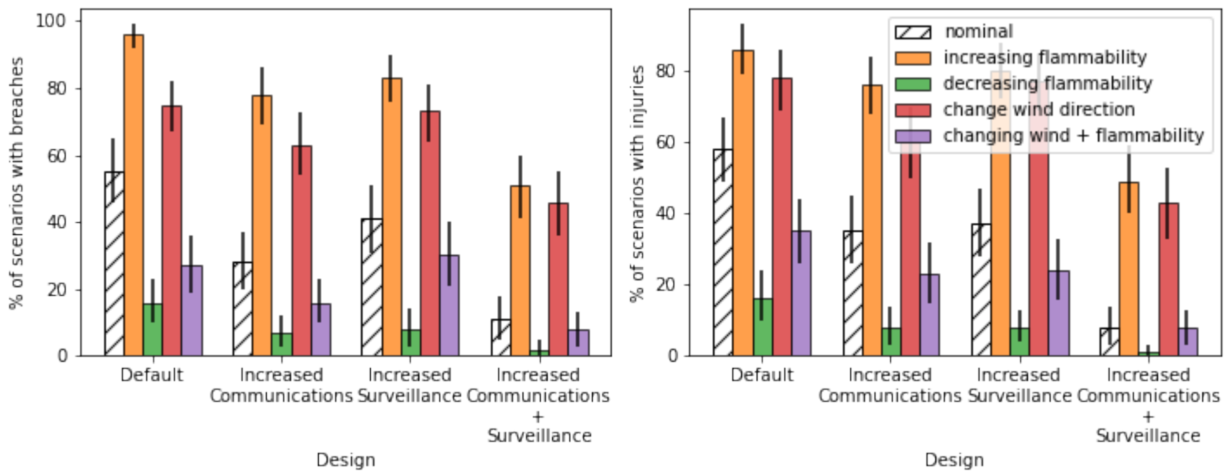


Figure 18: Percentage of the 100 replicates with breaches (left) and injuries (right) across the four design mitigations and five scenario variations involving changing winds and flammability.

As seen on the left in Figure 18, the percentage of replicates that resulted in breaches varied significantly across the different operation scenarios (i.e., decreased in the case of decreased flammability and changing wind and flammability, and increased for the rest). This shows the variability in the fire difficulty and the resulting response to changing wind and flammability and the importance of considering them in the hazard assessment of the technological mitigation strategies. The percentage of simulations that resulted in breaches decreased in simulations with technological mitigation strategies (increased communications, surveillance, and both) compared to the default response strategy (with no technological mitigations). When used individually, the reduction in breaches was higher for increased communications when compared with increased surveillance across all five operational scenarios (e.g., for increased flammability, 78% of replicates resulted in a breach with increased communications, whereas 83% resulted in a breach with increased surveillance). However, the reduction in the percentage of scenarios that resulted in a breach was significantly higher when these two mitigation strategies were combined. For example, for changing wind direction, 75%, 63%, 73%, and 46% of the replicates resulted in breaches for default, increased communication, increased surveillance, and combined technological mitigations, respectively. One outlier here is when changing wind and flammability are present, the percentage of simulations that result in breaches was higher for increased surveillance (30%) than the default configuration (27%). The increased complexity in the operational condition (changing wind and flammability when compared to wind or flammability changing alone) resulted in the risk of incorporating increased surveillance overcoming the benefit of the new technology, resulting in a higher percentage of replicates resulting in a breach. In general, these results show that the technological mitigations improved the firefighting capacity (especially when they are combined) across all operating conditions. The exception in the changing wind and flammability scenario with the increased surveillance shows the importance of weighing the risks versus benefits when introducing new technologies for wildland firefighting and the ability of fmdtools to help pinpoint them.

Like the percentages of breaches, the percentages of replicates with injuries vary with changing wind and flammability conditions (decreased with decreasing flammability and changing wind + flammability and increased with the rest, as seen on the right in Figure 18). The average injuries per replicate (as seen in Table 10) are consistent with the breach percentages in terms of how they compare with the nominal operating scenario. However, when comparing the design mitigation strategies, it is evident that the technological improvements reduced the percentage of scenarios with injuries and the average number of injuries per replicate. For example, the percentage of breaches is 16%, 8%, 8%, and 1% for default, increased communication, increased surveillance, and combined technological mitigations, respectively, for the decreasing flammability operating scenario, while the average injuries are 1.53, 0.79, 0.83, and 0.31, respectively. The percentage of scenarios with injuries decreased more with increased communications when compared to increased surveillance. However, the average number of injuries was somewhat variable (i.e., it was lower for increased surveillance during increasing flammability and decreasing flammability conditions and higher during the remaining conditions, as seen in Table 10). However, when these mitigations were combined, the percentage of breaches and the average number of injuries were significantly lower when compared to the rest of the mitigations. These results show that the proposed technological mitigations not only improve firefighting capacity but also safety and risk by minimizing injuries.

Table 10: Averages and 95% confidence intervals for number of injuries across the four design mitigations and five scenario variations relating to changing wind and flammability

Model	Default	Increased Communications	Increased Surveillance	Increased Communications + Surveillance
nominal	1.53 (1.036, 2.024)	0.79 (0.33, 1.25)	0.83 (0.412, 1.248)	0.31 (-0.581, 1.201)
increasing flammability	2.33 (1.989, 2.671)	2.01 (1.597, 2.423)	1.85 (1.519, 2.181)	1.17 (0.695, 1.645)
decreasing flammability	0.34 (-0.105, 0.785)	0.18 (-0.403, 0.763)	0.16 (-0.252, 0.572)	0.01 (-0.185, 0.205)
change wind direction	1.26 (1.03, 1.49)	0.92 (0.681, 1.159)	1.21 (0.988, 1.432)	0.69 (0.366, 1.014)
changing wind + flammability	0.74 (0.344, 1.136)	0.35 (0.048, 0.652)	0.53 (0.083, 0.977)	0.16 (-0.374, 0.694)

Example 3: Multiple Ignition Points and Smoke

Combinations of two or more hazardous environmental factors can elevate the difficulty level of a fire incident. In this example, we examine how multiple ignition points and smoke impact the simulation model with and without the proposed mitigation strategies. This environmental scenario is inspired by the CZU Lightening Complex incident [27], which began August 16th, 2020, from a series of lightening-ignited fires and was contained September 22nd, 2020. Throughout the incident, 86,905 acres were burned, and 1,490 structures were destroyed. Fires ignited in multiple locations throughout the Santa Cruz mountains on the California central coast, with some fire ignition locations recognized later than others. Early in the fire, the incident management team faced difficulties with inaccessible terrain and dense smoke. Aircraft were grounded for at least a full day due to high risk from smoke. In this scenario, UAS with advanced sensors could have increased firefighting capacity by supplementing aerial operations to provide surveillance on the fire location and spread through smoke.

To demonstrate the use-case of the SMARt-STEReO model, the proposed technology-based mitigation strategies of UAS for surveillance and increased communications throughput are examined in a scenario with multiple ignition points and smoke. Four cases are examined:

1. *Nominal:* one ignition point and non-impactful smoke
2. *Multiple Ignition points*: three ignition points and non-impactful smoke
3. *Smoke*: one ignition point with a hazardous amount of smoke
4. *Multiple Ignition points and smoke*: three ignition points with a hazardous amount of smoke

This experimental design can analyze each mitigation strategy's unique impact on each operational scenario, resulting in a 4 (mitigation levels) x 4 (operational scenario levels) analysis. Parameters for this analysis are defined in Table 9. While the size and resolution of the simulation is not comparable to the CZU fire, the effectiveness of the mitigation can still be evaluated in these difficult operational scenarios by comparing outputs to nominal scenarios with default operations (i.e., without technological mitigations). Example simulation progressions comparing a single ignition fire to a multiple ignition fire with identical grids are shown in Figure 19. From Figure 19, the difference in fire difficulty level is clear, with the multiple ignition point scenario resulting in more fire spread at all three times. Hence, fires with multiple ignition points are more difficult to contain. Single vs multiple ignition point scenarios also impact the amount of smoke and smoke spread, visible in Figure 20. Multiple ignition fires have both greater smoke density and smoke volume when compared to a single ignition fire.

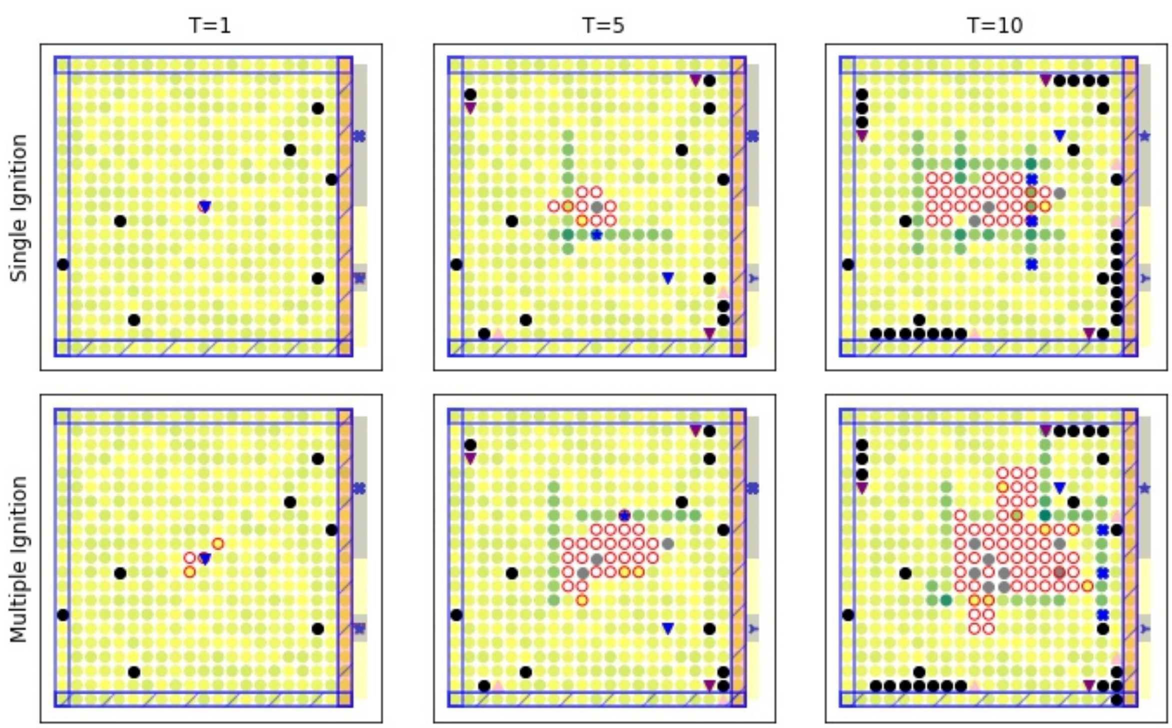


Figure 19: Fire progression at T=1, T=5, and T=10 between single (top) and multiple (bottom) ignition fires. Both fires occur on identical grids.

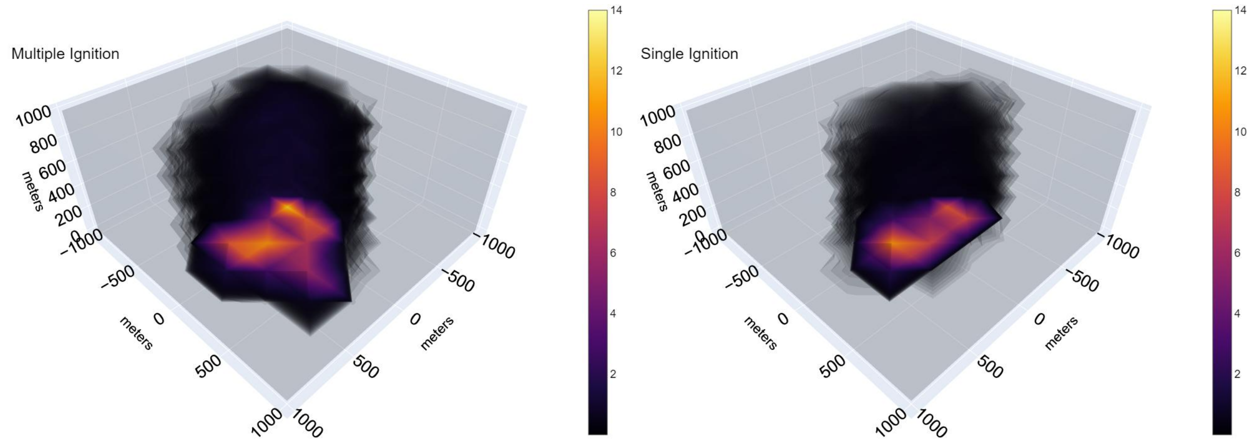


Figure 20: Smoke density and spread between single (right) and multiple (left) ignitions at T=10.

Each combination of design mitigation and operational scenario is simulated over the same 100 randomly generated fuel distributions. The percent of simulations with fire line breaches and with injuries is displayed in Figure 21. On the left, nominal scenarios (single ignition, no smoke) have the lowest percent of simulations with breaches (55%) with the default design and across the four design mitigations. The addition of smoke increases breaches in comparison to the nominal scenario (66%), while multiple ignition points have even more breaches (92%). In contrast, scenarios with both smoke and multiple ignitions have the greatest percent of simulations with breaches (98%). Increased communications greatly reduce the percentage of scenarios with breaches in nominal cases (26%) and when smoke is present (35%), with a more modest improvement in scenarios with multiple ignitions (64%) and both multiple ignitions and smoke (78%). Increased surveillance also improves results from the default design across operation scenarios, although the impact is slightly less than that of increased communications. With increased surveillance, multiple ignitions (87%) result in marginally more breaches than multiple ignitions with smoke (85%). While it is expected that the scenario with both conditions would result in more breaches, the difference is marginal with overlapping confidence intervals. The slight difference may be due to increase surveillance information, along with a communications lag, and no smoke resulting in higher risk operational decisions. That is, crews could be sent into areas of fast spreading fire identified by enhanced surveillance with stale information. Note that with increased surveillance, there are also more simulations with injuries in the multiple ignition scenario than multiple ignitions alone and the two are likely linked – more surveillance information that is delayed causes more risky decisions, which in turn result in injuries and a less effective response. Ultimately, the multiple ignitions and smoke scenario becomes nearly identical to the multiple ignitions scenario under increased surveillance, suggesting that increased surveillance eliminates the negative impact of smoke. When both increased surveillance and increased communications are considered, scenarios with smoke (5%) result in about as many breaches as the nominal scenario (8%). The percent of simulations with breaches in cases with both smoke and multiple ignition points is reduced to 53%, which results in 45% fewer scenarios with breaches when compared to the scenario with no mitigations. The design mitigations, and specifically cases with both increased communications and surveillance, decrease the number of scenarios with fireline breaches across operational variants. Thus, the proposed mitigations increase firefighting capacity by making a larger number of scenarios possible to suppress, especially in difficult to contain operational environments with multiple ignition points and smoke.

Similar results are seen with injuries in the graph on the right in Figure 21. The default design without technological mitigations results in the greatest percentage of simulations with injuries across scenarios, while the increased communications and surveillance mitigation results in the smallest percentage of simulations with injuries. With no mitigations, the nominal scenario has the least simulations with injuries (57%). Simulations with smoke have more simulations with injuries (75%), followed by multiple ignitions (80%), and multiple ignitions with smoke (90%). When compared to the default, increased communications throughput or increased surveillance alone results in almost half as many simulations with injuries in the nominal (31%, 36%) and smoke (33%, 49%) scenarios. These mitigations alone also have an impact on scenarios with multiple ignitions, along with multiple ignitions and smoke, although the impact is less pronounced. While increased communications or increased surveillance alone do decrease the percent of simulations with injuries across the scenarios, the most improvement comes from the combination of both mitigations. The percentage of nominal (3%) and smoke (7%) simulations with injuries is reduced to less than one-tenth the number of injuries in simulations with no mitigations. Similarly, multiple ignition scenarios (41%), as well as multiple ignitions with smoke (42%), have over 40% fewer simulations with injuries than in cases without mitigations. Hence increased communications and surveillance also increase operational safety and improve risk in hazardous operational environments through decreased injuries, in addition to increased firefighting capacity.

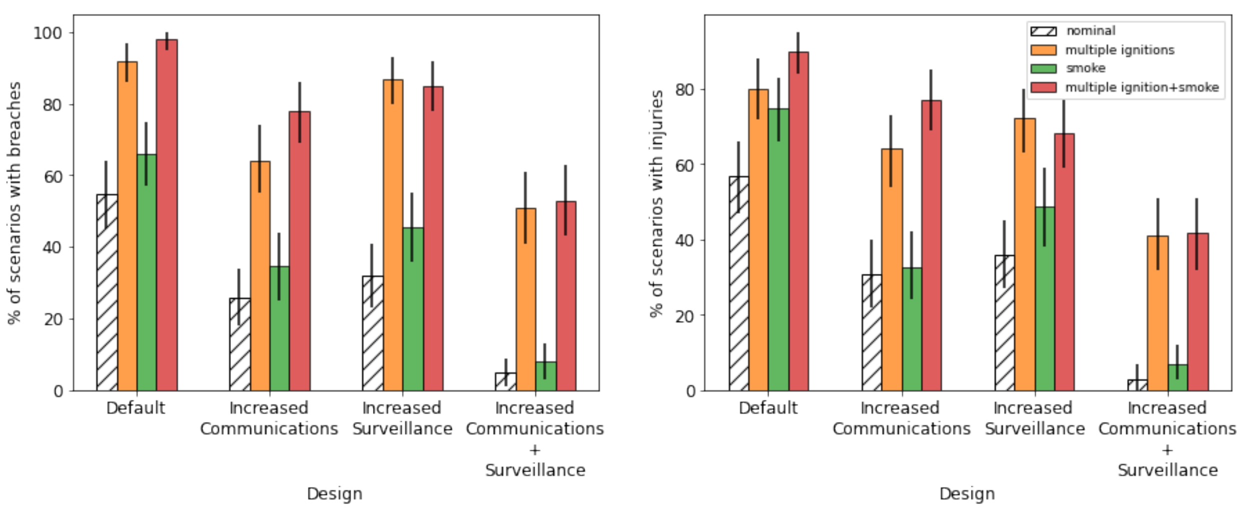


Figure 21: Percent of the 100 replicates with breaches (left) and injuries (right) across the four design mitigations and four scenario variations involving multiple ignition points and smoke.

The average number of injuries, fire line completion time, and fireline breach time per scenario is calculated in each case over the simulations and shown in Table 11. Notably, the nominal scenario results in the fewest injuries (1.46) and slowest breach time (t=35.982) on average in the default design, while all operational scenarios report similar fireline completion times. The most difficult operational scenario with both multiple ignition points and smoke results in the greatest number of injuries (2.36) and the fastest breach time (t=23.316) with no mitigations. However, once increased communications and surveillance mitigations are implemented, the number of injuries in the multiple ignition and smoke scenario drops to 0.91 injuries on average, which is less than the nominal scenario with no mitigations. Thus, the design mitigations increase safety in difficult operational scenarios to a degree that is comparable to nominal scenarios with no mitigations. Simultaneously in this scenario, the average fireline breach time increases to approximately thirty-one timesteps and the average fireline completion time decreases to about thirty-two timesteps. The mitigations decrease injuries, decrease fireline completion time, and increase fireline breach time across all operational scenarios. In turn, the proposed mitigations may allow for faster fireline completions and fewer injuries not only in nominal scenarios, but also scenarios with challenging operational environments involving multiple ignition points and smoke.

Table 11: Averages and 95% confidence intervals for number of injuries, completion time, and breach time across the four design mitigations and four scenario variations.

Metric	Scenario	Default	Increased Communications	Increased Surveillance	Increased Communications + Surveillance
Number of Injuries	*nominal*	1.46 (0.988,1.932)	0.58 (0.187,0.973)	0.68 (0.302,1.058)	0.05 (-0.285,0.385)
	multiple ignitions	1.90 (1.568,2.232)	1.54 (1.143,1.937)	1.57 (1.221,1.919)	0.99 (0.488,1.492)
	smoke	1.66 (1.33,1.99)	0.57 (0.18,0.96)	0.92 (0.585,1.255)	0.16 (-0.293,0.613)
	multiple ignition + smoke	2.36 (2.017,2.703)	1.74 (1.42,2.06)	1.64 (1.214,2.066)	0.91 (0.474,1.346)
Fireline Completion Time	*nominal*	36.156 (33.983,38.328)	34.527 (32.842,36.212)	35.103 (33.804,36.402)	34.568 (33.128,36.008)
	multiple ignitions	35.625 (31.392,39.858)	33.5 (31.348,35.652)	32.692 (30.763,34.622)	31.735 (30.65,32.819)
	smoke	36.265 (33.88,38.65)	33.785 (32.136,35.433)	34.833 (33.293,36.374)	34.826 (33.313,36.339)
	multiple ignition + smoke	37.5 (24.825,50.175)	35.864 (32.057,39.67)	33.933 (31.273,36.594)	31.915 (30.82,33.01)
Fireline Breach Time	*nominal*	35.982 (32.308,39.656)	32.385 (27.959,36.81)	30.875 (25.962,35.788)	43.2 (33.501,52.899)
	multiple ignitions	25.587 (23.288,27.886)	28.906 (25.545,32.268)	25.874 (23.556,28.191)	30.176 (26.813, 33.54)
	smoke	29.773 (27.239,32.307)	35.886 (30.552, 41.22)	32.043 (28.178,35.909)	46.875 (36.141,57.609)
	multiple ignition + smoke	23.316 (21.675,24.958)	28.179 (25.144,31.215)	24.588 (22.117,27.06)	31.057 (27.659,34.455)

Summary/Insights

These examples were presented to show the potential improvements of decreased communications lag and increased surveillance to wildfire response. As shown, both of these improvements increase the proportion of scenarios where the fire is contained while also decreasing the number of scenarios with injuries. In general, communications improvement increases firefighting capacity, resulting in a major reduction in breaches, while surveillance increases ground crew state awareness, resulting in a more pronounced reduction in injuries. The most improvement is seen when both improvements are present at the same time, with large reductions in both injury and breach scenarios compared to the present-state design. As shown in each example these performance improvements are robust to modelled fault modes, except for Aerial Supervisor Immobilization faults, which are too severe for an effect on containment to be made (see Figure 12 and Figure 13). Furthermore, while some faults still have high impact over all designs, such as Tanker faults (Figures 10-13) and long-duration communications faults (Figure 15 and Figure 16), there is still a marked reduction in injury and breach scenarios with decreased lag and increased surveillance. We conclude on the Example 1 that decreased communications lag and increase surveillance increase fault resilience, making hazardous outcomes (in terms of fireline breaches or injuries) less likely by (1) better positioning the response prior to the fault mode occurring (2) increasing firefighting capacity, making the existing response more likely to contain the fire (even when a fault occurs), and (3) increasing state awareness, making it easier for assets to evade approaching fires. However, while most equipment modes only affect individual assets (and thus have limited impact), large-scale communications faults with the potential to immobilize multiple assets at once can still significantly impact operations—to the point of negating performance improvements. Since the prevalence of these faults was not able to be evaluated in this model, it may be necessary to study how likely they are to occur using different technologies to ensure that technological improvements do not increase overall risk. By studying this prevalence, communications and surveillance improvements can be designed to prevent outages it might otherwise be prone to (e.g., by providing redundant communication paths or using technology not prone to interference).

As with fault mode resilience, the modelled technological mitigation strategies contribute to the resilience of the firefighting response by increasing firefighting capacity. As a result, Examples 2 and 3 show there is reduced potential for fireline breaches in varying external circumstances (i.e., smoke, multiple ignition points, changing wind conditions, changing flammability, and some combinations of these). Similarly, the increased communications and surveillance, as modelled (individually and in combination with surveillance), reduced the number of injuries across operating conditions (see Figure 18 and Figure 21), resulting in increased safety. The greatest improvements were seen when increased communications and surveillance were implemented together (see Figure 18 and Figure 21). When increased surveillance was implemented by itself, one operating condition (changing wind and flammability) saw a reduction in fireline completions, and the rest of the conditions saw modest improvements (see Figure 18 and Figure 21). Thus, if increased surveillance is to be chosen as a potential technological improvement, it should be implemented with increased communications to ensure that it does not increase the risk of fireline breaches and that the greatest improvements are realized.

Tool Limitations and Usage Considerations

MIKA outputs can support traditional hazard analysis and expert identification of hazards by automatically discovering hazards from incident reports. Hazards identified using MIKA are extracted from historical reports, and therefore, MIKA analyzes only the documented existing system state. At this stage, MIKA provides descriptive rather than predictive analysis and thus cannot analyze how risk changes throughout and across a single operation. It is always necessary for a human expert to interpret and assess the completeness of MIKA's results, as is the case with most natural language processing applications. Whenever there is high-quality data in natural language format, it may be reasonable to apply MIKA to augment normal hazard analysis activities. Depending on the novelty of the system and the quality of the data, the value of the results may vary. MIKA is likely to be most effective in systems without highly novel technologies and with extensive, diverse, and relevant data sets available. Regardless, as standard hazard analysis tends to rely heavily on expert input, MIKA has the potential to reduce human expert workload, of which the amount may vary, and reduce the risk of *not* identifying hazards that have already been identified in past incidents. Because human experts may exhibit bias, MIKA can supplement experts by concentrating on data-driven findings.

The SMARt-STEReO model developed in fmdtools is a high-level simulation of wildfire response. In this report, it was used to (1) provide a conceptual understanding of how hazards arise in wildfire response and (2) evaluate the effectiveness of improved surveillance and communications, both separately and as a combined measure. However, these analyses are limited in terms of scope and fidelity by the assumptions of the model (e.g. fire propagation, mechanisms for injuries, environment and fuel distributions, lack of vehicle conflicts, etc.—See "SMARt-STEReO Model Description"). Improved surveillance and communications are only a few changes which are being considered for wildfire response, with other changes including (1) pilot automation (2) a variety of missions for conventional UAVs and (3) improved aircraft safety management enabling coordination between UAVs and conventional aircraft (i.e., an IASMS).

Additionally, the model presently lacks the ability to model airspace conflicts which arise when placing UAVs in proximity with conventional aircraft. As a result, while it can model many aspects related to wildfire response, it has not yet been developed to represent the unique challenges related to technology introduction in aerial firefighting, such as airspace deconfliction.

Summary of Findings and Recommendations

The MIKA tool identifies hazards listed in Tables 4-8 and performs a data-driven risk analysis for each hazard, including effect, likelihood, severity, and overall risk. The only operational hazards categorized as high risk are Evacuations, yet many other hazards are categorized as serious. These high and serious-risk hazards not only effect response personnel, but also civilians at the wildland urban interface. Emerging operations and technology-enabled hazard mitigations can be designed with these considerations in mind. In contrast, the only manned aerial operations hazard categorized as high risk is Jumper Operations Mishap. This is primarily because most frequently occurring aerial operations hazards carry low severity of consequences. No unmanned aerial operations carry high risk in this scenario because their severity is lower due to the unmanned nature. That is, injuries and fatalities from unmanned aerial operations would only occur if a UAS impacted other operations or persons on the ground, which is very unlikely in a remote firefighting scenario. For ground crew operations, high risk hazards are Burns, Cargo Operations Overhead, Dehydration, Entrapment, Falling Objects, Heart Attacks, Heat Exhaustion, Inadequate Training or Certification, Vehicle Breakdown, and Vehicle Collision. There are more high-risk hazards for ground crew operations due to the greater potential for injury should a hazard occur.

The SMARt-STEReO model developed in fmdtools models the ability of response assets (ground crews, tankers, the incident commander etc.) to contain a fire. As presented in "Understanding Wildfire Hazard Dynamics," there is a narrow band of wildfire scenarios where the fire may be contained using firefighting techniques. Within this band, containment failure can occur when the firefighting scenario is too difficult for the firefighting capacity of the assets (e.g., because it spreads too quickly or because there are not enough assets). These containment failures not only constitute an operational failure; they can also lead to hazards for the ground crews. Additional safety effects occur because of circumstances not foreseen by the operators (e.g., a change in the windspeed or direction) or defined faults (e.g., equipment faults).

This model was then used to evaluate the potential improvements to communications and surveillance. Based on this comparison, we conclude that increased surveillance has the ability to increase ground crew safety by giving ground crews better information regarding approaching fires. Additionally, the simulation showed that decreased communication lag increases firefighting capacity by giving incident commanders more timely information, resulting in better (and faster) aerial drop and fireline locations. When combined, communications and surveillance improvements further had a synergistic effect, resulting in much fewer injuries and fireline breaches than otherwise. These improvements are robust to equipment faults as well as externally driven hazardous events. However, large-scale, long-duration communications faults may be an issue if they become frequent. Thus, any future communications technology used in wildfire response should be developed to prevent high-impact communication faults.

References

[1] J. Mercer, R. Mcswain and C. Ippolito, "Scalable Traffic Management for Emergency Response Operations (STEReO)," in *AIAA Aviation 2020*, Reno, NV, 2020.

[2] P. Kopardekar, J. Rios, T. Prevot, M. Johnson, J. Jung and J. E. Robinson, "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," in *AIAA Aviation and Aeronautics Forum (Aviation 2016)*, Washington, DC, 2016.

[3] FAA, "Safety Management Systems for Aviation Service Providers," US Department of Transportation, Washington, DC, 2015.

[4] NASA, "NASA General Safety Program Requirements," NASA, Washington, DC, 2021.

[5] NASA, "Expanded Guidance for NASA Systems Engineering Volume 1: Systems Engineering Practices," NASA, Washington, DC, 2016.

[6] S. Andrade and H. Walsh, "Knowledge Discovery for Early Failure Assessment of Complex Engineered Systems Using Natural Language Processing," in *2021 ASME International Design Engineering Technical Conference and Computers & Information in Engineering Conference*, Virtual, 2021.

[7] D. Hulse, H. Walsh, A. Dong, C. Hoyle, I. Tumer, C. Kulkarni and K. Goebel, "fmdtools: A Fault Propagation Toolkit for Resilience Assessment in Early Design," *International Journal of Prognostics and Health Management,* vol. 12, no. 3, 2021.

[8] S. R. Andrade and H. S. Walsh, "Machine Learning Enabled Quantitative Risk Assessment of Aerial Wildfire Response," in *AIAA Aviation Forum*, 2022.

[9] S. R. Andrade and H. S. Walsh, "Wildfire Emergency Response Hazard Extraction and Analysis of Trends (HEAT) through Natural Language Processing and Time Series," in *IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 2021.

[10] D. Hulse, S. Andrade, E. Spirakis, H. Walsh and M. Davies, "SMARt-STEReO: Preliminary Model Description," NASA, 2020.

[11] S. R. Andrade and D. E. Hulse, "Evaluation and Improvement of System-of-Systems Resilience in a Simulation of Wildfire Emergency Response," *IEEE Systems Journal,* 2022.

[12] H. Walsh, E. Spirakis, S. Andrade, D. Hulse and M. Davies, "SMARt-STEReO: Preliminary Concept of Operations," NASA, 2020.

[13] U.S. Forest Service Fire and Aviation Management, "2019 Aviation SMS Guide," 2019.

[14] D. E. Calkin, C. D. O’Connor, M. P. Thompson and R. Stratton, "Strategic Wildfire Response Decision Support and the Risk Management Assistance Program," *Forests,* vol. 12, no. 1407, 2021.

[15] NWCG Operations and Workforce Development Committee, "Wildland Fire Incident Management Field Guide," National Wildfire Coordinating Group, 2013.

[16] S. R. Andrade and H. S. Walsh, "What Went Wrong: A Survey of Wildfire UAS Mishaps through Named Entity Recognition," in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, 2022.

[17] S. Andrade and H. Walsh, "Discovering a Failure Taxonomy for Early Design of Complex Engineered Systems Using Natural Language Processing," *Journal of Computing and Information Science in Engineering (JCISE),* 2022.

[18] L. A. St. Denis, N. P. Mietkiewicz, K. C. Short, M. Buckland and J. K. Balch, "All-hazards dataset mined from the US National Incident Management System 1999–2014," *Scientific Data,* 2020.

[19] G. White, "Evaluation of systems to recognise and address safety issues promptly, effectively and universally and evaluation," Department of Natural Resources and Environment, 2002.

[20] U.S. Forest Service, "Operational Risk Management Guide," 2020.

[21] FAA, "Safety Risk Management Policy Order 8040.4B," U.S Department of Transportation, Washington, DC, 2017.

[22] Flight Safety Foundation, "Looking to the Future: Safety System Needs for Humanitarian UAS Operations," 2021.

[23] S. J. Hook, J. J. Myers, K. J. Thome, M. Fitzgerald and A. B. Kahle, "The MODIS/ASTER airborne simulator (MASTER)—A new instrument for earth science studies," *Remote Sensing of Environment,* vol. 76, pp. 93-102, 2001.

[24] V. Ambrosia and T. Zajkowski, Selection of Appropriate Class UAS/Sensors to Support Fire Monitoring: Experiences in the United States, New York: Handbook of Unmanned Aerial Vehicles, 2015.

[25] E. S. Chang and M. Shinozuka, "Measuring improvements in the disaster resilience of communities," *Earthquake spectra,* vol. 20, no. 3, pp. 739-755, 2004.

[26] L. Shen, B. Cassottana, H. R. Heinimann and L. C. Tang, "Large-scale systems resilience: A survey and unifying framework," *Quality and Reliability Engineering International,* vol. 36, no. 4, pp. 1386-1401, 2020.

[27] Calfire, "CZU Lightning Complex (Including Warnella Fire) Incident," August 2020. [Online]. Available: https://www.fire.ca.gov/incidents/2020/8/16/czu-lightning-complex-including-warnella-fire/. [Accessed 2022].

[28] P. L. Andrews and R. C. Rothermel, "Charts for Interpreting Wildland Fire Behavior Characteristics," US Department of Agriculture, Ogden, UT, 1982.