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REGULAR PAPER

# Flight performance analysis of aerial fire fighting

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**Abstract**
This paper investigates the operational patterns and techniques of aerial fire fighting. It is demonstrated that manoeuvrability and endurance are the main characteristics when choosing air tactical aircraft; focus is on load capability for helicopters and air tankers. Water tank filling and deployment techniques are evaluated. Aircraft using pressure deployment systems are found to produce more uniform and heavy coverage in comparison with gravity systems. ADS-B open source data of flight operations and performance was collected. Operational patterns are found to be independent on the size of particular aircraft category (non-amphibious and amphibious air tanker, helicopter, air-tactical aircraft). Effectiveness and cost are modelled using the retardant dropped per operation and the average number of daily missions. The largest aircraft, Type-I helicopters and very large air tankers (VLAT) are found to be the most effective water- and retardant-dropping aircraft. The best cost-to-litre-dropped ratio for water-dropping aircraft is attributed to Type-III helicopters and amphibious Type-III aircraft; for retardant-dropping aircraft, VLAT are most effective. To maximise fire fighting effectiveness, Type-I helicopters and VLAT should be used as far as possible, with pressure deployment systems.

## 1.0 Introduction

The phenomenon of wildfires have been studied by a variety of disciplines. Almost every field has its own definition. Some of them do not have quantitative thresholds regarding fire intensity, size, behaviour and impact. They are influenced by the distribution of fire sizes within each region or eco-region, geographical conditions and landscape vegetation [1]. A wildfire is defined as *a fire that is burning strongly and out of control on an area of grass, bushes or forest in the countryside*.

Even though wildfires can be natural phenomena, there is a significant increase in their occurrence and intensity due to human activities. This includes both major causes such as increased greenhouse gases emission from industrial processes, as well as activities on a smaller scale, such building next-to or within forests, uncontrolled deforesting using fire [1], or outright arson.

Extreme heat waves are five times more likely to occur now than 150 years ago; the likelihood is constantly increasing due to the phenomenon called fire-climate feedback loop: higher temperatures make the environment drier, allowing fires to burn longer and with greater intensity, leading to higher emission from forest fires. The situation is most critical in northern high-latitude boreal regions, which are warming at a faster rate as compared to the rest of the planet. This leads to extended fire seasons, increased fire frequency and severity, and hence larger burned areas. Over the past 20 years, the fire-related tree cover loss increased by a rate of about 3% per year, which constitutes about half of the total global increase [2].

Whilst some countries have always been prone to wildfires due to their geographic location and environmental features, others have started to experience this problem in the recent years. For some places, wildfires are a very recent problem. This is mainly the case for Southern Europe and South America.

Wildfires in the United States are concerning mainly in the south-west, due to dry environment. California regularly experiences this problem in the summer. The wildfire season has lengthened in those areas due to warmer springs, longer summer dry seasons and drier soils and vegetation. Furthermore, earlier spring melting and reduced snowpack cause decreased water availability [3].

Trends and patterns show the rapidly increasing problem of wildfires worldwide, both in dry, hot areas such as California or Australia, but also in northern latitudes, such as Alaska or Russia. In the former regions, this phenomenon worsened recently due to global climate change. Human activities have led to critical increase in burnt area and constant fire-climate feedback loop.

The most important advantage of aerial fire fighting is the possibility to combat fire in inaccessible places, which is often the case of wildfires. This, combined with the possibility of quick arrival and greater tank capacity of air tankers and helicopters, as compared to fire trucks, improves the effectiveness of initial and direct attack on fires with intense behaviour. Current fire suppression goals for California focus on keeping 95% of all wildfires at <10 acres. The importance of initial attack is shown by Ref. [4], where it was found that initial attack reduces the mean study area burn probability by 78%, as compared to a no-suppression scenario. Initial attack was found to be the most effective in recently burned areas (86% reduction), whereas mature, contiguous fuels moderated its influence (50%).

Aerial fire fighting is dangerous and risky for the crew involved, as is shown by the records of aircraft crashes and incidents recorded. Aircraft-crew fatalities increase with aircraft operating in high-risk conditions and low altitudes [1], and are a sad occurrence. There are a few limited studies on the use of unmanned air vehicles (UAV), which is a promising new development [5].

There is little technical literature in peer-review publications. This field is dominated by online news and several national organisations that provide up-to-date operations, data, maps, risks and procedures. In Europe, the main source of real-time information is the European Forest Fire Information System (EFFIS), managed by the Joint Research Centre. The Copernicus satellite observation system provides additional environmental data, measurements and imagining, all in real-time.

Flight paths are shown on maps using Google Earth Pro and compared to fire maps to demonstrate operational patterns. We provide a selection of flight data for selected fire fighting missions. The methods rely on ADS-B data. These data have become widespread in recent years, and several services, commercial and open-source, are available to supply a variety of data that cover much of the developed world. Recently, the authors used ADS-B to evaluate aviation emissions, both on long-range [6] and commuter flights [7] using the *OpenSky* database. In this instance, data from *FlightRadar24* have been used.

## 2.0 Aerial fire fighting context

Aerial fire fighting saw an increase in 1950s, when a significant surplus of military aircraft was transformed into fire fighting air tankers [8]. The US was a leading country on air tanker conversion. The first US fire-fighting aircraft was the Boeing Stearman 75 (1955) adapted by fitting a ~640 litres tank with a hinged fire gate. One of the first air tankers tested was the Grumman TBF-1 *Avenger*, in which the tank doors were released using electric bomb shackles. Furthermore, the amphibious Consolidated PBY *Catalina* proved to be an excellent platform as an air tanker due to its long loiter time and its large capacity.

The most dramatic changes of aerial fire fighting took place in 1960s when all aircraft models, fire-fighting tactics and retardants were developed. Similarly, airframes of military aircraft were modified to provide a tanker platform, including the Grumman F7F, the North American B-25 and AJ-1, Douglas A-26 and the Consolidated PB4Y-2 [8]. Most notable introductions include two North American AJ-1s with tank capacity of ~9,100 litres (1960), followed by a number of Boeing B-17s with capacity of ~6,000 litres, and ten Grumman F7F-3 with tank capacity of ~6,800 litres.

In the 1970s, a number of new aircraft was introduced. The most notable conversions include the air tanker Douglas DC-4, DC-6 and DC-7 aircraft, with some of them still in use today. The twin-engine Grumman S-2A was chosen as the replacement for Grumman TBM. More modern versions of

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the Grumman S-2 are in service up to this date. Larger air tankers were developed, such as the Lockheed P2 *Neptune* with a total capacity of ~11,350 litres. Among air-tactical aircraft, the military observation aircraft Cessna O-2 has often been used. New fire retardant chemicals were introduced and fire infrastructure improved [8].

While the US was a pioneer in non-amphibious air tanker conversion, major development of amphibious aircraft took place in Canada. After years of testing, the modern scooper system was introduced: it consisted of a retractable scooping probe that filled tanks in the hull. Based on this concept, the first amphibious fleets were introduced, with De Havilland DHC-2 *Beaver* and DHC-3 *Otter*, and Martin JRM-3 *Mars* being the most notable ones. Another milestone was the introduction of the first ever aircraft designed for fire-fighting, namely the Canadair CL-215 with a capacity of ~6,350 litres. An improved model CL-415 (1993) is an important shared asset in several European countries, with primary users fire and rescue services in Italy, France and Greece.

After the 1970s, development of fire-fighting aircraft slowed down. However, new models were still converted and introduced; the most notable ones include the Boeing 747 Supertanker (retired in 2018), the Bell UH-1F helicopter (the workhorse of the California fire-fighting agency today), the De Havilland Dash 8 being the most recent conversion. Aside from national institutions, contracting of private companies with their own fleets became popular in 1990s and remains so in some countries.

### *2.1 Fire retardant deployment techniques*

Water is not the best retardant, as it is easily scattered by wind and evaporated by high temperatures. All resources regarding fire retardants and their deployment techniques (single drop, multi drop, Bambi basket) are used for comparison and determining performance improvements. Flight parameters have been investigated in a number of studies, for example Ref. [9]. Basic features of different retardants are reviewed by Ref. [10], including effectiveness, environmental aspects, as well as the types most suitable for any situation. Reference (11) provides a comparison of drop patterns made with different retardants whilst maintaining other parameters constant. Filling and deployment was described by Ref. [12].

There are many factors that affect the retardant drop on the fire. They are both aircraft-dependent (tank size, its geometry and internal baffling) and retardant-dependent (flow rate, volume and flow characteristics). There are several types of retardants used for aerial fire fighting; their use depends on the planned outcome. The four main types are: water, long-term retardants, gels and foams.

Water is the most obvious, cheapest and most easily obtained retardant. Thanks to the presence of open water sources, the aircraft does not need to return to the airport in order to refill, provided that it is equipped by a siphon (heli-tankers), bucket (helicopters) or is an amphibious aircraft and the water reservoir is large enough for it to skim on. However, water is ineffective as it evaporates in the air due to wind shear and fire-generated heat. Thus, it is rarely used for indirect attacks; it is useful for direct attacks to lower the intensity of the fire. Long-term retardants can only be refilled at the airport. They are used for indirect attack by non-amphibious air-tankers, and for protection of critical areas.

There are two techniques employed to perform a retardant drop: a pressurised jet can be used to force the retardant out of the tanks through nozzles at a constant flow or tank door can open and retardant will be pulled out using gravity forces. Increasing the drop height gradually widens the drop whilst decreasing the coverage levels. If the wind speed increases, the drop widens and reduces the coverage level [13]. The ground drop patterns are dependent on the properties of the retardant. Chemical retardants make the water denser and less susceptible to wind shear; a higher density fluid results in a lower flow rate.

## 3.0 Aircraft characteristics

Aircraft used for aerial fire fighting can be divided into three categories: air-tactical aircraft, air tankers and helicopters. Air-tactical aircraft refer to either fixed-wing or rotary-wing aircraft that flies over a fire, monitors it and collects information about the incident, and send them to the tactical coordination

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commanders on the ground. This category of aircraft is used to lead air tankers which drop water and retardant to critical areas [14]. Air-tactical aircraft circle around the active edge of the fire for long periods.

Another class of fire fighting aircraft are air tankers (known also as water bombers), which are fixed-wing aircraft that are equipped with tanks and hence carry water or fire retardant and drop it on the fire, or in front of it to slow it down. The tanks can be filled on the ground, at the base, or by skimming water from reservoirs without needing to land in case of flying boats, which can land only on water, and amphibious aircraft. Air tankers can be divided in terms of their tank capacity. The largest of them are referred to as VLAT and carry over 19,000 litres of retardant. Next are Type-I LAT (large aircraft tankers), which can carry 11,500–19,000 litres of retardant. Type-II air tankers can load 6,000–11,500 litres of retardant and Type-III can load 400–6,000 litres. Some aircraft from the last two types can be referred to single engine aircraft tankers (SEAT).

Finally, helicopters can either be fitted with a tank or equipped with a bucket to carry water or fire retardant. Similarly to air tankers, tanks and buckets can be filled on the ground by siphoning water from any open-water sources, provided it is large enough. Helicopters are used to evacuate civilians at risk. As air tankers, helicopters can be divided into *Types*, depending on their tank or bucket capacity. Type-I includes the largest aircraft with a capacity of over 10,000 litres; Type-II are medium size helicopters with capacity of 1,200–10,000 litres; capacity of Type-III ones ranges between 450 and 1,200 litres.

Another important distinction is the fire combat method. It can be direct, parallel and or indirect. Direct attack is used when water or fire retardant is applied directly onto the flames and burning material. Indirect attack is used on large fires in anticipation of the fire movement; water or fire retardant is dropped on these areas to achieve a natural barrier. Parallel attack takes place when drops are made in a short distance from the fire's edge to burn out the control line [1].

In terms of fire suppression tactics, the attacks can be divided into initial and extended attack. The former refers to the first attack, where the particular strategy depends on its location, potential progression area and current weather conditions. Most fires are suppressed within the first burn period, i.e. the first two hours. The latter means that the fire burned beyond the area of origin and the initial attack phase.

An important limitation is the inability to fight extreme fires due to smoke, wind, updrafts and turbulence. In case of extreme wildfire events there exists a *difficulty to impossibility of aerial operations from smoke, wind and convective activity*. Several aspects need to be considered. First, heavy smoke can cause visibility issues. Even though aircraft navigation is greatly computerised, potential danger is enhanced when aircraft fly at the tree top level, multiple vehicles are in the sky at the same time, or operation takes place in mountainous terrain. Direction and wind speed need to be considered with regards to how to attack the fire. For water drops, high winds can make it difficult to deliver water to the ground.

### *3.1 Air-tactical aircraft*

Air-tactical aircraft supervise other aerial fire fighting aircraft operating over wildfires. They can also be used as lead planes for guided drops if required. Major design characteristic of such aircraft is manoeuvrability and speed. They can be fixed wing or rotary-wing aircraft. The former includes mostly single-engine vehicles such as the North American Rockwell OV-10 *Bronco*, Beechcraft Super King Air A200 and the Aero Commander 690B. Helicopters can also be used for fire supervision and tactical coordination and provide greater manoeuvrability than airplanes. These are usually single-engine helicopters.

One of the mostly used air-tactical aircraft is North American Rockwell OV-10 *Bronco*, which is a twin-turboprop aircraft used for light attack and observation. As the aircraft was designed for military purposes, the priority was effective operations from forward bases. It is capable of performing short take-off and landings, also on unimproved sites. This is an important performance: wildfires often take place in remote areas without large airports nearby. The air attack officer has a clear picture of the fire and can communicate clear information to other fire fighting officers.

The backbone of the United States Army's attack helicopter flee is the Bell AH-1 *Firewatch Cobra* [14]. The original model was designed to be an attack helicopter for a two person crew. The tandem arrangement of the seats provided better visibility for both crew members. The cockpit provides a clear vision of the fire for the air attack coordinator officer and for the pilot. Key performance includes climb rate of 1,600 feet/min, which allows it to make sudden ascents from the fire, for example in case of rescue mission. Such long operational time is important for an air-tactical aircraft, as the OV-10 *Bronco*.

As for the air-tactical aircraft, the key objective of the Bell AH-1 is to gather information about strength and direction of the fire and communicate with the ground coordinators. For this reason, cameras and infrared sensors have been added, providing photographs and thermal imaging even through thick smoke. The transmission equipment is capable of sending real-time information to fire fighting crews [14].

### *3.2 Air tankers*

Air tankers are fixed-wing aircraft equipped with an internal tank, which can be filled with water or fire retardant. They are classified according to their tank capacities into four categories: VLAT, Type-I LAT, Type-II air tanker and Type-III air tanker.

**Very large air tankers:** VLAT are capable of carrying ~19,000 litres of retardant. They include the McDonnell Douglas DC-10 and the Boeing 747 Supertanker (retired in 2020).

The McDonnell Douglas DC-10 is a converted wide body, either a DC-10-30 or DC-10-10 passenger jetliner. It is used for this purpose since 2006; at the date of writing, four air tankers are in still operation, all being DC-10-30 aircraft. The aircraft includes three separate external tanks mounted along the centre-line with a combined capacity of ~45,400 litres of water or other retardant and can perform a drop in 8 seconds. To maintain constant centre of gravity throughout the flight, the DC-10 has internal baffles to prevent the retardant from moving. The manufacturer claims that all three tanks can be filled simultaneously on the ground in 8 minutes. Unlike the Boeing B747, the DC-10's tanks are gravity systems: when the tank doors open retardant is pulled out by gravity.

**Type-I large air tankers:** Large air tankers (LAT) are converted passenger or military aircraft. They are capable of transporting from 11,500 to 19,000 litres of fire retardant. These is the most numerous air tanker type, including the Boeing 737, British Aerospace BAe-146 and old Douglas DC-6 and DC-7.

Unlike the air tankers mentioned, the Lockheed C-130 *Hercules* does not need to be converted to fire fighting. It can be loaded with a Modular Airborne Fire Fighting System (MAFFS), which is a self-contained unit. That solution enables fire fighting agencies to use military aircraft for fire-fighting purposes as an emergency backup resource without permanent conversion required. In the USA MAFFS equipment is located at eight bases and it is expected to take 24 hours for an aircraft to arrive at the scene of the fire, as it needs to be withdrawn from its regular military missions [15]. Apart from the C-130 *Hercules*, MAFFS can also be implemented into the Embraer C-390.

The MAFFS program was established in the USA in 1970 to provide emergency support to ordinary aerial fire fighting fleet. A modular tank system that can be implemented into military aircraft only in case of emergency was developed. It included a series of five pressurised fire-retardant tanks with a combined capacity of 10,220 litres and weighted about 5,000kg [15]. The control module is installed in the aircraft and includes the master control panel, loadmaster's seat and discharge valves. Apart form the retardant tanks each module includes a pressure tank with compressed air, which stays on ground during air operations and is used to recharge the system. When deploying the retardant it exists through two tubes which extend out the plane's aft cargo bay doors. If deployed at once, ~10,220 litres of retardant are dispersed in 5 seconds, producing a pattern 18m wide and 400m long. Reloading lasts 8 minutes [15].

In 2007, an improved version of the MAFFS system was developed (MAFFS II). The capacity of the system was increased to 11,000 litres and five single tanks were replaced with a single large tank. Two on-board air compressors were included, resulting in no need to pressurise the tanks on the ground,

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which shortens significantly the turn-around time. The system deployment was also changed: retardant is discharged through a plug in the paratroop drop door on the side of the aircraft instead of opening a cargo ramp door [15]. Such solution decreases drag significantly and keeps the aircraft pressurised during the drop sequence. Even though the aircraft is suited to transport heavy payload of maximum 19,000kg, it can achieve a climb rate 2,000 feet/min and requires a take-off distance of ∼1km.

**Type-II air tanker:** Type-II air tankers are capable of transporting 6,000–11,500 litres of fire retardant. They typically have two or four engines. There is significantly less of them than Type-I air tankers, with the most popular one being amphibious Canadair CL-215 and its successor the Canadair CL-415. Non-amphibious models include the now retired Lockheed P-2 *Neptune*, P-3 *Orion* and the De Havilland DHC-8.

The De Havilland Dash 8-400AT was designated from Dash 8-400MRE Fireguard and configured from a passenger regional airliner. The Dash 8-400AT was chosen for this role due to its superior low-speed manoeuvrability in rugged terrain, little susceptibility to service difficulties, fuel-efficiency and ability to operate from 1,500m airstrips. The aircraft was fitted with an external 10,000 litre retardant tank. An endurance of 3.5 hours allows the aircraft to be refuelled once every few missions.

The Canadair CL-415 is based on the older CL-215, one of the first and most widely used amphibious aircraft built specifically for aerial fire fighting. The CL-415 aircraft are best utilised for initial attacks and are most commonly used for direct attack on the fire edge.

The aircraft is equipped with four water tanks installed in the main fuselage with a total capacity of 6,140 litres. Its main feature as an amphibious aircraft is the ability to fill the tanks while skimming over the water surface and scooping the water with two hydraulically operated scoops. The CL-415 is also equipped in a hose adaptor on each side of the fuselage. Therefore, the tanks can be filled while the aircraft is on the ground. The length of the water source should be at least 1.85km long and 1.8m deep.

**Type-III air tanker:** Type-III air tankers are the smallest aircraft considered and are capable of loading 380 to 6,000 litres of water or fire retardant. They are typically single-engine aircraft and are often referred to as SEAT. Unlike the Canadair CL-415, all Type-III air tankers are aircraft converted for fire fighting purposes, not built for this mission.

One of the most commonly used Type-III air tanker is the Grumman S-2T *Tracker*, introduced in 1954 first purpose-built, single airframe anti-submarine warfare aircraft to enter service for the United States Navy. They have been used for fire fighting purposes in California since 1970, with original S-2A air tankers being replaced by the Grumman S-2T. The capability of the Grumman S-2T to carry heavy loads proved extremely useful for fire fighting purposes; the aircraft was converted to carry up to ∼4,540 litres of retardant. Also, its high speed and manoeuvrability allows it to make quick and frequent returns to the base for retardant refills, as well as dive over the fire area for accurate drops. Therefore, the Grumman S-2T are used for rapid initial attacks, responding to the most remote areas within ∼20 minutes.

The Air Tracktor AT-802 Fire boss is a variant of the American agriculture aircraft AT-802F (1990), equipped with amphibious floats, which enable it to land and take-off from water surface. It is categorized as a Type-III SEAT. The aircraft is powered by 1,200kW turboprop engines which enable it to take-off in 600m and land on open-water reservoirs and most airports.

Even though the maximum capacity of the AT-802 is only 3,000 litres, thanks to the addition of amphibious floats it is capable of delivering multiple drops in a short time, provided that there is an open-water source of sufficient dimensions in the vicinity of the fire. It is mainly used for a fast initial attack and can carry water, phosphate-based retardant, gel and foam fire retardants.

### *3.3 Helicopters*

The last category of fire fighting aircraft considered are helicopters, which usually have not been designed specifically for this purpose but converted from military ones. Therefore they are capable of

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both transporting personnel and cargo and of direct attacks on the fire by performing water drops, either from the tanks mounted inside or from the baskets attached to their under-bellies. Due to significantly smaller size than air tankers, they are usually used for smaller, slower fires and perform single-drop direct attacks.

Fire fighting helicopters can be grouped into 3 types, depending on their size and capacity. Type-I are able to carry over 10,000 litres of water, either in a bucket or an internal tank. Particular models are also able to transport up to 15 people, but not while delivering retardant. Type-II helicopters are medium-size helicopters, and can carry between 1,200 and 10,000 litres of water or fire fighting personnel and equipment, much less than Type 1 due to smaller size. Finally, Type-III can use only between 450 and 1,200 litres of water in a bucket and four to five fire fighters at a time, however due to their small size they can cruise with higher speed; therefore, they arrive at the scene and perform the initial attack quicker [14].

The important advantage of helicopters is the fact that they do not need to return to the operating base to refill. Helicopters equipped with a bucket hover over near open water (lakes, rivers) to refill.

In order to analyse the performance of fire fighting helicopters, three models are analysed: Type-I Sikorsky S-64 *Skycrane*, equipped in an internal tank capable of carrying ~10,000 litres of water; Type-II UH-1H *Super Huey*, which is equipped with a water bucket with capacity of 1,450 litres or a fixed tank with 1,600 litres; Type-III Bell 206B *Jetranger*, that uses a heli-bucket with capacity of 454 litres [14].

**Type-I helicopter:** These helicopters have the largest load capacity, typically of 10,000 litres. They include both heli-tankers (with an internal tank) and helicopters (carrying a heli-bucket). Important advantages of this type is the amount of water they can deliver, quick turn-around time and pin-points accuracy. However, due to the large weight and numerous descents and ascents, the cost of their operations is considerable. Due to the size of their buckets or tanks, Type-I helicopters usually need deep water sources, which are not available everywhere. Type-I helicopters include a variety of models, both civil and military ones converted for fire fighting [14], in particular the Sikorsky S-64 *Skycrane*.

During fire fighting operations a crew of three is onboard: a pilot, co-pilot and an operator. The S-64 was also modified and a tank with a capacity of 10,030 litres was fitted. It can be filled by a draft hose in less than a minute while the aircraft is hovering over an open-water source. The minimum depth of water for refill is 0.45m and it takes 45 seconds to refill. The tank uses the gravity system; doors are controlled by the operator and the retardant is dropped using gravity. The whole tank may be dumped in <3 seconds.

**Type-II helicopter:** Type-II helicopters are capable of transporting up to 1,200 litres of water and up to nine fire fighters at one time, hence are very effective for initial attack. They include both helicopters fitted with a tank for the purpose of fire fighting and civil passenger/cargo aircraft utilising the heli-bucket and on the call-when-needed contract, as Bell 212 or Bell 412. As most other helicopters used for fire fighting, the Bell UH-1H *Super Huey* is a military aircraft fitted for cargo transport, mapping, short haul rescues and retardant dropping. Its primary mission is responding to initial wildfires. It is fitted with a water bucket with capacity of 1,450 litres, or a fixed 1,600 litre tank.

**Type-III helicopter:** These helicopters are the smallest available and are rarely fitted with internal tanks; instead, they are capable of carrying either 454–680 litres of water in the heli-bucket. Also, they can carry a number of fire fighting crew, usually four to six persons. Although they have smaller capacity, they have a higher cruise speed than typical Type-II helicopters, and arrive faster at the scene of an initial attack. Aerial fire fighting Type-III helicopters are the Bell *JetRanger* 206B, Bell 407, MD 500D [14].

The Bell 206B *JetRanger* is one of the most popular helicopters. It is a light two-bladed, single- and twin-engine multi purpose utility helicopter. The aircraft can carry buckets of up to 454 litres of water [14].

## 4.0 Methods and tools

Obtaining data necessary for the analysis of aerial fire fighting fleet and their operations can be divided into two tasks: first, the background regarding its limitations and advantages, aircraft type characteristics and fire retardant refilling and dispersion techniques is to be analysed; second, the analysis of real time historical data for particular fire fighting missions is conducted using *Flightradar24*. Datasets include CSV (comma separated values) and KML (Keyhole Markup Language) records with heading, altitude, coordinates, time stamps of the flight at every instance. This is then compared to historical data regarding wildfires (location, intensity, direction). Combining data obtained using both approaches allows to establish conclusions regarding current aerial fire fighting techniques and propose performance improvements. Registration numbers are found using official fire fighting agencies. Flight paths are compared to fire maps, which are supplied by government websites or public forums [16].

Even though the resources regarding aerial fire fighting are not specific, combined with data gathered independently, they provide enough background information. Limitations and advantages can be evaluated and described, characteristics of each aircraft type determined and appropriate diagrams created, retardants used described and compared, and maps created using Open Source Data.

*Flightradar24* is an internet-based service used for flight tracking information. It includes both real-time information and time-lapse replays of historical flights: tracking information, origins and destinations, flight numbers, aircraft types, positions, altitudes, headings and speeds. The system allows a user to search the database by airline, aircraft model, aircraft type, area or airport. Its main source of data collection is from volunteers and satellite-based Automatic Dependent Surveillance–Broadcast (ADS-B) receivers.

Models of different sizes, tank capacities, deployment techniques, ages and construction characteristics were selected to account for as many parameters as possible. The main source for aircraft selection was the Fire Recognition Guide provided annually by Ref. [14], which includes main performance characteristics of fire fighting aircraft used by CAL FIRE (air tanker, helicopter, air-tactical, etc.).

### *4.1 Flight data analysis*

For air-tactical aircraft the OV-10A *Bronco* was chosen to represent the fixed-wing aircraft operation as it is the most commonly used and a lot of data is available. Additionally, to include rotary-wing air-tactical aircraft, the Bell AH-1 Firewatch was chosen. For non-amphibious air tankers, a variety of sizes is considered. The only VLAT analysed is the DC-10. The Boeing B747 is no longer in operation. For Type-I LAT, the Lockheed C-130 *Hercules* was chosen, due to implementation of the *Modular Airborne Fire Fighting Systems*. For Type-II, the De Havilland Dash 8-400AT was selected, as it is one of the newest aircraft converted. Finally, the Type-III Grumman S-2T is also analysed, as it is one of the most popular aircraft. For amphibious aircraft, Type-II Canadair CL-415 and Type-III Air Tractor 800AT are analysed to identify operations of water scoopers, as well as the design characteristics of the aircraft designed specifically for aerial fire fighting purposes (as opposed to previously mentioned air tankers, converted for that purpose). For helicopters, Type-I Sikorsky S-64 *Skycrane*, Type-II Bell UH-1Y and Type-III Bell 206B were chosen to represent different capacities and helicopter designs.

With aircraft chosen, the registration number must be noted in order to observe its operations. The registration was obtained from official fire-fighting agencies such as CAL FIRE (California, US), Conair Group (Canada) or Protezione Civile Vigili del Fuoco (Italy). The *Flightradar24* database was searched for an aircraft by its registration. To find an actual fire-fighting mission, the position of the aircraft was compared against historical data on wildfires. Such flights take place in the summer period (May-October in California; July-August in Canada and Italy); origin and destination airport is usually the same. Information about location of fires was obtained from official government sources, such as the *Incidents Overview* interactive map provided by the US National Wildfire Coordinating Group (available online).

**Single mission operations:** For each aircraft type, a number of operations was analysed to provide information about flight parameters (speed, altitude) and flight path. For each flight, a CSV was processed.

KML files with flight path were plotted on a map using *Google Earth Pro*. The fire position and the area from the date of operation was obtained. Table A2 shows the flights identified, corresponding fires for a number of aircraft (registration, port of origin and destination, date, time of arrival and departure and flight duration).

**Daily series of missions:** Apart from actual flight information, the aircraft operation through the day was considered to obtain information about its time on-ground. This was done for non-amphibious air tankers, which need to return to the airfield for refuelling and refilling. To obtain such data, days with a number of consecutive operations around the same fire were considered for one non-amphibious air tanker from each type. Table A3 in the appendix shows missions identified for each aircraft category.

### *4.2 Aircraft effectiveness and cost comparison*

Using data for a number of missions from *FlightRadar24* (see Appendix), a cost comparison is proposed. The daily operating rate was determined as a sum of hourly rate (that includes fuel costs, maintenance, crew, etc.) as obtained from theoretical online sources and cost of fire-retardant (in case of non-amphibious air tankers; for amphibious air tankers and helicopters water was assumed to be free).

Data include aircraft registration number, flight date, port of origin and destination, actual time of departure and arrival (ATD, STA), flight duration, number of drops. We calculated time spent on the ground, total drop, single-mission and overall effectiveness, taken as the average of all missions.

From the data, the average number of drops per mission was determined. Then the maximum theoretical number of missions per 12 hours was obtained by dividing 12 hours by the sum of average mission duration and average time spent on the ground. Multiplying number of missions and number of drops/mission yields a number of drops per 12 hours. Assuming a cost of fire retardant of $0.87/litre (at the time of writing), and multiplying it by the number of drops per 12 hours and maximum capacity of non-amphibious air tankers gave the cost of fire retardant per day. Daily flight time was obtained by multiplying average number of missions per average mission duration. The total flight time per day was obtained by multiplying hourly operation cost of an aircraft times daily flight time. The price of dropping one litre of water/retardant was determined by dividing the daily operating cost per number of litres dropped during the day i.e. the maximum tank capacity multiplied by number of drops/day.

The effectiveness of representative aircraft was evaluated as a ratio of the amount of water/retardant that was dropped on the fire and mission duration. To incorporate the effect of on-ground time, days with at least two consecutive flights to the same fire are considered. Then, time for one mission was determined as an addition of the flight time and time spent on-ground before it (after previous mission to the same fire). Missions that occurred as first on the particular day or after long period of time (over two hours) should be disregarded, as they provide no information about the time the aircraft was prepared for the actual mission (refuel, refill). The effect of in-flight refilling was considered for helicopters and amphibious aircraft by noting from the map and altitude chart the number of descents performed to the open water source and then over the fire. The overall drop was the aircraft capacity multiplied by number of descents. It was assumed that all aircraft are filled to their maximum capacity (both from open water sources and at the airport) and that they were filled at the start of the mission. For each aircraft model at least five missions (i.e. five different fires) should be taken into account. If on a particular day an aircraft performed more than two flights to one fire, the mission effectiveness average was considered.

## 5.0 Results and discussion

A number of missions is analysed for a selection of aircraft, as specified in Table A2. They are examined with focus on operational patterns, their performance characteristics (speed, altitude) and flight paths. Using historic fire maps, the flight operation is overlay onto the actual fire area.

**Air-tactical aircraft:** Air-tactical aircraft OV-10 *Bronco* and AH-1 helicopters were analysed. Table A2 includes their missions. The flight path was compared to the wildfire area in Fig. 1.

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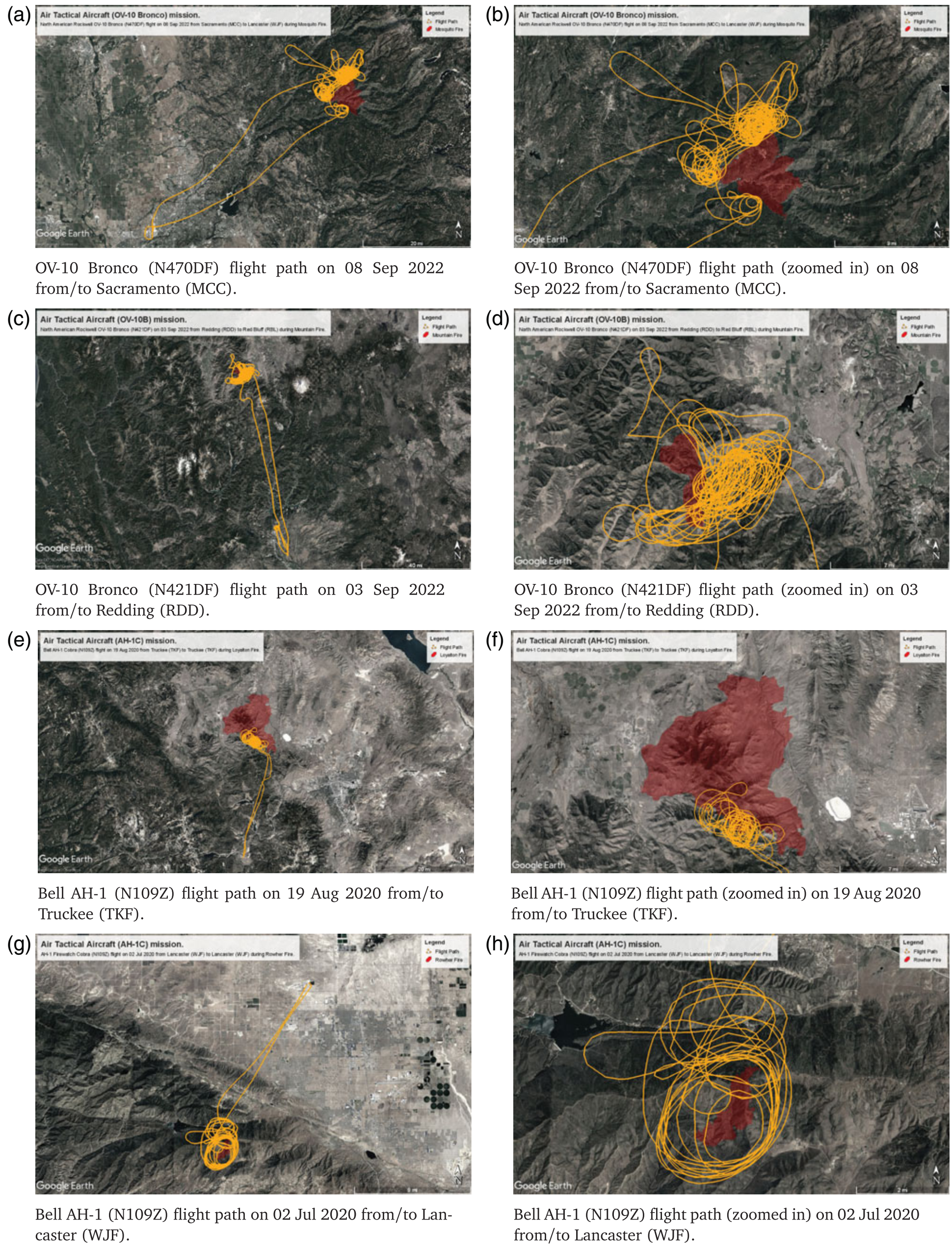


(a) OV-10 Bronco (N470DF) flight path on 08 Sep 2022 from/to Sacramento (MCC).

(b) OV-10 Bronco (N470DF) flight path (zoomed in) on 08 Sep 2022 from/to Sacramento (MCC).

(c) OV-10 Bronco (N421DF) flight path on 03 Sep 2022 from/to Redding (RDD).

(d) OV-10 Bronco (N421DF) flight path (zoomed in) on 03 Sep 2022 from/to Redding (RDD).

(e) Bell AH-1 (N109Z) flight path on 19 Aug 2020 from/to Truckee (TKF).

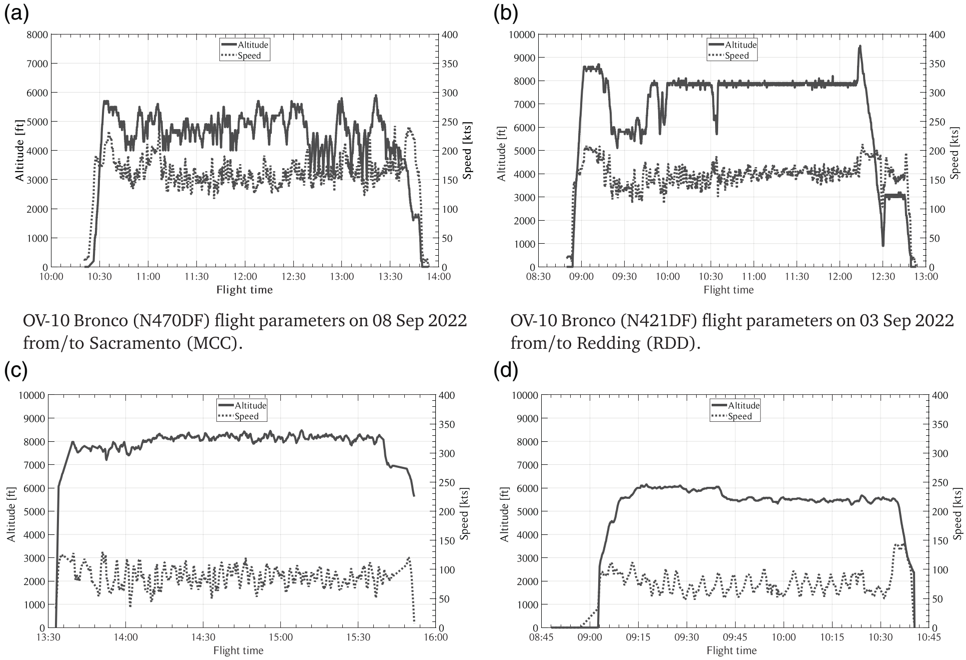
(f) Bell AH-1 (N109Z) flight path (zoomed in) on 19 Aug 2020 from/to Truckee (TKF).

(g) Bell AH-1 (N109Z) flight path on 02 Jul 2020 from/to Lancaster (WJF).

(h) Bell AH-1 (N109Z) flight path (zoomed in) on 02 Jul 2020 from/to Lancaster (WJF).

***Figure 1.*** *Flight paths of air tactical aircraft for selected fire operations. Fire maps from web servers in the public domain: www.wildfiretoday.com, www.nwcg.gov and others.*

From all the maps shown, the air-tactical aircraft circle around the fire rather than over it. When concerned with the big fire, as in the case displayed in Fig. 1(a) or in Fig. 1(f), the aircraft circled over the wildfire front. In case of smaller fires, such as in Fig. 1(d) or Fig. 1(h) the aircraft was capable of circling around its whole area. The difference between a rotary- and fixed-wing aircraft is also clear. Due to much smaller manoeuvrability of the latter, the aircraft needed to perform a turn with greater radius. However, the mean speed of the OV-10 *Bronco*, 120kt, is almost twice of the speed of the Bell AH-1,




(a) OV-10 Bronco (N470DF) flight parameters on 08 Sep 2022 from/to Sacramento (MCC).

(b) OV-10 Bronco (N421DF) flight parameters on 03 Sep 2022 from/to Redding (RDD).

(c) Bell AH-1 (N109Z) flight parameters on 19 Aug 2020 from/to Truckee (TKF).

(d) Bell AH-1 (N109Z) flight parameters on 02 Jul 2020 from/to Lancaster (WJF).

***Figure 2.*** *Flight parameters of air tactical aircraft (selected fire operations).*

meaning that the aircraft can cover greater area of the fire in shorter time. The straight lines over the fire probably show aircraft leading air tankers for more accurate drops. OV-10 *Broncos* missions lasted for over three hours.

In Fig. 2, the OV-10 circled with variable velocity – ranging from 120kt (not considering climb and descent) to 243kt for both missions considered, meaning that it flew with almost its maximum speed of 250kt at some parts of the mission. Changes in speed correspond to changes both in flight path and changes in altitude, which are determined by the terrain around the fire. The case of the western slopes of the Sierra Nevada mountain range affected the flight path of the aircraft. In contrast, a fire took place in the Klamath Mountains (Northern California), where the altitude differences are less significant; thus, they have relatively constant height and speed.

The Bell AH-1 missions considered lasted 2:24 and 1:38 hours, respectively. The fuel economy was not maximised. For both missions the aircraft maintained relatively constant altitude through the flight; for the Rowher Fire, which took place in the terrain of average altitude of 4,400 feet, the aircraft circled at mean altitude of 8,000 feet, or 3,600 feet above the fire. For Loyalton Fire, it flew only 2,000 feet above the surface. The variable speed is due to numerous turns, with mean of 70kt, to improve observation.

**Air tankers:** To analyse the operational pattern of air tankers, both amphibious and non-amphibious aircraft and all types were considered. First, three missions of non-amphibious aircraft were analysed: VLAT DC-10, Type-I C-130H and Type-III Grumman S-2T. Two missions of amphibious air tanker were examined: Type-II Canadair CL-415 and Type-III AT-802.

**Non-amphibious air tanker:** Figure 3 shows the overall and zoomed-in flight path of the DC-10, C-130H, Dash 4-800AT and Grumman S-2T for missions considered in Table A2. Flight parameters of the same missions are shown in Fig. 4. The flight path of an air tanker is much simpler as compared to air tactical aircraft. The same pattern is evident for all non-amphibious air tankers, regardless of their

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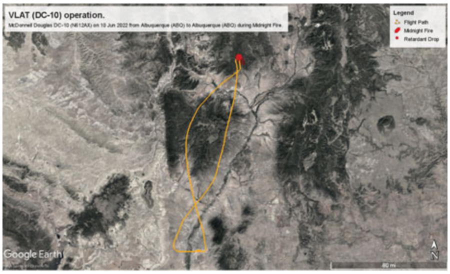
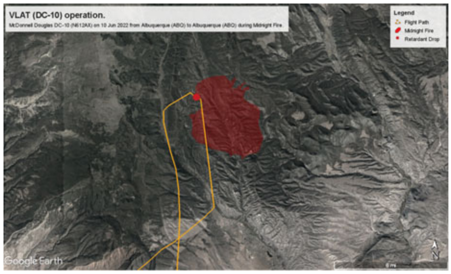
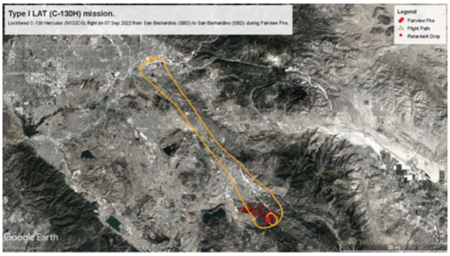
(a)


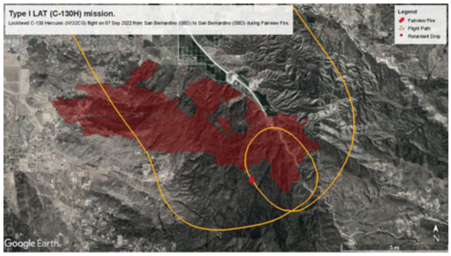

DC-10 (N612AX) flight path on 10 Jun 2022 from/to Albuquerque (ABQ).

(b)



DC-10 (N612AX) flight path (zoomed-in) on 10 Jun 2022 from/to Albuquerque (ABQ).

(c)



C-130H (N132CG) flight path on 07 Sep 2022 from/to San Bernardino (SBD).

(d)



C-130H (N132CG) flight path (zoom) on 07 Sep 2022 from/to San Bernardino (SBD).

(e)

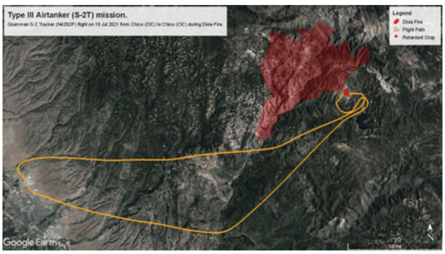


Dash 4-800AT (C-FFQF) flight path on 13 Jun 2021 from/to Kenai (ENA).

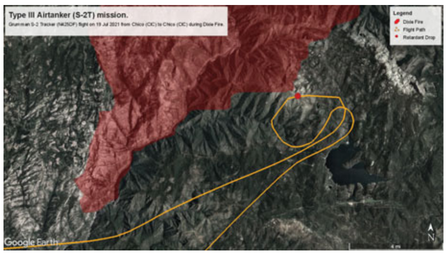
(f)



Dash 4-800AT (C-FFQF) flight path (zoomed in) on 13 Jun 2021 from/to Kenai (ENA).

(g)



Grumman S-2T (N425DF) flight path on 19 Jul 2021 from/to Chico (CIC).

(h)



Grumman S-2T (N425DF) flight path (zoomed in) on 19 Jul 2021 from/to Chico (CIC).

***Figure 3.*** *Flight paths of non-amphibious air tankers for selected operations; fire maps for web services such as www.wildfiretoday.com and the US National Wildfire Coordination Group (www.nwcg.gov).*

size: take-off, climb, travel to fire location, loop to target altitude, drop retardant and fly back. Drops are performed close to the fire front but not directly onto the fire area.

For fire missions considered, the DC-10 aircraft took off from Albuquerque (ABQ) and travelled ~150km to the location of the fire. The aircraft climbed to a cruise altitude of 11,000 feet and after 10 minutes at 350kt circled to lose altitude and velocity, as shown in Fig. 4(a). The drop in altitude corresponds to the spot on the map that can be deducted as the point where the retardant was deployed.

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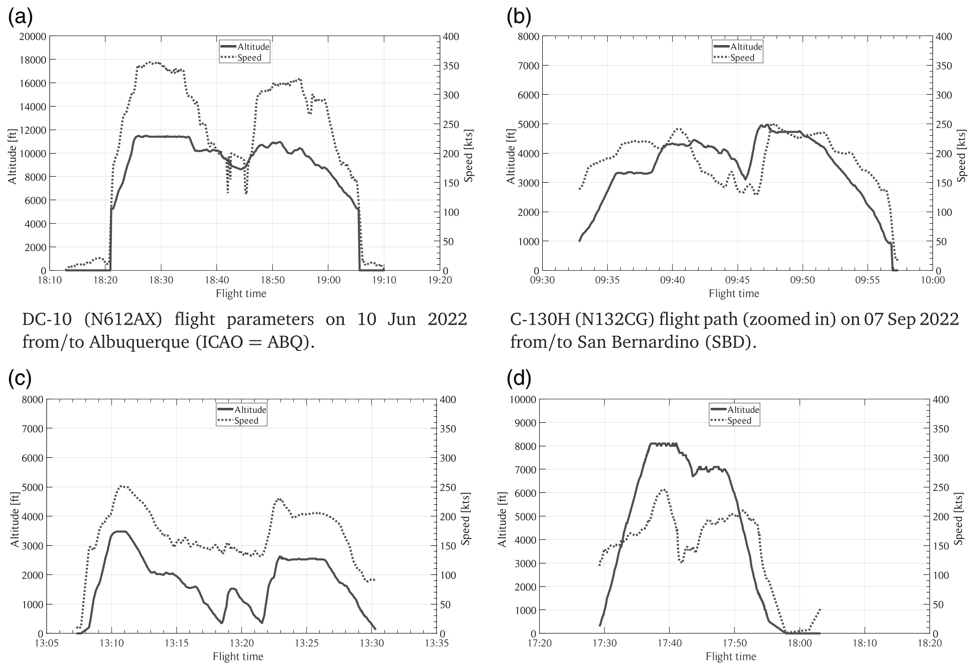


DC-10 (N612AX) flight parameters on 10 Jun 2022 from/to Albuquerque (ICAO = ABQ).

C-130H (N132CG) flight path (zoomed in) on 07 Sep 2022 from/to San Bernardino (SBD).

Dash 4-800AT (C-FFQF) flight parameters on 13 Jun 2021 from/to Kenai (ENA).

Grumman S-2T (N425DF) flight parameters on 19 Jul 2021 from/to Chico (CIC).

***Figure 4.*** *Flight parameters of non-amphibious air tankers.*

Two sudden drops in velocity correspond to the turns. After retardant release the air tanker performed a sudden ascent back to the same cruise altitude and descended back to the airport. A sudden deceleration corresponds to the turn performed when aligning with the runway.

A similar flight pattern is shown for the Lockheed C-130H mission: aircraft take-off, climb, travel to the fire location and looping with retardant drop. This drop is visible as a sudden dive. The aircraft then climbs steeply with a rate of climb of about 1,900 feet/min back to the altitude of 5,000 feet and slowly descends back to the airport. The mission time was only 24 minutes at 250kt, during which ∼15,000 litres were dropped.

For Type-II, De Havilland Canada Dash 8-400AT, as shown in Graphs 3(e), 3(f) and 4(c). Due to the proximity of the fire to the airport the climb took only few minutes, after which the aircraft was cruising with the speed of 250kt at an altitude of 3,200 feet. Two drops in altitude are visible and correspond to the same location; the aircraft decreased the altitude by about 1,300 feet in 2 minutes, resulting in descent rate of 750 feet/min. After two drops it climbed steeply with a rate of 2,000 feet/min. For this fire the aircraft operates from a relatively small airport with the longest runway ∼2,400m.

Finally, the mission of the Grumman S-2 Tracker is shown in Graphs 3(g), 3(h) and 4(d). The pattern is as for air tankers mentioned: the S-2T took off, climbed to an altitude of 8,000 feet and attained maximum speed of 246kt; it circled over the fire and performed a drop near the wildfire front, which is seen as a drop in both altitude (to 6,500 feet) and speed to 150kt. Afterwards, it climbed slightly and descended to the airport. The mission took ∼20 minutes. Even though Type-I air tankers can operate only from larger airports and have longer range, they can achieve higher speeds, resulting in similar turn-around time.

As non-amphibious air tankers perform multiple operations through the day (as opposed to air tactical aircraft, non-amphibious air tankers and helicopters, which need to go back to the airport only to refuel and usually perform two to three operations thorough the day), series of operations should be considered.

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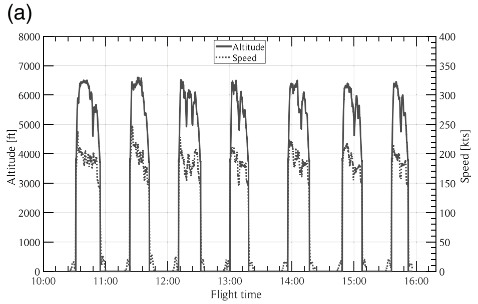
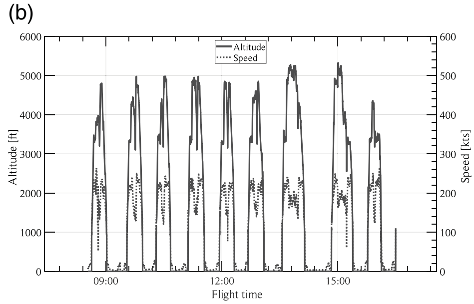
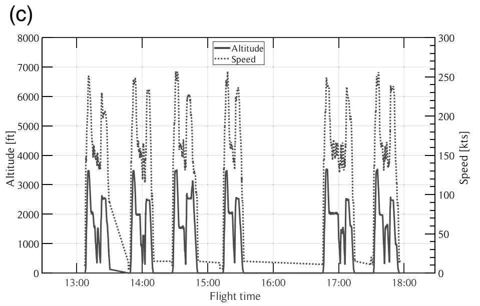


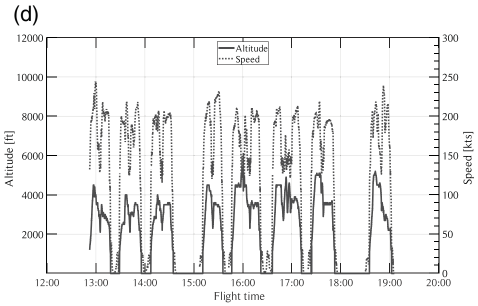

DC-10 (N522AX) series of flights parameters on 05 Aug 2022 from Helena (HLN) to Casper (CPR).




C-130H (N132CG) series of flight parameters on 07 Sep 2022 from/to San Bernardino (SBD).




Dash 4-800AT (C-FFQF) series of flight parameters on 13 Jun 2021 from/to Kenai (ENA).




Grumman S-2T (N435DF) series of flight parameters on 29 Aug 2022 from/to San Bernardino (SBD).

***Figure 5.*** *Series of flights parameters for each type of non-amphibious air tanker.*

Figures 5 and 6 show the flight paths and parameters for multiple operations conducted in one day for each type of non-amphibious air tanker, namely DC-10, C-130H, DHC-8 and S-2T. Each aircraft conducts similar missions with short breaks at the airport for refuelling and retardant refilling.

The DC-10 (VLAT) spends an average of 29 minutes on-ground, with minimum time of 26 minutes. This is more that the filling time presented by theoretical data of 19 minutes; this does not include time needed for refuelling, taxi and potential maintenance. The Type-II C-130H spends an average of 27 minutes on the ground with minimum time of 21 minutes. Theoretical filling time for this aircraft is 8 minutes. The discrepancy is more significant than for the DC-10. The Dash 8-400 spends a minimum of 18 minutes on the ground; no data was found regarding its filling time. Finally, the smallest of the air tankers considered, the Grumman S-2T, showed a turn-around time of only 11 minutes. In summary, the theoretical data regarding filling time is in line with the analysis carried out. However, the time may be extended due to refuelling, taxi, etc.

**Amphibious air tankers:** Amphibious air tankers are capable of scooping water from open water reservoirs, resulting in decreased turn-around time and increased efficiency. Two most common amphibious air tanker are Type-II Canadair CL-415 and Air Tractor AT-802; two missions for each aircraft will be analysed, as in Table A2. Selected flight parameters and tracks are shown in Figs. 7 and 8, respectively.

Two missions of the CL-415 show similar pattern: aircraft takes-off, climbs to the altitude of ~5,000 feet in order to reach the fire and descents either to the water source to fill the tank, or to perform the drop over the fire, provided that the tank has been previously filled in the airport base. Then the scooper repeats the pattern a number of times; I-DPCD performed 15 dives to the Mediterranean Sea (12km away), Fig. 8(a), whereas I-DPCN filled its tank 19 times in open water reservoir (Lago Poma, 10km away). Each dive is accompanied by a sudden deceleration, but the aircraft does not stop completely.

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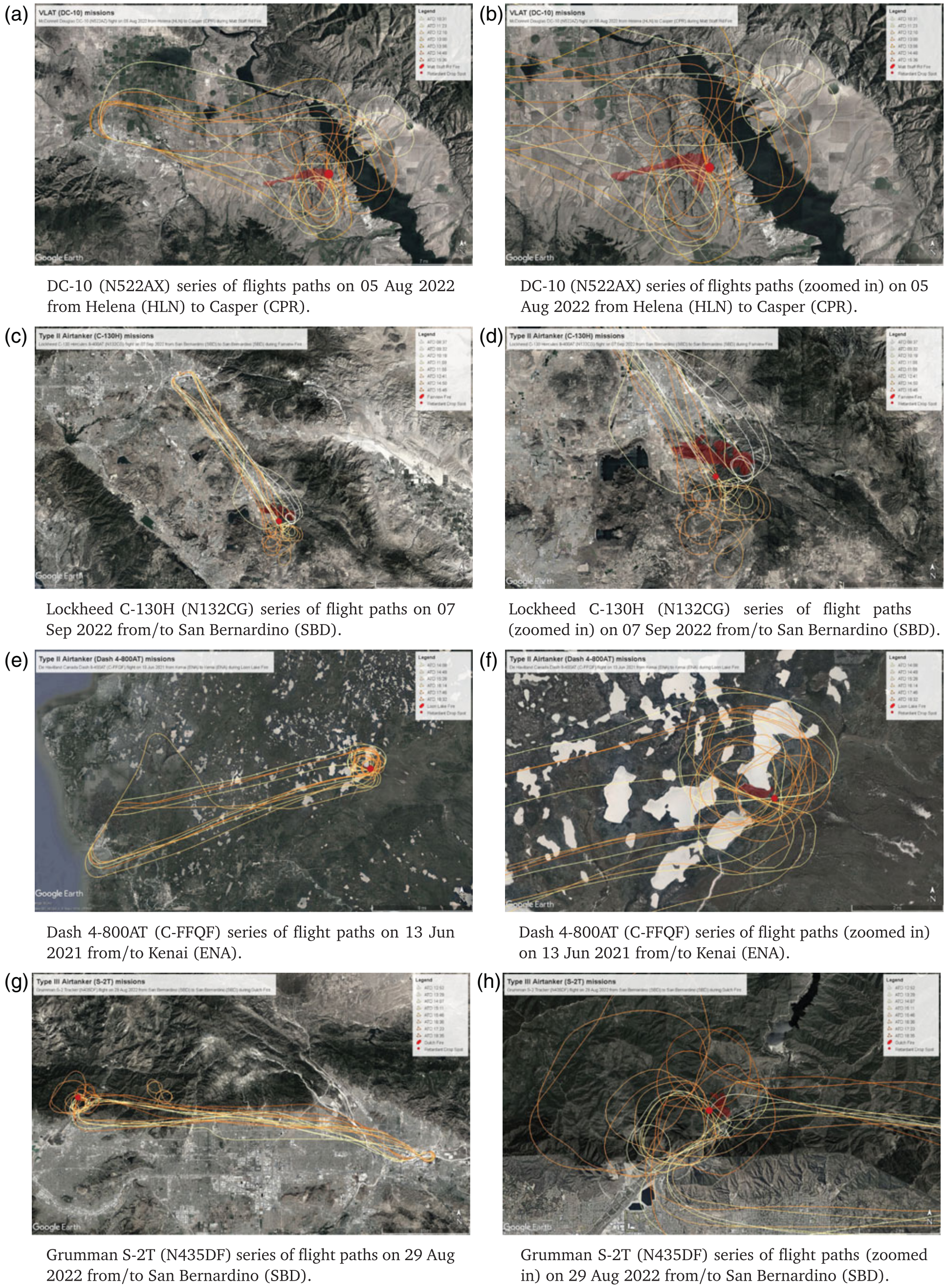


(a) DC-10 (N522AX) series of flights paths on 05 Aug 2022 from Helena (HLN) to Casper (CPR).

(b) DC-10 (N522AX) series of flights paths (zoomed in) on 05 Aug 2022 from Helena (HLN) to Casper (CPR).

(c) Lockheed C-130H (N132CG) series of flight paths on 07 Sep 2022 from/to San Bernardino (SBD).

(d) Lockheed C-130H (N132CG) series of flight paths (zoomed in) on 07 Sep 2022 from/to San Bernardino (SBD).

(e) Dash 4-800AT (C-FFQF) series of flight paths on 13 Jun 2021 from/to Kenai (ENA).

(f) Dash 4-800AT (C-FFQF) series of flight paths (zoomed in) on 13 Jun 2021 from/to Kenai (ENA).

(g) Grumman S-2T (N435DF) series of flight paths on 29 Aug 2022 from/to San Bernardino (SBD).

(h) Grumman S-2T (N435DF) series of flight paths (zoomed in) on 29 Aug 2022 from/to San Bernardino (SBD).

***Figure 6.*** *Series of flight paths for each type of non-amphibious air tanker. Fire maps from web servers in the public domain: www.wildfiretoday.com, www.nwcg.gov and others.*

The length of the water source from the I-DPCN mission is approximately 4.5km long, hence it was capable of performing a scoop (aircraft subsequently lost in October 2022, with 2 fatalities); I-DPCD needed a distance of ∼3km. Both missions lasted about 2.5 hours.

Similar pattern is evident for the the AT-802: as shown in Fig. 8(e) and (g), the aircraft circles between the water reservoir and area of the fire (∼25km apart for EC-NDU and 3km for VH-AWU), performing

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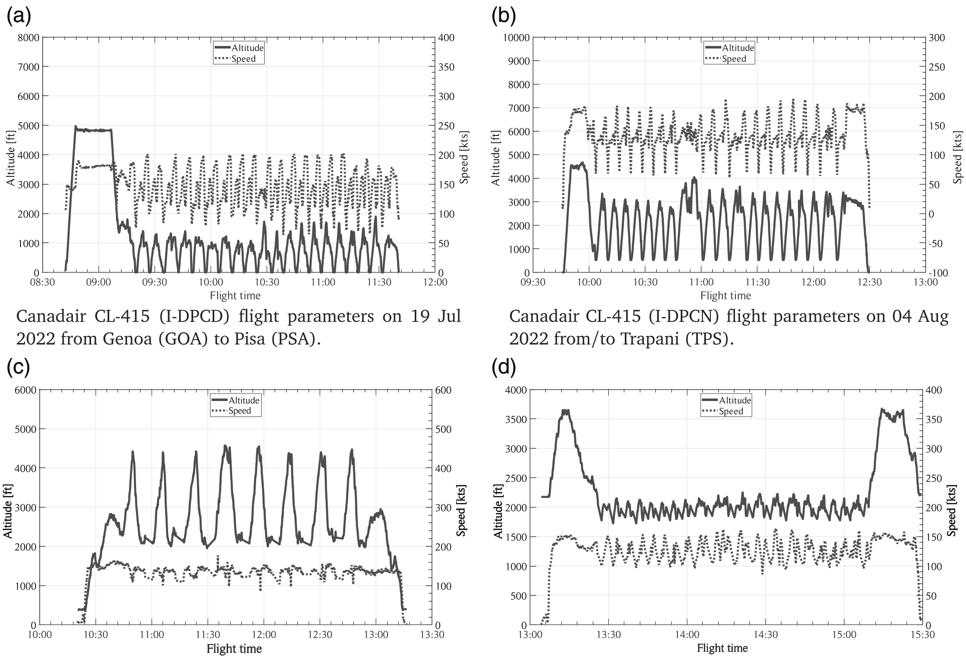


(a) Canadair CL-415 (I-DPCD) flight parameters on 19 Jul 2022 from Genoa (GOA) to Pisa (PSA).

(b) Canadair CL-415 (I-DPCN) flight parameters on 04 Aug 2022 from/to Trapani (TPS).

(c) AT-802 (EC-NDU) flight parameters on 18 Jun 2022 from/to Sabadell (QYS).

(d) AT-802 (VH-AWU) flight parameters on 21 Jan 2023 from/to Toowoomba (TWB).

***Figure 7.*** *Flight parameters for amphibious air tankers.*

drops directly onto the fire. Refilling requires ∼30 seconds with a deceleration to ∼90kt. In contrast to the CL-415, the AT-802 needed a distance of ∼2km for water scooping in both missions. The operations lasted 2:26 hours and 2:53 hours, during which 8 and 19 drops were performed, respectively.

Amphibious air tankers dominate non-amphibious ones in terms of turn-around time, provided that a water source of sufficient size is available in the vicinity of the fire. From the data collected, Type-II Canadair CL-415 can reach higher speeds, better rate of climb, and comparable endurance. On the other hand, due to its smaller size, Type-III AT-802 can scoop water faster and from a smaller water reservoir.

**Helicopters:** For helicopter operation, three missions of each helicopter type were analysed, namely the Sikorsky S-64 *Skycrane*, Bell UH-1Y *Super Huey* and Bell 206B *Jetranger*. Figure 9 shows the flight parameters thought the mission, and Fig. 10 shows the respective flight tracks. All helicopters circle between water sources and fire front; altitude and speed fluctuate.

The mission indicated for the Sikorsky S-64 took place in the central San Gabriel Mountains in the north of Los Angeles, California. From Fig. 10(b), The S-64 performed a total of 15 round trips from the wildfire front and a water reservoir, dropping over 150,000l of water. Dives to the water reservoir can be recognised on Fig. 9(a) as descents from an altitude of 3,500 feet (where the fire took place) down to 650 feet, accompanied by drops in speed to almost 0kt for ∼15 seconds. After each of those stops, the aircraft climbed with a rate of ∼700 feet/min and travelled to the fire front, dropping water directly on the fire (performing a direct attack). The mission lasted ∼2 hours.

Similar pattern can be observed for the Bell UH-1Y *Super Huey*: it performed a total of 26 round trips from the water reservoir to the fire front. Due to the proximity of the water reservoir one trip took ∼3 minutes and the altitude change was only 500 feet. Each refill is accompanied by a decrease of speed to almost zero for ∼10 seconds; the aircraft was stationary when refilling. Increased refill time is the result of deployment of the snorkel.

Finally, a mission of the smallest helicopter (Type-III Bell 206B *JetRanger*) is shown in Figs. 10(e), (f) and 9(c): the aircraft circulates between an open-water reservoir and an area of the fire.

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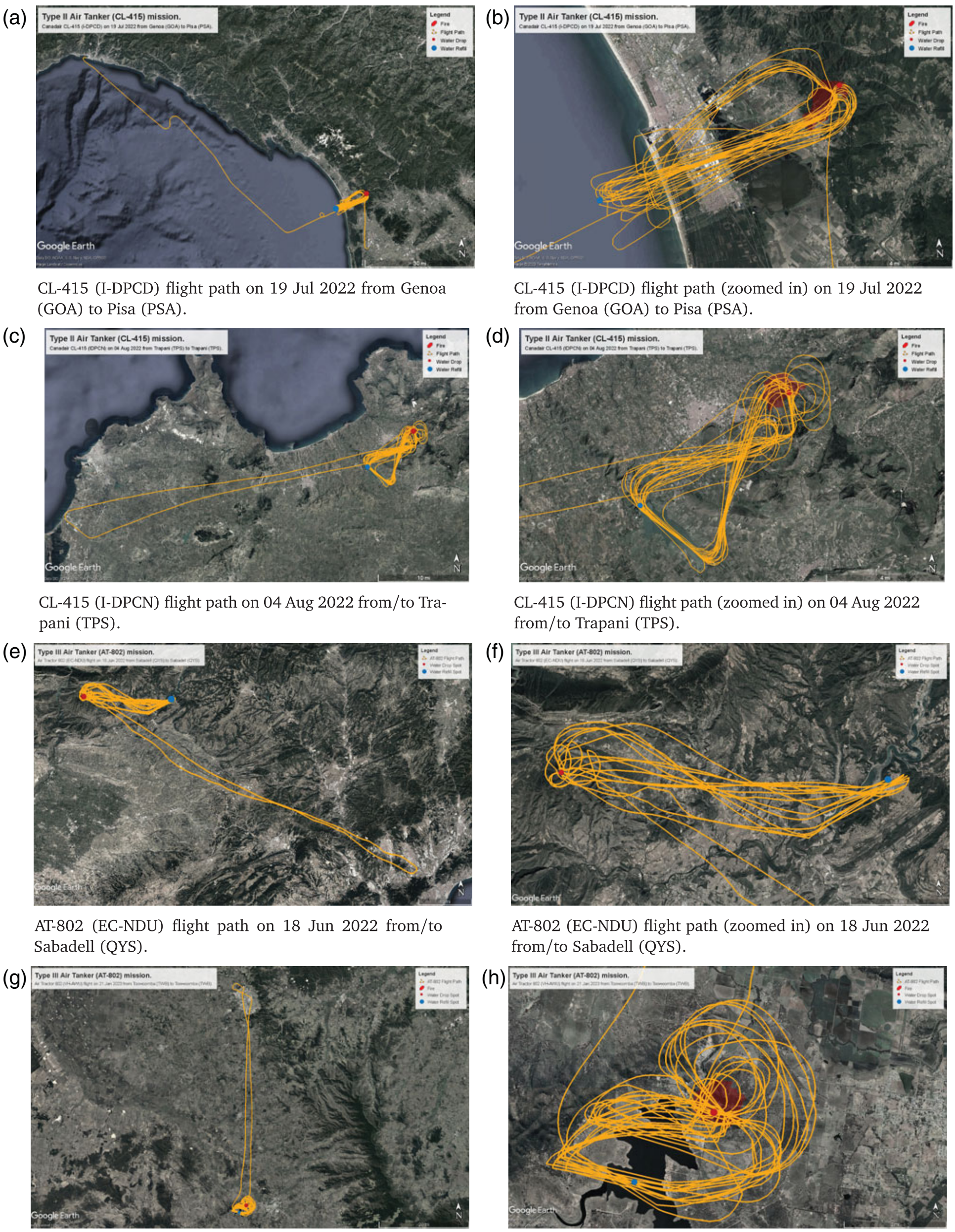



(a) CL-415 (I-DPCD) flight path on 19 Jul 2022 from Genoa (GOA) to Pisa (PSA).

(b) CL-415 (I-DPCD) flight path (zoomed in) on 19 Jul 2022 from Genoa (GOA) to Pisa (PSA).

(c) CL-415 (I-DPCN) flight path on 04 Aug 2022 from/to Trapani (TPS).

(d) CL-415 (I-DPCN) flight path (zoomed in) on 04 Aug 2022 from/to Trapani (TPS).

(e) AT-802 (EC-NDU) flight path on 18 Jun 2022 from/to Sabadell (QYS).

(f) AT-802 (EC-NDU) flight path (zoomed in) on 18 Jun 2022 from/to Sabadell (QYS).

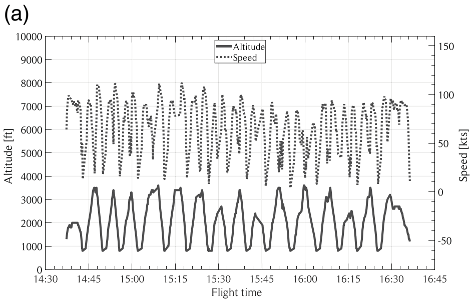
(g) AT-802 (VH-AWU) flight path on 21 Jan 2023 from/to Toowoomba (TWB).

(h) AT-802 (VH-AWU) flight path (zoomed in) on 21 Jan 2023 from/to Toowoomba (TWB).

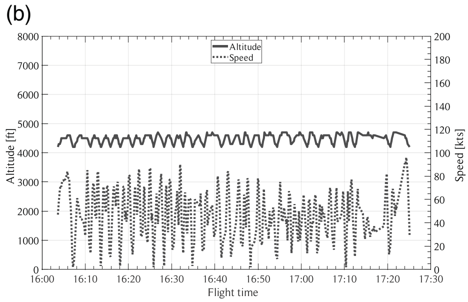
***Figure 8.*** *Flight paths of amphibious air tankers for selected flights. Fire maps from NASA and others.*

During a mission lasting almost 2 hours the aircraft performed 11 refills, which is shown as altitude drops to the level of the reservoir for a time of few seconds to refill its heli-bucket each time.

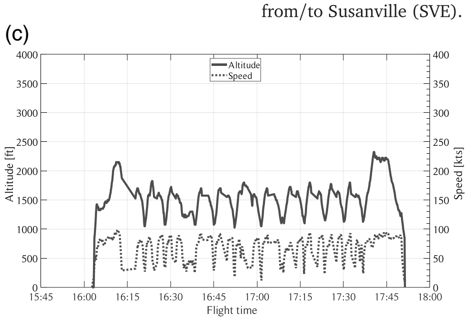
As all types of helicopters use the same scheme of operations and usually can access the same open water reservoirs, the dominance in effectiveness of Type-I helicopters is clear: they are faster (e.g., they can perform more trips between fire and water refill locations) and have greater tank/bucket capacity.




Sikorsky S-64 (N4037S) flight parameters on 18 Aug 2020 from/to La Verne (POC).




Bell UH-1 (N497DF) flight parameters on 20 Aug 2020 from/to Susanville (SVE).




Bell 206B (N306FD) flight parameters on 17 Jul 2020 from/to Van Nuys (VNY).

***Figure 9.*** *Flight parameters of helicopters.*

### *5.1 Cost comparison*

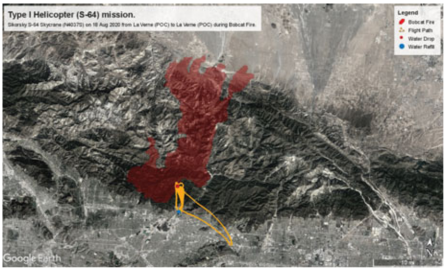
To determine the most effective fire fighting techniques, operating cost of aircraft should be analysed. Using the data collected, notional values of retardant cost, aircraft hourly rates, the daily cost of the aircraft models can be assessed. At least five missions for each aircraft were analysed, where one mission is attributed to one airport of origin/destination and one fire.

Table A4 was derived with data compiled for these missions. This table shows the key flight and cost parameters: average time on the ground before the mission, average mission duration, average number of drops per mission, average number of missions per day (12 hours) and hence total retardant and flight cost per day. Figure 11 shows the relation of daily operating costs with tank capacity.

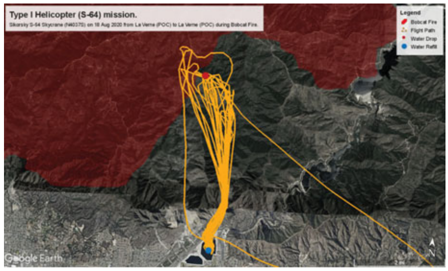
For non-amphibious fixed-wing aircraft daily operating costs increase linearly with tank capacity, Fig. 11(a). This is caused by increased cost of retardant, as well as higher operating costs. Also, as shown in Fig. 11(b), for this type of aircraft, the DC-10 can be said to have the most favourable ratio of cost to the litres of retardant dropped ($1.01), while Type-II BAe-146 and B737, and Type-III Grumman S-2T have the worst (1.26, 1.31 and 1.27, respectively). Type-II aircraft often use airports of the same size as Type-I; thus, they have the same distance to the fire location but deliver significantly smaller drops, deteriorating cost to litre-dropped ratio. The Grumman S-2T is the oldest of the aircraft considered and has relatively poor fuel efficiency in comparison with more modern aircraft.

Amphibious aircraft and helicopters are significantly cheaper to operate than non-amphibious aircraft as the cost of fire retardant is zero, Fig. 11(a). The smallest helicopter, Type-I Bell 206B, has the lowest cost of dropping one litre of water. Amphibious aircraft are less cost-effective than helicopters, even though both of these aircraft use water as retardant. This is caused by increased hourly rates of fixed-wing aircraft, lower number of total drops and lower manoeuvrability: the fixed-wing aircraft uses a significant amount of flight time to descent and line with the water source to scoop from.

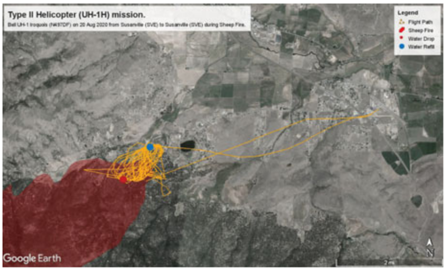
The purchase cost is excluded from the analysis; most of the air tankers (B747, DC-10, BAe-146, B737, DHC-8, AT-802A, S-2T) and helicopters with fitted tanks (CH-47, S-64, UH-1H) must be

(a)


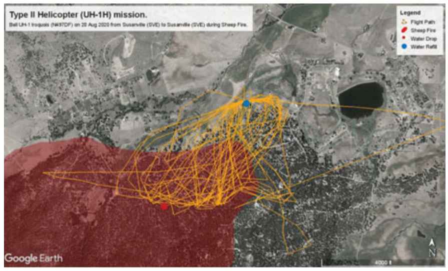

Sikorsky S-64 (N4037S) flight path on 18 Aug 2020 from/to La Verne (POC).

(b)



Sikorsky S-64 (N4037S) flight path (zoomed in) on 18 Aug 2020 from/to La Verne (POC).

(c)



Bell UH-1 (N497DF) flight path on 20 Aug 2020 from/to Susanville (SVE).

(d)



Bell UH-1 (N497DF) flight path (zoomed in) on 20 Aug 2020 from/to Susanville (SVE).

(e)



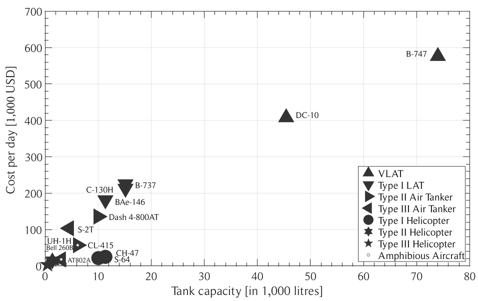
Bell 206B (N306FD) flight path on 17 Jul 2020 from/to Van Nuys (VNY).

(f)

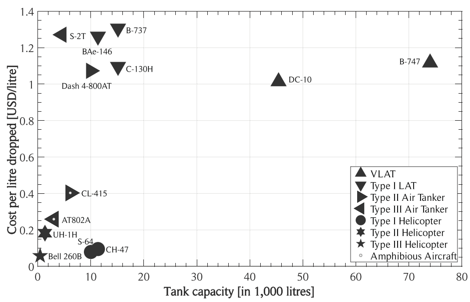


Bell 206B (N306FD) flight path (zoomed in) on 17 Jul 2020 from/to Van Nuys (VNY).

***Figure 10.** Flight paths of helicopters. Fire maps from Ref. [16].*

(a)



Cost/tank

(b)



Cost/litre

***Figure 11.** Aircraft cost comparison.*

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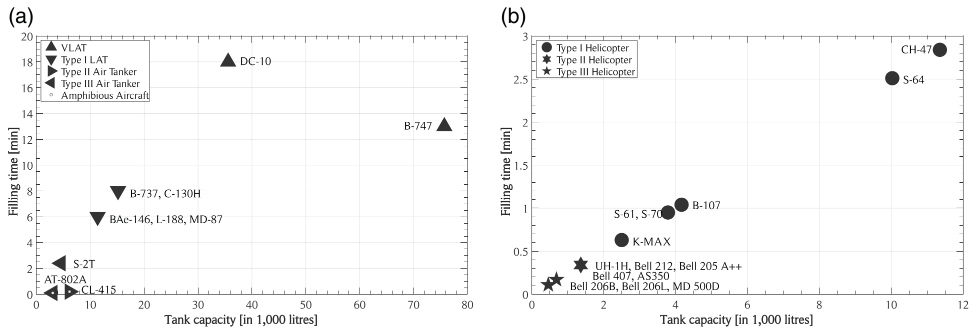


Fixed-wing aircraft. Rotary-wing aircraft.

***Figure 12.*** *Correlation between refilling time and tank capacity of chosen fire fighting aircraft.*

converted to fire fighting missions, in contrast to the Canadair CL-415 designed specifically for this operation, the C-130H (with removable tank) and the Bell 206B (with heli-bucket).

### *5.2 Filling time*

The refilling time depends on the category of the aircraft considered – scooping water from water reservoirs is usually faster than refilling at the airport. To assess the aircraft effectiveness, this factor needs to be taken into account. Unfortunately, theoretical values for filling time are not available for many aerial fire fighting aircraft. These values are approximated and compared to flight data.

Non-amphibious air tankers are not capable of filling their tanks by scooping water from nearby water sources. The Interagency Airtanker Board states that for all air tankers, the system shall provide a means of supplementing the filling process to achieve ∼1,900 lit/min. However, some air tankers are capable of higher refill rate. On the other hand, the amphibious air tankers are capable of sweeping water from open-water sources, which significantly exceeded this rate. The Canadair CL-415 is capable of refilling its ∼6,100 litres tank in 12 seconds and the Air Tractor AT-802 (with capacity of ∼3,000 litres) in only 6 seconds (refill rate of ∼30,000 lit/min). Figure 12(a) compares the refilling time needed for particular aircraft with different tank capacity. For the B747, data was obtained from Ref. [12]. Data are not available for other aircraft; they were calculated using the IAB guidance of minimum refill rate.

As amphibious air tankers, helicopters are capable of either siphoning water from open-water sources (in case of heli-tankers) or simply filling the bucket attached to their bellies. Systems currently in use are capable to gather water at rates ranging from 1,700 to 4,000 litres/min [12]. Best performance values result in a maximum of 3 minutes refill time for the largest Type-I heli-tankers and only 6 seconds for Type-I heli-tankers with a heli-bucket with a capacity of 454 litres. Figure 12(b) summarises the filling time versus capacity of most commonly used aerial fire fighting rotary-wing aircraft.

The effectiveness of amphibious aircraft is evident. However, we must take into account that time and fuel are needed for frequent dives to the water source.

There is a linear correlation between refill time and tank capacity for helicopters, Fig. 12(b). Considering that all types of heli-tankers refill in the same water source and take similar time to reach the fire, Type-I heli-tankers are the most effective. Table A1 shows filling times and tank capacity of all aircraft.

### *5.3 Effectiveness comparison*

At least five missions for each aircraft are analysed, where one mission is attributed to one airport of origin/destination and one fire. Table A4 contains all missions used for analysis with all important data

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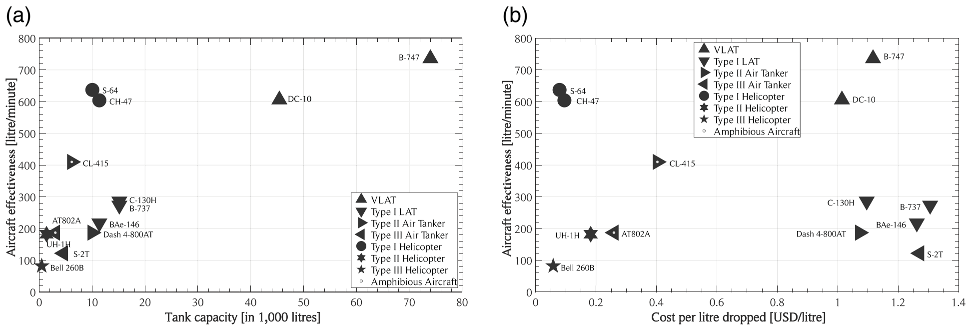


***Figure 13.*** *Aircraft effectiveness comparison.*

necessary to recreate the analysis, as well as efficiency calculated for each mission. Using the average values for each aircraft model, Table A4 was derived. Plots of effectiveness and tank capacity, as well as effectiveness and cost of dropping one litre are shown in Fig. 13.

The efficiency of rotary-wing aircraft increases significantly with tank capacity, Fig. 13(a). Type-III Bell 206B efficiency was determined as 82 litres of water per operational minute of flight; Type-II Bell UH-1H of 182 and Type-III S-64 and CH-47 as 637 and 604, respectively. However, efficiency in this case is not proportional to the tank size: the S-64's tank is ∼22 times larger than that of Bell 206B, but its efficiency only 8 times higher; similarly, Type-II Bell UH-1H has a capacity ∼4 times higher than the Bell 206B; however, its efficiency is ∼2.5 times larger. This is caused by differences in performance, such as speed or time on the ground. As shown in Table A4, Type-I helicopters spend on ∼50 minutes on the ground between runs, whereas Type-II and III spend only 25 minutes.

The effectiveness non-amphibious fixed-wing aircraft increases with tank capacity, as shown in Fig. 13(a). Tank capacity and effectiveness are proportional for Type-I and Type-II air tankers, i.e. C-130H with tank 1.5 times larger than the Dash 800-4AT is capable of dropping 1.5 times more retardant per operational minute. Aircraft of increasing size spend more time on the ground between runs (Table A4): around 50 minutes for VLAT, an average of 35 minutes for Type-I LATs, 33 minutes for Type-II and 27 minutes for Type-III, the tank capacities greatly increase air tanker's efficiency. The most effective air tanker was determined to be the Boeing 747, thanks to its greater capacity than any other aircraft.

The effect of amphibious aircraft must to be considered. Type-II air tanker CL-415 has efficiency twice as high as Type-II Dash 800-4AT; the AT-802A has efficiency over twice higher than the S-2T, even though its tank is smaller. Amphibious air tankers spend significantly more time on the ground between runs (over two hours); this time is balanced by the number of drops without the need to return to the airport.

Comparing the fixed- and rotary-wing aircraft, we conclude that Type-III helicopters are less effective than Type-III air tankers, Type-II helicopters are comparably effective as Type-II non-amphibious aircraft and Type-I helicopters are significantly more effective than Type-I aircraft and similarly effective as VLAT. However, even though helicopters and amphibious air tankers show greater efficiency than non-amphibious aircraft with comparable tank capacity, these aircraft drop water, not retardant, which is more effective in most cases. From Fig. 13(b), the best ratio for water-dropping aircraft is Type-I helicopters, whereas for retardant-dropping air tankers the best ratio is attributed to VLAT.

## 6.0 Conclusions

Aerial fire fighting offers a significant superiority over ground fire fighting: it is quick and effective, it can access hard-to-reach places. However, it carries considerable risk and operating costs.

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The recent availability of ADS-B data for these flight operations allows detailed analysis of performance of a variety of flight systems. From the data examined, it was found that missions can last over three hours, during which they circle around the wildfire with variable altitude and speed, as a result of changing terrain and manoeuvrers. Flight patterns have been demonstrated for a selection of wildfires. In general, potential improvements in path planning and manoeuvres of aircraft are difficult to access without detailed information about fire activity such as intensity or direction.

The main difference between fixed- and rotary-wing air-tactical aircraft lies in their manoeuvrability: helicopters are capable of much steeper climb and turn rates, fly at lower speeds and on lower altitudes. Fixed-wing air-tactical aircraft perform guided drops of the air tankers. Air-tactical aircraft are usually small, single or twin-engine military vehicles converted from reconnaissance missions.

The mission of air tankers is to deliver retardant to the fire line; aircraft with large cargo area and powerful propulsion systems are chosen for this role. Non-amphibious fixed wing air tankers are usually converted wide-body aircraft. The Lockheed C-130 with removable aerial fire fighting unit is a very useful solution. From the flight data, it was found that all non-amphibious air tankers follow the same pattern: travel to the fire location, loop to lose altitude, drop, climb back to their cruise altitude, and return to base. As they use fire retardant rather than water, they perform an indirect attack.

VLAT reach higher speeds and altitudes, but can only use large airports, often far from the fire location, and hence perform longer missions (48 minutes for VLAT, 37 minutes for Type-I, 33 minutes for Type-II, 27 minutes for Type-III). They also need more time on the ground to refill and refuel (~29 minutes, as compared to ~11 minutes for Type-III). VLAT were found to be the most effective fire fighting aircraft, with the lowest cost per litre dropped (among retardant-dropping aircraft). Water showed the weakest coverage, being more prone to dispersion by wind.

For amphibious air tankers, endurance is important alongside cargo capacity, since their missions can last for over two hours. Water is obtained from nearby open water sources and multiple drops are performed. This gives them a great advantage over air tankers: the effectiveness of Type-II amphibious and non-amphibious air tankers was found to be 410 and 187 lit/min, respectively, and for Type-III the values were 187 and 122 lit/min, respectively. The operating cost of non-amphibious air tankers is significantly lower than for the same type of amphibious ones due to zero costs of retardant. Flight data analysis showed that the larger air tanker the greater length of the open water source is needed: Type-III Air Tractor AT-802 needed ~2km, whereas Type-II Canadair CL-415 needed ~3km.

Using helicopters for fire fighting operations is easier than air tankers since they do not need reconversion; they only must be equipped with a heli-bucket. However, some heavy military models are being fitted with tanks in order to increase cargo capacity. As the amphibious air tankers, helicopters use water reservoirs to obtain water by performing multiple descents to it and remaining stationary for a couple of seconds when filling the bucket or tank. The larger the helicopter, the longer is needed to refill (15 seconds for Type-I S-64, 10 seconds for Type-II Bell UH-1H and just a few seconds for the Bell 206B). Short refill time and manoeuvrability gives helicopters a significant advantage. With respect to drop patterns; drop from a Bambi bucket is longer and narrower than drop from the heli-tanker S-64.

The same types of air tankers and helicopters can be compared. From Table A4, for Type-I helicopters are over twice as effective as non-amphibious air tankers (217 lit/min for the BAe-146 versus 637 lit/min for the S-64). For Type-II, the most effective are amphibious air tankers; helicopters and non-amphibious air tankers show the same effectiveness (182 lit/min dropped by the UH-1H and 187 lit/min dropped by the DHC-8). For Type-III, both amphibious and non-amphibious air tankers dominate over helicopters. All helicopter types indicate lower cost of dropping retardant/water than air tankers.

To maximise drop amount and minimise operational costs, Type-I helicopters are recommended as the workhorse for water-dropping aircraft. Since the retardant has a significant advantage over water for indirect attack, non-amphibious air tankers cannot be substituted with anything. VLAT are recommended as retardant-dropping aircraft when large airports are nearby. Unfortunately, with fires emerging in more and more deserted area, this may not be the case; hence, focus should also be laid on developing Type-III air tankers. The pressurised retardant deployment system was found to be more effective than gravity systems and is recommended to be implemented into greater number of air tankers. To eliminate conversion costs, portable systems such as MAFFS could be fitted into more aircraft.

New unmanned aircraft systems are a very promising improvement. Various types are identified as a potential substitute to monitor the fire without putting people life at risk. This includes Type-1 and 2 UVA with longer range and endurance (high altitude long-endurance UAV, medium-range UAV, tactical UAV or close-range UAV) for monitoring the whole fire beyond visual line of sight, as well as Type-3 and four UAV that are portable, hence can be launched from the fire-line and flown within line of sight.

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## Appendix A: Tables and Data

*Table A1.* Aircraft capacity and corresponding filling time

| Category | Type | Model | Code | Filling time (min) | Capacity (l) |
|---|---|---|---|---|---|
| Air tanker | VLAT | Boeing 747 Supertanker | B-747 | 13.00 | 75,710 |
| ” | ” | McDonnell Douglas DC-10 | DC-10 | 18.80 | 35,580 |
| ” | Type I LAT | British Aerospace 146 | BAe-146 | 6.00 | 11,360 |
| ” | ” | Boeing 737 BC | B-737 | 8.00 | 15,140 |
| ” | ” | Lockheed C-130 Hercules | C-130H | 8.00 | 15,140 |
| ” | Type II | Canadair CL-415 | CL-415 | 0.20 | 6,140 |
| ” | ” | De Havilland Dash 8-400AT | Dash 8-400AT | 5.28 | 10,000 |
| ” | Type III | Grumman S-2T | S-2T | 2.40 | 4,540 |
| ” | ” | Air Tractor AT-802 | AT-802A | 0.10 | 3,000 |
| Helicopter | Type I | Sikorsky S-64 “Skycrane” | S-64 | 2.51 | 10,000 |
| ” | ” | Kaman “K-Max” | K-MAX | 0.63 | 2,500 |
| ” | ” | Boeing 234 “Chinook” | CH-47 | 2.84 | 22,350 |
| ” | Type II | Bell UH-1H “Super Huey” | UH-1H | 0.34 | 1,360 |
| ” | Type III | Bell 206B JetRanger III | Bell 206B | 0.11 | 450 |

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***Table A2.*** *Single missions considered in the present study [17]*

| Aircraft | Type | Model | Code | Reg. no. | Flight | Date | Origin | Destination | Fire | STD | ATD | STA | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Non-amphibious airtanker | VLAT | McDonnell Douglas DC-10 | DC-10 | N612AX | TNKR910 | 10-Jun-22 | Albuquerque (ABQ) | Albuquerque (ABQ) | Midnight Fire | 20:06 | 19:21 | 19:06 | 0:45 |
| ” | Type I LAT | Lockheed C-130 | C-130H | N132CG | TNKR132 | 7-Sep-22 | San Bernardino (SBD) | San Bernardino (SBD) | Fairview Fire | 9:57 | 9:32 | 8:57 | 0:24 |
| ” | Type II | De Havilland Dash 8-400AT | Dash 8-400 AT | FGD540 | FGD540 | 13 Jun 21 | Kenai (ENA) | Kenai (ENA) | Loon Lake Fire | 14:31 | 14:08 | 13:30 | 0:26 |
| ” | Type III | Grumman S-2 | S-2 | N425DF | T89 | 19-Jul-21 | Chico (CIC) | Chico (CIC) | Dixie Fire | 17:56 | 17:29 | 16:55 | 0:26 |
| Amphibious air tanker | Type II | Canadair 415 | CL-415 | IDPCD | CAN07 | 19-Jul-22 | Genoa (GOA) | Venice (TSF) | – | 12:10 | 9:42 | 11:05 | 2:24 |
| ” | Type II | Canadair 415 | CL-415 | IDPCN | IDPCD | 4-Aug-22 | Trapani (TPS) | Trapani (TPS) | Evia Fire | 13:29 | 10:46 | 12:29 | 2:43 |
| ” | Type III | Air Tractor AT-802 | AT-802 | VHAWU | AWU | 21-Jan-23 | Toowoomba (TWB) | Toowoomba (TWB) | Warwick Fire | 14:01 | 14:01 | 16:39 | 2:26 |
| ” | Type III | Air Tractor AT-802 | AT-802 | EC-NDU | ECNDU | 18-Jun-22 | Sabadell (QYS) | Sabadell (QYS) | – | 15:21 | 12:24 | 14:16 | 2:53 |
| Air tactical | Fixed wing | Rockwell OV-10A | OV-10 | N470DF | A505 | 8-Sep-22 | Sacramento (MCC) | Lancaster (WJF) | Mosquito Fire | 13:49 | 10:26 | 12:49 | 3:24 |

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***Table A2.*** *Continued.*

| Aircraft | Type | Model | Code | Reg. no. | Flight | Date | Origin | Destination | Fire | STD | ATD | STA | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ” | ” | Rockwell OV-10A | OV-10 | N421DF | A240 | 3-Sep-22 | Redding (RDD) | Red Bluff (RBL) | Mountain Fire | 12:49 | 8:53 | 11:49 | 3:56 |
| ” | Rotary wing | AH-1 Firewatch | AH-1C | N109Z | N109Z | 19-Aug-20 | Truckee (TKF) | Truckee (TKF) | Loyalton Fire | 15:56 | 13:33 | 14:57 | 2:24 |
| ” | ” | AH-1 Firewatch | AH-1C | N109Z | N109Z | 2-Jul-20 | Lancaster (WJF) | Lancaster (WJF) | Rowher Fire | 10:40 | 9:02 | 9:40 | 1:38 |
| Helicopter | Type I | Sikorsky S-64 | S-64 | N4037S | N4037S | 18-Aug-20 | La Verne (POC) | La Verne (POC) | Bobcat Fire | 16:41 | 14:36 | 15:37 | 2:01 |
| ” | Type II | Bell UH-1Y Venom | UH-1 | N497DF | N497DF | 20-Aug-20 | Susanville (SVE) | Susanville (SVE) | Sheep Fire | 17:30 | 16:00 | 16:29 | 1:29 |
| ” | Type III | Bell 206B JetRanger | Bell 206B | N306FD | N306FD | 17-Jul-20 | Van Nuys (VNY) | Van Nuys (VNY) | Brush Fire | 17:51 | 16:03 | 16:51 | 1:48 |

**Table A3.** *Selected series of missions of non-amphibious aircraft (from Flightradar24)*

| Type | Model | Type code | Reg. no. | Flight no. | Date | Origin | Destination | Fire | STD | ATD | STA | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VLAT | McDonnell Douglas DC-10-30(ER) | DC-10 | N522AX | TNKR912 | 5-Aug-22 | Helena (HLN) | Casper (CPR) | Matt Staff Rd Fire | 10:55 | 10:31 | 9:55 | 0:24 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 11:44 | 11:23 | 10:44 | 0:21 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 12:32 | 12:10 | 11:32 | 0:22 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 13:21 | 13:00 | 12:20 | 0:21 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 14:17 | 13:56 | 13:17 | 0:21 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 15:09 | 14:48 | 14:09 | 0:21 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 16:01 | 15:36 | 14:56 | 0:20 |
| Type I LAT | Lockheed C-130 Hercules | C-130H | N132CG | TNKR132 | 7-Sep-22 | San Bernardino (SBD) | San Bernardino (SBD) | Fairview Fire | 9:01 | 8:37 | 8:01 | 0:24 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 9:57 | 9:32 | 8:57 | 0:24 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 10:40 | 10:18 | 9:40 | 0:22 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 11:32 | 11:08 | 10:32 | 0:25 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 12:19 | 11:56 | 11:19 | 0:22 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 13:05 | 12:41 | 12:05 | 0:25 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 14:08 | 13:34 | 13:08 | 0:35 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 15:23 | 14:50 | 14:23 | 0:33 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 16:07 | 15:45 | 15:07 | 0:22 |
| Type II | De Havilland Dash 8-400AT | DHC-8 | FGD540 | FGD540 | 13 Jun 2021 | Kenai (ENA) | Kenai (ENA) | Loon Lake Fire | 14:31 | 14:08 | 13:30 | 0:22 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 15:10 | 14:49 | 14:10 | 0:21 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 15:50 | 15:28 | 14:50 | 0:23 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 16:38 | 16:14 | 15:33 | 0:19 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 18:14 | 17:46 | 17:14 | 0:28 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 18:55 | 18:32 | 17:55 | 0:23 |

**Table A3.** *Continued.*

| Type | Model | Type code | Reg. no. | Flight no. | Date | Origin | Destination | Fire | STD | ATD | STA | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type III | Grumman S-2 Tracker | S-2T | N435DF | T72 | 29 Aug 2022 | San Bernardino (SBD) | San Bernardino (SBD) | Gulch Fire | 13:18 | 12:52 | 12:18 | 0:26 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 13:55 | 13:29 | 12:55 | 0:26 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 14:34 | 14:07 | 13:34 | 0:27 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 15:35 | 15:11 | 14:35 | 0:25 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 16:22 | 15:46 | 15:22 | 0:36 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 17:11 | 16:36 | 16:11 | 0:35 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 17:52 | 17:23 | 16:52 | 0:29 |
| ” | ” | ” | ” | ” | ” | ” | ” | ” | 19:02 | 18:35 | 18:02 | 0:27 |

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***Table A4.*** *Aircraft efficiency and cost comparison; data analysis with all missions considered*

| Category | Type | Code | Capa-city (l) | Effi-ciency (L/min) | Time on ground (hr:min) | Mission time (hr:min) | Drops per mission | Missions per day | Drops Drops per day | Reta-rdant cost per day ($) | Flight time per day (min) | Hour rate ($) | Flight cost per day ($) | Total cost per day ($) | Cost of 1 litre drop ($/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air tanker | VLAT | B-747 | 74,000 | 736 | 0:53 | 0:49 | 1 | 7 | 7 | 448,782 | 347 | 22,000 | 127,415 | 576,198 | 1.12 |
| ” | ” | DC-10 | 45,420 | 606 | 0:33 | 0:47 | 1 | 9 | 9 | 349,952 | 423 | 8,200 | 57,854 | 407,806 | 1.01 |
| ” | Type I | BAe-146 | 11,356 | 217 | 0:23 | 0:33 | 1 | 13 | 13 | 124,918 | 422 | 8,000 | 56,223 | 181,141 | 1.26 |
| ” | ” | B-737 | 15,142 | 273 | 0:15 | 0:48 | 1 | 11 | 11 | 149,920 | 549 | 8,220 | 75,149 | 225,069 | 1.31 |
| ” | ” | C-130H | 15,142 | 286 | 0:26 | 0:29 | 1 | 13 | 13 | 168,799 | 376 | 7,000 | 43,824 | 212,623 | 1.10 |
| ” | Type II | CL-415 | 6,136 | 410 | 1:02 | 2:11 | 12 | 2 | 23 | – | 253 | 13,500 | 57,003 | 57,003 | 0.40 |
| ” | ” | DHC-8 | 10,000 | 187 | 0:23 | 0:33 | 1 | 13 | 13 | 110,002 | 427 | 3,600 | 25,626 | 135,627 | 1.07 |
| ” | Type III | S-2T | 4,542 | 122 | 0:12 | 0:27 | 1 | 18 | 18 | 70,817 | 490 | 4,000 | 32,639 | 103,456 | 1.27 |
| ” | ” | AT-802A | 3,028 | 187 | 1:23 | 2:11 | 13 | 2 | 23 | – | 239 | 4,500 | 17,936 | 17,936 | 0.26 |
| Helicopter | Type I | S-64 | 10,030 | 637 | 0:49 | 2:21 | 12 | 2 | 27 | – | 328 | 3,920 | 21,446 | 21,446 | 0.08 |
| ” | ” | CH-47 | 11,356 | 604 | 0:53 | 2:22 | 10 | 2 | 23 | – | 325 | 4,600 | 24,932 | 24,932 | 0.10 |
| ” | Type II | UH-1H | 1,363 | 182 | 0:25 | 1:16 | 13 | 4 | 57 | – | 339 | 2,500 | 14,105 | 14,105 | 0.18 |
| ” | Type III | Bell 206B | 454 | 82 | 0:25 | 0:53 | 14 | 9 | 124 | – | 489 | 400 | 3,257 | 3,257 | 0.06 |