Quantifying Weather Tolerance Criteria for Delivery Drones – A UK Case Study

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Abstract— **As demand for final mile delivery has increased, the use of delivery drones is being explored in many countries, including the UK. Despite offering perceived benefits over existing methods in terms of delivery speed and reliability, there is little understanding of the design criteria needed for drones to actually realise them. This paper investigates how reliability and resilience of deliveries vary by transport mode, relating to the delivery success (i.e., can a delivery be made in a given time-window), and the flexibility of this success (i.e., how many different time windows are possible).**

Comparing the performance of current UK ground transport modes and drones using historic weather and reliability data, a review of the factors that contribute to what makes a reliable and weather resistant drone service is presented. Results suggested that a significant wind tolerance would be required to achieve a level of service equal to ground transportation, with VTOL platforms requiring tolerances ranging from 14 m/s (Solent region), to more than 23 m/s (Scottish Hebrides). Fixed-wing platform tolerances were not as high, with a tolerance of 10 m/s achieving flights on almost all days in all case study areas.

It is likely that some locations cannot reliably be served by drone and must depend on contingency options when flights are not possible. With significant variations in tolerance requirements, and notable seasonal variances, applications of delivery drones should be considered on a case-by-case basis, comparing to existing modes, to ensure reliable supply chains are realised.

Keywords—drone, UAV, wind tolerance, reliability, resilience

I. BACKGROUND

Demand for final mile parcel deliveries has grown by 30% in the last 5 years (avg. 6% per annum.) [1], creating significant challenges with respect to reducing the environmental impact of the industry whilst remaining reliable and financially sustainable [2]. Modal shift towards cargo bikes [3], [4], walking porters [5], and motorbikes/mopeds [6] is being explored by multiple carriers, particularly where the urban environment reduces the efficiency of traditional logistics vehicles (vans/light goods vehicles, LGVs), or travel speeds are of particular importance.

The potential for aerial drones (a.k.a. unmanned/uncrewed aerial vehicles, UAVs) as a delivery method is also being explored in many countries [7]–[12], with case studies being tested in both low-income and high-income countries (LICs and HICs), respectively. A large proportion of use cases test medical applications, delivering items such as pathology samples [13], medicines and vaccines [14], or blood for transfusion [12]. Other applications for consumer goods [10] or food/drink [11] are also being tested.

A key perceived benefit of delivery drones, particularly in medical applications, is faster delivery and improved reliability; however, many studies and trials fail to acknowledge the effects of weather conditions on operations. With a variety of use cases having been explored, industry reports and peer-reviewed studies may have overstated the benefits of such applications as a result, ignoring or downplaying some of the key limitations of the technology [15]–[17]. Additionally, the published performance metrics for drones may have not been tested in extreme conditions with weather tolerance being one area where design tolerance may be overinflated.

Conversely, some studies that question the application of drones for last-mile delivery have emerged [18]–[21], citing the challenges around regulation, safety, noise, cost, and resilience. Furthermore, there is debate over whether some use cases are valid, with Ireland's Manna drone claiming their drone delivery to be "'zero-emission" and "greener" than existing deliveries [8], whilst also claiming that drones will replace already green gig-economy pedal cyclist jobs [22]. In the USA, UPS have also noted significant issues with flyability in inclement weather [23]. Such articles highlight the large challenges and emphasise that delivery drones may not be the complete solution [21], [24], begging the question, what criteria do drones need to meet to become viable in the long-term with regards to cost, performance, and reliability.

In the case of the National Health Service (NHS) in the United Kingdom (UK), many delivery drone trials are exploring the expedited movement of time-sensitive items such as patient samples and medicines [13], [25], however, no trial has developed into a sustained and commercial operation. This is, in part, due to airspace and regulation challenges, though reliability is also an important contributing factor [23], [26]. Healthcare supply chains have been cited as needing to be reliable to enable quality care [27], [28], suggesting that should a new delivery method be implemented, any uncertainty in terms of delivery success and timing may be problematic. Understanding the minimum service criteria is key to developing such a system.

To this end, this study presents a comprehensive literature review comparing delivery drone performance against ground transport modes for last-mile delivery, followed by a desktop analysis quantifying the required weather performance criteria for drones to be capable of realising benefits over well-established ground transportation. Focussing on the reliability and resilience of deliveries (i.e., can a delivery be made in a given time-window), and flexibility of deliveries (i.e., how many different time windows are possible), the investigation answers the research question "What are the required weather tolerance characteristics for a delivery drone to be sustainable and competitive for long-term operations in different settings in the UK?".

II. Literature Review

When compared to existing modes of transport, drones are often marketed as more reliable, more environmentally friendly (lower energy and emission), safer (fewer road traffic accidents), cheaper to run, and faster (end-to-end delivery) [21], [29]; however, few studies have sought to encompass the full extent of operations or realistic constraints into their assessments.

VillageReach, who specialise in healthcare supply chain improvement in LICs, often with the use of drones, developed a healthcare supply chain integration framework, noting that supply chains need to be resilient, sustainable (financially), people centred, and equitable [30].

To further understand what the operating criteria may be in relation to the performance of delivery drones in different weather environments, this paper focuses on the resilience aspects of operations.

A. *Weather Resilience*

Schenkelberg [31] investigated the potential reliability concerns associated with delivery drones and identified the need for contingency planning in case of failure alongside existing transport methods.

With designs and the reliability of components varying significantly between drones being used, it is difficult to generalise on performance in that respect; therefore, one of the main external factors affecting reliability, weather conditions, is the subject of this paper.

The effects of weather can impact on journey reliability (whether a journey is made or not) and punctuality (how close to the planned schedule a journey is). In this study, the main focus relates to reliability as this is the more fundamental indicator for whether deliveries are possible by each mode.

Weather is generally not a problem for road-based deliveries in HICs such as the UK, except during extreme weather events such as life-threatening wind storms [32], [33], floods [34], or heavy snow [35]. In LICs, this trend follows in areas where all-weather roads are accessible and vehicles are well maintained, but where all-weather roads are not present, the performance of vehicles can vary significantly [36]. In the event of heavy precipitation, roads can become impassable and result in failed delivery, or surfaces can hinder vehicle progress and delay the arrival of goods. Introducing less reliable legs of a journey, such as transport over water (e.g., by ferry), will likely reduce the potential resilience of the delivery operation. A reduction in flexibility is also likely given that ferry crossings are scheduled and may run with a limited frequency.

Crewed air transport is also typically quite resilient, but the threshold for a weather event to cause flight disruption is lower than that of ground freight [37], [38]. Commercial jets have crosswind limits but virtually no headwind limit other than during take-off and landing, where gusting crosswinds can cause issues with alignment to the target runway [39]. Using different runways will allow the crosswind component to change and enable take-off/landing. Vertical Take-Off/Landing (VTOL) platforms, such as helicopters, do not have this luxury as they are fixed in orientation and have zero airspeed on take-off until transition into forward flight is complete.

Other modes, such as rail freight and shipping, are also generally quite resilient, though lighter, faster vessels are more susceptible to weather disruption at times when larger ships continue as scheduled [40]. Based on these trends, it could be said that faster transport comes at a cost of reduced reliability.

With respect to drones, the platform configuration can dictate how resilient operations can be at times of bad weather [41], [42]. The means of take-off/launch will dictate which type of wind the platform is susceptible to. For example, fixed-wing aircraft are not as sensitive to constant winds (unless extreme) and their ability to fly safely is most affected by the size of the gust amplitude (difference between gust and constant wind) during take-off and landing, particularly when crosswinds are prevalent, much like with crewed aircraft [39].

Meanwhile, VTOL drone platforms are susceptible to both gusts and the constant wind, with gusts affecting their stability [41], [43], and all winds affecting their required banking angle (Figure 1), reducing stability and increasing the risk of propellor strike on take-off/landing and motor burnout due to increased drag during cruise. Hybrid VTOL-fixed-wing platforms can avoid the cruise issues of fully VTOL platforms but can still suffer the take-off/landing limitations. Meanwhile, catapult launch systems of some fixed-wing platforms will negate most wind-related issues of take-off [12].

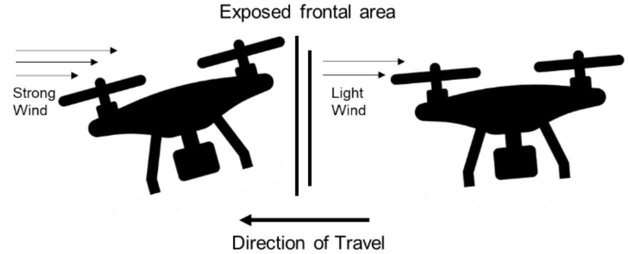

Figure 1. Demonstration of the effects of strong winds on VTOL drones

It should also be noted that the delivery mechanism used will also dictate how safe/reliable it is to complete a delivery in different operating conditions. For example, deliveries that are lowered from the drone by cable may be more challenging in strong winds due to the stability required for the drone to hover in a near stationary position and the energy demand resulting from this.

Following a thorough audit of the delivery drones in production/testing at the time of writing [44], the authors' found that the majority of drone providers do not list a weather tolerance of their platforms. Those manufacturers that did report such characteristics were not consistent in what they were reporting, and rarely stated the frame of reference, e.g., a wind speed limit, but no designation of whether this relates to gust or constant speeds, nor specifying whether the limit applied to take-off/landing or cruise.

Gao et al. [45] conducted a similar audit of drones more generally and noted particular ambiguity around drone specifications. As part of their study of drone flyability, it was found that if weather tolerances were increased from 0 mm/h to 1 mm/h and 10 m/s to 15 m/s (sustained wind, gusts ignored), global flyability was improved from 41% to 87% of hours. Whilst these findings help to define the criteria in which drones can be more successful, the absence of gust effects and consideration of different configurations (fixed-wing, VTOL, etc.) limits their use when developing a competitive delivery drone offering. Furthermore, identifying what the equivalent ground transport mode achieves is key for decision making.

Modelling in Gao et al.'s study [45] identified that flyability over large bodies of water significantly limited flyability due to increased winds. In the context of the UK, this is particularly challenging due to the proximity to the Atlantic Ocean. Mainland Europe was seen to be less hostile, though Northern Europe suffered similar challenges.

A notable drone characteristic which has been explored in several drone case studies in the UK, is the ability to travel over water to better connect more remote communities [13]. For these use cases to achieve sustained and reliable operation, understanding the performance criteria is particularly important.

Oakey et al. [24] studied the viability of such a delivery drone service, collecting pathology samples from local clinics. Weather limitations to specific NHS origin-destination (O-D) pairs were applied using sustained wind data at all sites and wind gust data at the delivery location. It was found that weather conditions would have prevented flights on 19% of days (10 m/s wind tolerance), making reliability of the service a challenge. The study also highlighted a trade-off between a potential speed benefit and uncertainty of delivery success.

B. Indirect Effects of Weather

Whilst not necessarily affecting whether a delivery can be made, weather effects can influence the speed of deliveries.

Should a delivery be attempted at a given point in time, adverse weather conditions may potentially affect travel conditions such that ground speeds (as opposed to airspeed) may be significantly slower. For ground transportation, this can be seen if road conditions are significantly worsened, e.g., surface damage by flood water, or if a road is closed for safety, e.g., a bridge in high winds. In aviation, this is more obvious, with headwinds greatly reducing the speed of delivery [46]. Conversely, delivery speeds can also be increased if winds are tailwinds. The speed of delivery is not likely to vary significantly over short distances, though certainty over delivery timings, particularly in emergencies is important for maintaining resilient supply chains [47].

The quality of the existing infrastructure can make a significant difference to average travel speeds, with road safety and congestion, and ferry timetabling directly impacting the speed of travel. In Rwanda, where "Zipline" operate, 70% of the road network is in poor condition and up to 27% can be impassable (2020/21) [36], particularly at times of flooding [48], potentially impacting travel speeds and making drone services more competitive. Comprehensive plans are in place to improve the network and make all roads passable by 2027, so there is potential that road transport may become significantly faster and dramatically reduce the advantages of drones. For brevity, this paper does not investigate these issues further, though they are important to highlight, particularly when considering if there is a realised benefit of using drones.

Several studies of drone flyability have been presented by existing literature, though there are evident gaps in terms of applying such flyability to given use cases and comparing them to existing transport methods to establish the requirements for delivery drones to be competitive and reliable. This paper addresses these gaps, and assesses the potential implications of the flyability trends through a desktop study.

III. METHODOLOGY

Building on the study by Oakey et al. [24], this paper presents a series of desktop analyses that compare the journey reliabilities of different delivery methods due to the effects of weather. The study then identifies criteria that need to be met for drones to achieve competitive and sustainable operation.

To best align with other drone use cases and the previous research [24], this study focused on a medical context in the UK, though the methods and findings can apply to delivery drones more generally. Furthermore, the results are likely to apply to countries with similar climates. A series of different environments were tested to enable a comparison of the different applications and modes that could be used. The environments explored include the following:

- Urban Setting (2-16 km), London, UK [49], inter-hospital.
- Rural Setting (8-64 km), Scottish Highlands/Islands, UK [13]. Potentially including a water crossing, Oban – Mull.
- Inter-Urban Setting (8-128 km), Solent region, UK [25], [50], Southampton – Bournemouth. Potentially including a water crossing, Portsmouth/Southampton – Newport, Isle of Wight.

As a comparator, Zipline's operations in Rwanda were also investigated to identify the weather tolerances of their established drone logistics network.

- Inter-Urban/Urban-Rural (8-128 km), Rwanda [12], blood distribution to remote clinics.

To capture the typical reliability of services, weather data from a whole year (Mar 2019-Feb 2020) were captured for several key use cases in each environment. The data were provided by the MeteoStat API for all cases [51], with analyses using average wind speeds, and peak gust speeds. The API returned a range of other values, including wind direction, precipitation, temperature, pressure, humidity, and dewpoint, but these were not required in the analysis.

In the case of Zipline, the weather station data did not capture peak gusts, so a monthly mean gust factor was derived (Equation 1, below) from another data source to approximate [52], based on the simple gust factor model explained by Harris et al. [53]. The direction of winds was not consistently recorded, so peak gusts were assumed to be the limit for VTOL aircraft (Equation 2, below), and the gust amplitude was used for fixed-wing aircraft (Equation 3, below).

$$\begin{aligned}\boldsymbol{Derived\ Peak\ Gust} &= \boldsymbol{Avg.Wind\ Speed} \\ &\quad \times \boldsymbol{Month\ Peak\ Gust\ Factor} \\ &= \boldsymbol{Avg.Wind\ Speed} \times \frac{\boldsymbol{Month\ Mean\ Wind}}{\boldsymbol{Month\ Peak\ Gust}} \end{aligned} \quad (1)$$

$$\boldsymbol{VTOL\ Required\ Tolerance} = \boldsymbol{Peak\ Gust} \quad (2)$$

$$\begin{aligned}\boldsymbol{Fixed\ Wing\ Tolerance} &= \boldsymbol{Gust\ Amplitude} \\ &= \boldsymbol{Peak\ Gust} - \boldsymbol{Avg.Wind\ Speed}\end{aligned} \quad (3)$$

A drone was assumed to be able to realise a delivery if its tolerance was greater than or equal to the given wind speed (gust amplitude for fixed-wing or peak gust for VTOL). The calculated tolerances correspond to the required maximum peak gust resistance for VTOL platforms, and the maximum required gust amplitude resistance for fixed-wing platforms with respect to a given service level. Delivery success on a given day means at least one hour's wind measurements in the daily window was within the tolerance of the drone. Delivery flexibility is given by the number of hourly periods in the daily window that were within the drone's tolerance.

Peak gust was used for VTOL platforms due to being the maximum absolute wind that would need to be resisted during all stages of flight (take-off/cruise/landing). Meanwhile, fixed-wing craft benefit from the stability of their wing providing lift, meaning that they can largely tolerate constant winds with little impact on stability (direction dependent), and their flight capability is most affected by the gust amplitude, or the change in wind speeds. Hybrid craft would behave as VTOLs during take-off and landing, and as fixed-wing during cruise.

Rainfall was not included in this comparison, as it is assumed that at least a basic level of precipitation tolerance is inherent to give improved flyability, as suggested by Gao et al. [45]. Likewise, ground vehicle traffic data were excluded from the analysis to limit the scope of the study to solely delivery success, as opposed to delivery time reliability.

In the Solent and Hebridean case studies, drones were used where existing transport requires travel over water or other challenging terrain, so performance data for the 'competing' service was used to set a benchmark for reliability. The Solent data was extracted from posts by @HoverTravelLtd on Twitter, where service updates was consistently posted during times of disruption [54]. The Hebrides data were collected from the Caledonian MacBrayne performance data made available on their website [55]. In both cases, data from Mar 2019-Feb 2020 (inclusive) were used to avoid the effects of the COVID-19 pandemic and match the weather data period.

IV. Results

In the UK, access to all weather roads is exceptionally high, with 97% of the rural population living within 2 km of an all-weather roads (a.k.a. rural access index, RAI [56]). Within reason, it can be assumed that road vehicles can operate in any weather conditions on the mainland, with the exception of extreme events such as heavy snowfall or flooding. Translating this to a delivery success rate, it could be assumed that road vehicles will be able to deliver on ~100% of days (i.e., delivery is possible at some point of the day). In terms of flexibility, it can also be assumed that road vehicles can deliver during ~100% of hours in a given day, meaning weather conditions do not limit when the vehicles can be used successfully. As a result, the main resilience issues for freight in the UK are caused by traffic conditions and ferry/hovercraft performance and not road passability.

In comparison, 80% of rural Rwandans live within 2 km of an all-weather road, and road passability data are not available, making it difficult to assume the near certainty seen in HICs [36]. The reduced level of all-weather road access is likely to lower freight reliability by road, making the drone performance benchmark far more reserved.

Figure 2 shows the percentage of days in the 12-month period when a flight is possible (between 0800-1700), for a given wind tolerance by drone. The VTOL plots are based on the peak gust data measured by the local weather stations, whilst the fixed-wing (FW) plots are based on the gust amplitude. This could be viewed as the performance level achieved for routine or non-urgent deliveries. Meanwhile, Figure 3 shows the percentage of hours between 0800-1700 throughout the 12-month period when a flight is possible. This could be viewed as the flexibility of a given drone service.

Both plots demonstrate a general trend of VTOL platforms having a significantly lower service level than a fixed-wing platform in the same service area, owing to a need to tolerate the maximum absolute wind in the area, as opposed to just the difference between the gust and constant wind. As would be expected, the daily delivery realisation service level is higher than the hourly service level, as only one hour within the time window need be flyable for a daily success. The ferries achieve high performance levels in both cases.

1) *Solent Use Case*

In the Solent, there are multiple ways for freight to cross from the mainland to the Isle of Wight, with a few hundred crossings per day between all operators, meaning frequency of service is not an issue [57]. The main source of uncertainty comes from the reliability of services in poor weather, with the hovercraft option being the least resilient. Despite its vulnerability to adverse conditions, delivery would have been possible on 99.6% of days in the period Mar 2019 – Feb 2020. In terms of realised service flexibility, 95.4% of timetabled services were successfully completed, suggesting that the deliveries are likely to be possible at most times of day and year.

For a drone to match this level of service when the time of day is not important, a 14 m/s tolerance is required for VTOL drones, and 6m/s for fixed-wing drones. To match the timetabled service success rate (flexibility), VTOL and fixed-wing platforms must be capable of flying in 13 m/s and 6m/s winds, respectively.

2) Hebrides Use Case

In the Scottish Hebrides, the majority of ferries are operated by one company (Caledonian MacBrayne), with varying frequencies that depend on demand. The exact use case explored by the drone operator 'Skyports' was between Oban and Mull, in the Inner Hebrides, where services typically operate approximately every 2 hours [55]. Across all timetabled services in the Inner Hebrides, 97.3% were realised in the period Mar 2019 – Feb 2020, whilst at least one timetabled service operated on 100% of days. This suggests that the services are very resilient, though potential delivery delays could be substantial if a scheduled service is missed or not completed.

For drone services to match the ferry services in terms of timetabled service resilience, a wind tolerance of

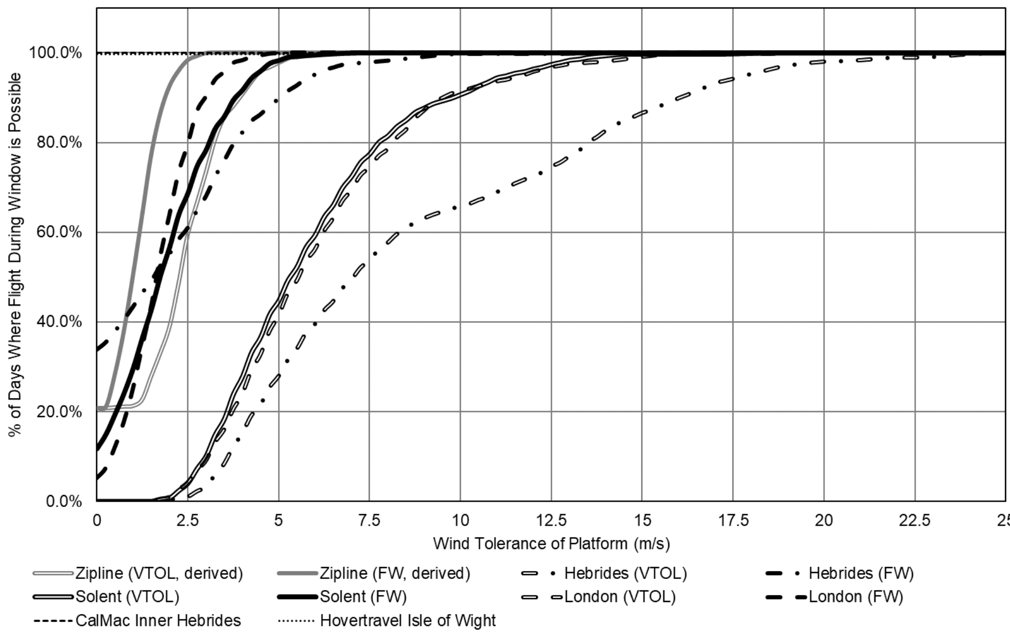

Figure 2. Predicted drone reliability by day at different wind tolerances in different use cases based on a weather window 0800-1700 March 2019-Feb 2020. VTOL = Vertical Take-off/Landing, FW = Fixed-wing. Fine dashed lines indicate ferry service benchmarks.

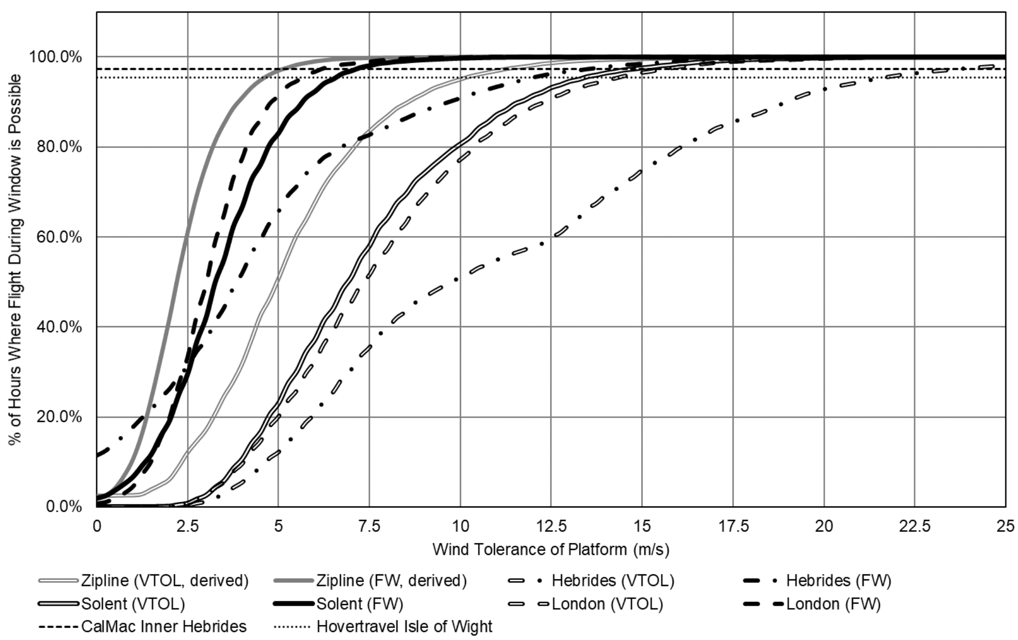

Figure 3. Predicted drone flexibility by hour at different wind tolerances in different use cases based on a weather window 0800-1700 March 2019-Feb 2020. VTOL = Vertical Take-off/Landing, FW = Fixed-wing. Fine dashed lines indicate ferry service benchmarks.

approximately 23 m/s would be required for VTOL platforms, and 13 m/s for fixed-wing. If the time of day is not important, a wind tolerance of 23 m/s for VTOL platforms and 10 m/s for fixed-wing platforms would be required to realise a delivery at any point in the day.

For other parts of the Scottish Islands, such as the Outer Hebrides, the ferry service is less resilient and frequent, meaning that the expected drone service level is also lower; however, the weather conditions in these more remote areas can be more hostile, so operating performance may have to increase to achieve this.

3) *London Use Case*

In London, there is near certainty over deliveries being possible, but there may be reasonable variability in terms of van journey times due to being a very dense urban environment [58]. These issues may be alleviated by using cargo cycles and motorbikes, which are generally less susceptible to traffic congestion delays.

To guarantee equivalent levels of both service and flexibility, VTOL drones must be capable of flying in 22 m/s winds, whilst fixed-wing drones must be capable of flying in 11m/s winds.

4) *Rwanda Use Case*

On investigation of Zipline's largely successful operations in Rwanda, it becomes quickly apparent that the winds experienced are considerably less hostile than in the UK case studies.

For maximum flexibility with VTOL platforms, a tolerance of around 12.5 m/s would be needed, whilst around 5 m/s would guarantee delivery on a given day. Fixed-wing platforms could have full flexibility with a tolerance of 7.5 m/s and guarantee delivery with just a 3 m/s tolerance. These limits align with Gao et al.'s study of wind speeds, which indicated significantly improved flyability when upgrading tolerances from 10m/s to 14 m/s.

5) *Seasonality*

Exploring the distribution of flyability throughout the year (Figure 4), it is quickly seen that the UK based sites experience very seasonal trends, with the late spring-autumn period (April-October) offering the best rates of flyability. The hovercraft's performance also followed with seasonality, potentially making contingency planning for drones more difficult, however, other more reliable crossings are also present in the region. Meanwhile, the operations in Rwanda, where the Zipline case study operations take place, suffered minimal seasonal variance in terms of wind (rainfall may affect operations differently).

Gao et al. [45] also noted seasonal effects, with latitudes closer to the equator having consistently higher flyability. This follows in the UK case studies, with Solent experiencing better flyability than London and the Hebrides.

V. Discussion

As would be expected, a clear advantage is seen in using fixed-wing platforms instead of VTOL in all of the case studies; however, using fixed-wing in most UK case studies is not realistic or practical due to space limitations, meaning the required wind tolerances are much higher due to the need for VTOL capability.

Zipline's catapult launch offers a reasonable compromise, though regulators may be more concerned about delivery safety in the UK, limiting the deployment of such a system. In addition to reduced regulation [59], the Rwandan comparator stipulates wind tolerances need not be as high; hence, successful operations are far easier to establish. Nevertheless, challenges evidently remain in terms of operational cost [12].

Relating the UK service levels and performance criteria to achieving a successful delivery service, it becomes apparent that even within one country, the effect of environments can vary significantly. As a result, it is likely that the drone operators will have to (i) cater for the worst-

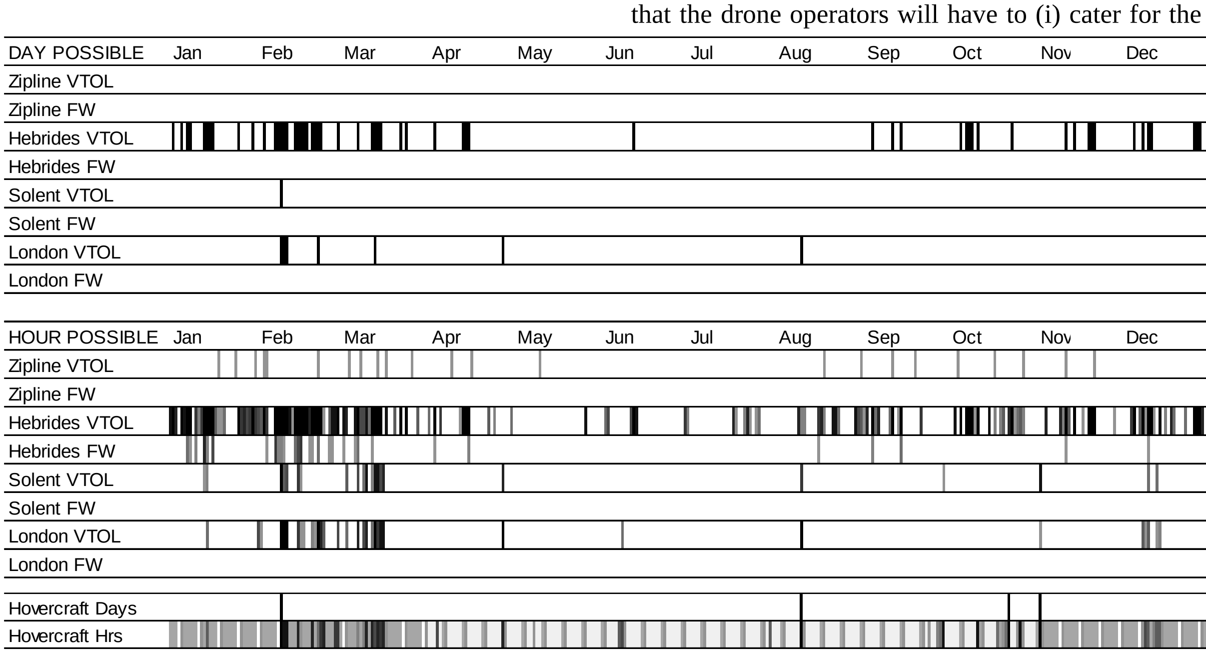

Figure 4. Predicted drone flyability based on 14 m/s wind tolerance. Top: days flights possible, middle: hours flights possible, bottom: days/hours Solent hovercraft was possible. Black indicates no flyability, white indicates full flyability. FW = fixed-wing, VTOL = vertical take-off/landing.

case scenarios; or (ii) limit the scope of the drone services offered.

In the case of the former, any drone used would need to be sufficiently engineered to match or better the current service levels. In Scotland, where ferry services are significantly less frequent, there may be some scope for reducing these criteria, though the trade-off between flight uncertainty and improvement in flexibility may be a challenging compromise to achieve. Conversely, catering for the worst-case across all the environments would help to minimise costs and improve technical reliability if just one drone model is used.

Should operators choose to limit the scope of drones, services would be operated on the premise that flights would not be possible on some days, with potentially very little notice given. Supply chains require service reliability, and rehearsed contingency options would be a key part of this approach.

Oakey et al.'s original study proposed taxis as an alternative option on the mainland [24], whilst other studies have proposed using patient transfer vehicles that already operate in the area. Cross-water delivery contingency could be served by competing ferry services, though the disruption caused by the increase in delivery times would need to be accounted for.

The seasonality of drone use could be advantageous, as it may allow drone flights to service routine deliveries during the summer, whilst the poor service offered in winter can be replaced my traditional methods. In terms of a service offering, this may not necessarily be attractive, given the potential skew in supply chain efficiency throughout the year.

To fully leverage the range of benefits offered by delivery drones (e.g., energy reduction, time improvements, etc.) whilst minimising the impact of weather disruption, it may be preferable to use a combination of modes, as suggested by Goodchild and Toy [60], regardless of the environment where they are being deployed.

VI. Conclusions

Drones present a novel method of transporting goods and have potential benefits in terms of speed, environmental impact, and cost. Literature has often overstated their speed advantages, though there are many cases where there are clear benefits in their adoption.

This paper has presented a review and analysis of the factors that contribute to making a reliable and weather resistant drone service. Comparing the performance of current ground transport modes and drones using historic weather and reliability data, it was found that consideration of the competing modes and the environment they operate in is key for services to be viable and resilient.

Investigating key case study areas in the UK, results suggested that a fairly significant wind tolerance would be required to achieve a level of service equal to ground transportation. To match ground transport modes, VTOL platforms required a tolerance in the region of 14 m/s in the Solent, 22 m/s in London, and above 23 m/s in the Scottish Hebrides. Fixed-wing tolerances need not be so large, with a gust amplitude tolerance of 10 m/s achieving flights on almost all days in all case study areas. In contrast, a well-established drone network in Rwanda only required wind tolerances of ~7.5 m/s (fixed-wing) and 12.5 m/s (VTOL) for full flexibility, supporting the findings of Gao et al. [45].

Despite fixed-wing platforms being more resistant to weather influences, VTOL platforms may be more suitable in many use cases, meaning that delivery drones wind tolerances must be improved for successful operation. Furthermore, an absence of sufficiently capable platforms is potentially limiting the establishment of successful drone delivery networks in windier countries.

Given the high tolerances required, it is likely that there will be some locations that cannot reliably be served by drone and must depend on contingency options when flights are not possible. Seasonality may give some relief in terms of management of contingency and vehicle arrangements, though may be challenging to realistically leverage.

Identifying how to manage contingency and minimise disruption is important; however, some case studies/deliveries may not be able to use contingency options if the supply chain depends on predictable delivery. With significant variations within one country, it is advisable to assess delivery drone applications on a case-by-case basis and consider all available transport methods to ensure that the best options are used.

Acknowledgment

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