Essays in the Regulation of Drones and Counter-Drone Systems

by

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Abstract

Rapid growth in the use of drones potentially delivers significant economic benefits, but it has also given rise to considerable public concern about safety risks, infringement of privacy, and other unwelcome surveillance and observation. Drones are able to be operated remotely from the pilot, making it difficult to identify the operator and attribute liability for harm caused. This in turn means that existing regulatory frameworks might not induce an efficient level of drone-related harm.

The first substantive chapter of this thesis considers measures to address concerns about privacy and surveillance. I propose the adoption of a package of measures including: tort law reform, the promulgation of a "Code of Practice for Drone Operations" under New Zealand's Privacy Act 1993, a remotely-readable identifier to identify approved operators, provision for aerial trespass by unmanned aircraft, provision for the destruction of unmanned aircraft committing trespass, and the clarification of what constitutes a privacy violation by broadcast or closed-circuit television and video systems.

Fundamental to those proposals are the concepts of drone registration and the legalisation of the right to self-defence against drones. Registration requires that a drone is registered with the regulatory authorities, with a registered drone being traceable back to the owner of the drone. Registered drones may also be required to carry a remotely-readable identifier. Legalisation of self-defence allows bystanders to take defensive actions against drones, with the potential for a drone to be destroyed. Both of these mechanisms provide a means by which the operator of a drone faces some cost if they are causing harm, and thus may induce more efficient actions by the drone operator.

This thesis establishes a theoretical framework for self-defence, registration, and registration in conjunction with self-defence. Conditions are established under which each will be the preferred form of regulation. It is also established that the status quo, with neither registration nor self-defence, is likely to be optimal when harm from drone activity is relatively low.

The conditions established around when self-defence is efficient also provide the conditions for the regulation of counter-drone systems. I identify the legal impediments to the implementation of drone-detection systems and counter-drone systems in New Zealand, and propose a regulatory framework to allow the adoption of those systems.

Acknowledgments

I wish to express my gratitude to my supervisor Emeritus Professor Lew Evans for his support and advice, commencing from when I first approached him with the idea of writing a Masters' thesis on the regulation of unmanned aircraft. His questioning led me to expand the scope of my thesis from purely safety-related matters to consider a much wider breadth of harm potentially caused by drones, including privacy violations and the effects of surveillance, and then further increase the depth of my thesis so that a PhD was more appropriate.

I also wish to thank my secondary supervisor, Dr Paul Calcott, who became part of my supervisory team when I changed from a writing a Masters' thesis to writing a PhD thesis. Paul introduced me to the wonderful world of LaTeX and python, as well as providing guidance to my model building to help achieve a more structured result. He both encouraged me to simplify my model building and suggested new lines of enquiry.

I approached the oral defence not really knowing what to expect; Professor Evans and Dr Calcott assured me that I had nothing to be concerned about, but at some level I half expected the process to be something like a cross-examination in the High Court. As it turned out, my oral defence was an enjoyable affair, and one that I would happily repeat again. Thank you to Professor Nicholas Agar who chaired the committee: the tone you set made it easy to relax and focus on the task at hand. Thank you also to the examination committee - Professor Robert Hahn, Professor Basil Sharp, and Dr Vladimir Petkov - both for making the examination process enjoyable and for your helpful comments for future publications.

I would also like to thank Air Commodore Steve Moore (retired) for his initial topic suggestion. I was talking to Steve in the officer's mess at RNZAF Base Ohakea soon after he had taken up the position of Deputy Director General Aviation at the Civil Aviation Authority. When I asked him what questions would be of most interest to him in his new role, he suggested that the regulation of unmanned aircraft, particularly the institutional arrangements for regulating safety. This thesis is probably not quite what he had in mind, but his suggestion provided the basis for this entire endeavour.

Thanks also go to Nicola McCloy for her assistance in editing several of the papers produced as part of this thesis, and the helpful comments she offered as part of that process. I must also thank the various anonymous peer reviewers of those papers: even when I disagreed with their comments, they always helped me refine and strengthen my arguments, and on occasion to discard lines of argument that lacked robustness.

Finally, I would like to thank Heather Andrews for introducing me to the world of aviation and aviation regulation. That began a journey of writing manuals of operating procedures (expositions) for scenic flight operators and Adventure Aviation operators, and ultimately to writing expositions for drone operators, teaching drone operators, and working with the emerging realm of drone regulation. Without that introduction I would never have embarked on writing this thesis.

Contents

Chapter 1

Introduction

Drones are aircraft without a person on board. Civilian drones typically carry a camera as their primary payload, but may also dispense agrichemicals, or deliver packages including medical supplies. Consulting studies estimate that the potential use of drones could deliver significant benefits to the economy (Andrews & Shelley, 2015; McIlrath, 2019). However, drones may also be the agent of harm, whether inadvertently, negligently, or intentionally. The characteristics of drones are such that such harm may be more likely than with manned aircraft, and it may be difficult to identify the operator and attribute liability. Around the world, regulators are faced with the problem of establishing a regulatory regime that facilitates attainment of the benefits that widespread drone use promises, while also controlling the amount of harm. An important area of policy research is the extent to which existing legal and regulatory frameworks designed for manned aircraft might require amendment to address the challenges posed by drones.

This thesis analyses the efficiency of two of the main policy options for controlling the harm from drones: registration and the use of counter-drone systems. Registration requires all drones above a certain threshold to be registered with the regulatory authority; it might or might not also be accompanied by some means of remote identification. The assumption is that registration will enable the drone to be identified in the event of a harmful event, and thereby enable legal sanctions to be imposed. Counter-drone systems are electronic and physical systems that may repel, take control of, or destroy a drone. They may be thought of as a subset of a broader set of actions that might be considered to be utilising “self help” remedies against drones. Another subset of this broader set is drone detection systems which enable a bystander to detect and possibly identify a drone, and then take action to reduce the likelihood of harm or mitigate any harm that does occur. Registration and self-defence could be considered as as alternative mutually-exclusive policies, but my analysis shows that both, together, may at times being more efficient than either individually.

The remainder of this introduction is structured as follows. Section 1.1 briefly summarises the potential sources of harm from drones and the characteristics of drones that make that harm more likely with drones than with manned aircraft. Section 1.2 discusses the traditional approach to attribution of liability for harm within the aviation industry, as well as the different approach adopted for privacy violations. The difficulty of identifying the operator of a drone, and hence attributing liability, is noted. Section 1.3 presents my research questions. Section 1.4 discusses the ability of law and economics analyses to provide meaningful policy predictions to answer those research questions. Finally, section 1.5 provides an outline of the thesis structure, including the broad positioning of the analysis within the wider literature.

1.1 Potential for Harm

As I detail in Appendix A, the potential sources of harm from drones are manifold. Drones can be used to conduct unwelcome surveillance and may result in privacy violations. They can cause harm to an individual if they fly into a person, or if they suffer an in-flight failure and crash. A collision with a manned aircraft could be catastrophic, potentially injuring the pilot of a small manned aircraft or destroying the engine of a jet aircraft, both instances of which could potentially result in fatalities. More prosaically, but with significant economic impact, a drone can cause disruption to electricity supply, with several reported power outages resulting from drones crashing into power supply infrastructure. Drones may also be intentionally used for malicious purposes, such as facilitating the commission of crime, national security breaches, and conducting terror attacks.

Drones are usually piloted remotely, but they may also fly autonomously. The absence of a person on board a drone means that the aircraft can be significantly smaller, lighter, and cheaper than a manned aircraft. This in turn means that drones can be used for many purposes that are uneconomic with manned aircraft. The absence of a pilot on board also means that there is a reduced incentive to take precaution against some forms of physical harm.

While the various types of harm described above can also be perpetrated with a manned aircraft, the cost and difficulty of doing so with a manned aircraft is much higher. The capital and running costs of a manned aircraft are much higher than the same costs for a drone. A pilot of a manned aircraft is also required to undergo significant training, usually at considerable personal expense, before gaining a licence that enables them to fly an aircraft. The operator of a drone, on the other hand, can purchase a drone relatively cheaply from a consumer electronics store, is not required to hold a licence, and within a matter of minutes after the purchase can fly the drone.

1.2 Attribution of Liability

In most harmful situations arising with drones, the potential victim lacks knowledge of the level of care that needs to be taken to avoid harm, or avoiding harmful situations has a high cost from the disruption of existing activities. Strict liability is an appropriate legal standard when the victim is unable to readily take precaution, or the cost of the victim taking precaution is much higher than the cost of the injurer taking precaution (Shavell, 1980). It is difficult if not impossible for the (potential) victim to know the level of care of any aircraft operator and therefore how much precaution to take, but it is straightforward for the aircraft operator to exercise a reasonable standard of care. Appropriately, therefore, aviation typically imposes strict liability for damage caused by an aircraft or by an object falling from an aircraft. Jakubiak (1997) summarises the liability regime that applies to commercial aviation in the United States, concluding that the various doctrines of liability "appear strikingly similar to common-law imposed strict liability". In New Zealand, s97 of the Civil Aviation Act 1990 imposes strict liability with contributory negligence. The allowance for contributory negligence means that where a person on the ground takes some action that contributes to the crash of an aircraft, or does not reasonably avoid an aircraft, then they will also bear liability.

Even though strict liability may in theory apply to physical harm, it typically does not apply to harm caused by potential privacy violations. For example, New Zealand's Privacy Act 1993 requires that information collection intrudes to an unreasonable extent for an actionable interference with privacy to occur, but what this standard means in practice is currently unclear for drones (Shelley, 2016). New Zealand's Privacy Commissioner has previously held that if a drone is not recording then there is no information collected, so there is no interference with privacy (Privacy Commissioner, 2015). It is not possible for a bystander to know whether or not a drone is recording, so they also cannot know whether to take precaution or whether it is worth the cost of initiating a complaint with the Privacy Commissioner. The Privacy Commissioner's ruling also creates an obvious incentive problem, providing an incentive for drone operators to simply claim that they were not recording any information. There may, therefore, be insufficient attribution of liability for privacy violations under existing New Zealand law, and it may be necessary to utilise an alternative means to provide sufficient incentives for an efficient level of privacy violations.

Manned aircraft are large and prominently marked with registration codes, enabling relatively easy identification of the registered operator of an aircraft that is engaged in an activity potentially causing harm. A drone, on the other hand, is small and cannot be readily identified (Patterson, 2017). Commonly available drones have the capability to stream live video back to the pilot, who may be located some considerable distance away from the subject being observed. There is therefore much less likelihood of any given regulation or legal right being enforced with drones than with manned aircraft.

1.3 Research Questions

Froomkin and Colangelo (2015) argue that the practical problems associated with attributing liability for harmful events perpetrated with a drone mean that self-defence remedies may be appropriate to: if the operator of a drone cannot be identified then the law is not going to be able to ensure a just outcome, and self-help may be the only practical means of protecting oneself from a wrong. An alternative is whether mandatory registration of drones would enable the identification of a drone and hence attribution of liability.

These two alternative approaches to controlling or mitigating the harm that may arise from the use of drones provide the motivation for this thesis. My primary research questions are:

1. Under what circumstances will the use of self-defence against drones be efficient?

2. Under what circumstances will the registration of drones be efficient?
3. What combination of registration and self-defence is optimal?

A secondary research question is whether there are any other regulatory instruments that will aid in achieving efficient harm reduction.

1.4 The Utility of Law and Economics Predictions

As with all law and economics analysis, at least from the economic perspective, the formal economic analysis in chapters 3, 4, and 5 pre-supposes *homo economicus* is a reasonable model of human behaviour. Although the psychological and behavioural economics literature suggests that there are significant limitations to the assumption of *homo economicus* (Barron, 2009; Kahneman & Tversky, 1979; Nickerson, 1998), formal economic analysis nevertheless provides useful predictions.

Both homo economicus and the regulatory authority are assumed to have perfect knowledge, but in reality knowledge is bounded. In the first instance, people may not even know of the laws and regulations that apply. For example, in a survey conducted in 2017, a little more than half of New Zealand resident drone users (56%) and overseas resident drone users in New Zealand (55%) self-identified as being aware of the rules relating to drones and having at least a basic knowledge of those rules (Colmar Brunton, 2017). If people are not aware of the rules then they cannot consciously choose to either comply or not comply with those rules: both compliance and non-compliance will be fortuitous rather than planned.

Logically, the problem of a lack of awareness could be solved by education. However, the results of the Colmar Brunton (2017) survey suggest that perhaps education will not be a panacea. New Zealand resident drone users' self-identified awareness of specific rules ranged between 56% and 78% of drone users, with only 35% to 59% always complying with those rules, depending on the particular rule. Being aware of a rule clearly does not guarantee compliance with that rule. On the other hand, given the ability to identify the operator of an errant drone is very low and therefore the probability of enforcement is also low, it is perhaps unsurprising that people would choose not to comply with a regulatory rule that imposes some constraints on the individual's behaviour.

The question then naturally arises as to why some people choose to comply while others do not. Whether people comply with regulations, and the reasons for compliance or non-compliance, can be considered from both instrumental and normative perspectives (Tyler, 1990). The instrumental perspective reflects *homo economicus*, with people electing to comply or not comply on the basis of self-interest based on costs and benefits: this is the standard perspective of law and economics literature. The normative perspective holds that people will comply with a law because they view the law as just and moral, and therefore believe that they should comply despite personal cost, whereas they might not comply with a law that they consider lacks legitimacy. The normative perspective rests in part on the concept that social norms exist which provide the basis for assessing whether something is just or moral. One such social norm may be the rule of law (Licht, 2008) in which case individuals may obey the law simply because it is the law.

One instrumentalist approach that includes the role of social norms is that proposed by Cooter, Feldman and Feldman (2008). Their starting point is the empirical literature which finds that people tend to overestimate the level of undesirable behaviour in others, but at the same time assume that other people are just like they are. Cooter et al. (2008) show that when there is a social sanction for violating the social norm, the first bias will shift the equilibrium and result in a greater level of norm violation than is optimal. Conversely, the second bias will reinforce the underlying tendency of the individual to either comply with the norm or violate the norm.

Even where the stable equilibrium is a social norm that generally supports rule compliance, heterogeneity amongst the population will result in some people choosing to violate the norm because of the relatively high benefit that they receive from doing so. For example, an Australian study found that drivers travelling for business and drivers travelling behind schedule were more likely to exceed the speed limit (Fildes, Rumbold & Leening, 1991) - both groups who could be expected to have a high valuation of their time and potentially high costs of failing to arrive at a destination on time.

The instrumentalist approach is unable to explain all observed behaviour. Some groups within the population may view a law as lacking legitimacy because they view that law as unjust or immoral (Tyler, 1990). An empirical example of this is provided by Watling and Leal (2012), who report statistically significant negative correlations between the likelihood of violating specific driving laws and the perceived legitimacy of enforcement of that particular law. The existence of knowledge asymmetries may help to explain differing views as to the legitimacy of the law, with a law being viewed as not justified if it constrains behaviour to a significantly greater extent than suggested by the information held by a particular group or individual. These asymmetries may be due to the cost of acquiring knowledge for either the group or the regulator. It may be, for example, that the group has private information that is costly for the regulator to obtain. Another potential explanation is that all parties receive the same information but make their decisions on a filtered sub-set of that information. There is considerable evidence that people accept information that is consistent with their beliefs, but block or otherwise dismiss information that conflicts with those beliefs. In the psychological literature this is known as “confirmation bias” (see, for example, the survey provided by Nickerson, 1998). In his discussion of the relevance of psychological discoveries to economics, Rabin (1998) suggests that at least part of the confirmation bias may be due to “hypothesis-based filtering” that acts to block information if dissonance is high.

Although these departures from the assumptions of *homo economicus* provide a richer view of human behaviour and choices, they do not render the central conclusions from a formal law and economics analysis invalid. Individuals comply with a law if there are relatively low costs to them from compliance, evaluated broadly to include social sanction, privately held information, and the direct cost of compliance. Where those costs are high then non-compliance could be expected. The result is much the same as predicted by instrumental perspective based on rational assessment of costs and benefits. Thus we see that law and economics is able to offer a rational framework to explain why law has come to be. Even with judge-made common law, decided on the specifics of individual cases, the law is seen to converge over time to what the law and economics literature would predict (Cooter, Kornhauser & Lane, 1979; Gennaioli & Shleifer, 2007).

Where relevant, the predictions from the theoretical analysis in this thesis are tested against observed law. For existing situations, there is no instance where the theoretical analysis suggests a different approach to that embodied in existing law. Accordingly, it is with confidence that we can accept that this thesis also provides a theoretical framework “that yields valid and meaningful ... predictions about phenomena not yet observed”

(Friedman, 1953). The policy conclusions from this thesis have real world application and are readily implementable.

1.5 Thesis Structure

This thesis is a law and economics thesis. The phrase “law and economics” suggests a unified discipline, but in reality law and economics is a multidisciplinary endeavour between economists and lawyers, each with their own traditions of analysis. For the economist, law and economics is normally characterised as the economic analysis of law, and as such we expect to see formal analytical models of economic behaviour which provide positive predictions of how changes to laws and regulations can achieve more efficient outcomes. But there is also another side to law and economics: the application of economic principles to legal problems by lawyers, with the intent that the analysis will be comprehensible to lawyers who do not have a strong economic background. While there are some excellent legal analyses that do include in-depth theoretical economic analyses (such as Posner and Landes (1980)), others may have only the minimum level of economic analysis required to support the paper’s conclusions (such as Badawi (2012) and Posner (1985)). Legal analysis is also concerned with fact patterns, existing law, and how the subject of the analysis is either similar to or can be distinguished from other cases and existing law. This thesis straddles both traditions of law and economics, with considerable detail included on existing legal and regulatory frameworks. I argue that self-defence against drones is consistent with existing law allowing self-defence; my analysis also demonstrates from an economic perspective that there are distinguishing characteristics between drones and unmanned aircraft which imply different regulatory regimes are appropriate for each.

Chapter 2 is written in the legal tradition of law and economics: it is the application of economic principles to what is primarily a legal analysis of privacy violations and surveillance by unmanned aerial systems. This chapter is a stand-alone essay that proposes a package of regulatory measures, including: a Code of Practice for Drone Operation issued under the Privacy Act 1993, drones to carry a remotely-readable encoded radio frequency identification beacon, and the right to take self-defence against drones. These measures all seem logically appropriate, but without a rigorous economic analysis it is not possible to determine when registration (the remotely-readable encoded radio frequency identification beacon) and self-defence are individually optimal, when they are jointly optimal, and when neither should be employed.

Chapters 3, 4, and 5 then provide a formal economic analysis of the relevant issues. Chapter 3 is a stand-alone essay that develops a formal model of self-defence, identifying the circumstances in which self-defence with the potential destruction of drones is efficient. Chapter 4 is the final stand-alone essay of this thesis, developing a formal model of registration, and identifying the circumstances in which registration is efficient. Chapter 5 draws the analyses of registration and self-defence together, identifying when the two policies are jointly optimal, and when one policy is preferable to the other.

In chapter 3 I argue that self-defence is one of three dimensions of the broader concept of self-help, in which a person who suffers a loss as a consequence of the actions of another can take steps to prevent, minimise, or remedy the loss without resort to the courts. The first dimension of self-help is precaution, where actions are taken to prevent an undesirable outcome from occurring. Precaution is an integral feature of Shavell (1980)'s analysis of liability rules in a model of bilateral precaution where both the injurer and victim can take precaution. The second dimension of self-help, that of taking direct action to to stop an undesirable event while it is occurring, is well recognised by the law but not studied extensively in the literature. The law allows self-defence remedies against both crime and torts, generally in situations where it is important to stop a significant loss or harm from occurring. The third dimension of self-help, that of post-event actions to mitigate loss, is analysed by Badawi (2012) in the context of a game of a creditor recovering a debt from a debtor. In Badawi's model, self-help is efficient if the probability of violence is low and the expected costs of self-help are less than the certain costs of going to court.

I present a formal model of a two-person game where the two parties are a drone operator and a bystander. The bystander will experience harm but is able to exert some level of effort in self-defence that may ultimately result in the destruction of the drone. This model is primarily applicable to the second dimension of self-help, taking action to stop an undesirable event while it is occurring. Three scenarios are analysed: a simultaneous game where the drone operator and the bystander make their decisions simultaneously; a leader-follower game with the drone operator as leader; and a leader-follower game with the bystander as the leader.

My analysis suggests that self-defence would be efficient when there is a low probability of identifying the drone operator, harm is at least moderately high, and the cost of destruction is relatively low. My analysis also predicts that actions which might destroy an aircraft with people on board would be prohibited, which is what we observe codified in the Montreal Convention (United Nations, 1975) and in New Zealand's Aviation Crimes Act 1972.

It could be argued that the low probability of identifying the drone operator could be overcome by registration of drones, a policy which has been implemented in the United States, Canada, and the United Kingdom. Registration has been adopted uncritically in these jurisdictions, with no evidence to suggest that the efficacy of the registration regimes has been evaluated. There has also not been any theoretical consideration of whether registration should even be expected to achieve its policy objectives.

Chapter 4 analyses the extent to which registration by itself could be welfare-enhancing. Somewhat counter-intuitively, registration by itself is only welfare-enhancing if there is a high probability of identifying the drone operator in the absence of a registration identifier. When the probability of identifying the drone operator is low then the drone operator can bypass the registration scheme with little fear of sanction, and thus the registration scheme is ineffective.

There is a significant overlap between the circumstances when it is efficient to utilise self-defence and those when it is efficient to utilise registration. Chapter 5 analyses the situations in which one policy will be preferable to the other, and when both policies should apply. Given the low probability of identifying the operator of a drone that is not carrying an identifier, the optimal policy prescription is the status quo (no registration and no self-defence) when harm is low, but voluntary registration and the right for bystanders to engage in self-defence when harm is moderate to high.

Chapter 6 summarises the results of this thesis and provides policy conclusions, including a practical proposal of the legislative and regulatory changes required to enable the utilisation of drone-detection systems and counter-drone systems in New Zealand. Applying the analysis of chapter 4, it is apparent that drone-detection systems should not be registered, but counter-drone systems should be restricted to persons who are licensed and registered under an appropriate regulatory regime.

Chapter 7 provides conclusions.

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Chapter 2

Proposals to Address Privacy Violations and Surveillance by Unmanned Aerial Systems[1]

Synopsis

This chapter reviews some of the privacy and surveillance concerns created by drones, and considers the effectiveness of existing New Zealand law in addressing those concerns. I propose the adoption of a package of measures including: tort law reform, the promulgation of a "Code of Practice for Drone Operations" under the Privacy Act 1993, an encoded radio frequency beacon to identify approved operators, provision for aerial trespass by unmanned aircraft, provision for the destruction of unmanned aircraft committing trespass, and the clarification of what constitutes a privacy violation by broadcast or closed-circuit television and video systems.

2.1 Introduction

Within just a few years, small drones have gone from being of only military interest and an obscure hobby to now being popular consumer items with a growing range of commercial applications. Commonly available drones have the capability to stream live video back to the pilot, who may be located

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[1] This chapter was first published as the paper Shelley (2016) 'Proposals to address Privacy Violations and Surveillance by Unmanned Aerial Systems', *Waikato Law Review*, 24(1). Changes to the published work are: conversion from New Zealand Legal Style Guide referencing to APA v6 referencing and associated edits for readability; use of the term "drones" rather than unmanned aerial systems or "UAS"; and addition of references to Bradley-Smith (2015) and Hunt (2019).

some considerable distance away from the subject being observed. While there are potentially material benefits accruing from the use of drones, the ability to observe a subject from afar gives rise to significant legal issues that must be addressed.

Many people are concerned at the prospect of being observed by an unknown surveillant using a drone. In New Zealand, there have been news articles about drones being used to film into another person's property (Harris, 2015), taking photographs of children at a public swimming pool (Bonnallack & Young, 2015), frightening animals in people's backyards (Wells, 2015), and hovering outside windows at night (Nicoll & Hunt, 2018). In Australia, a woman discovered that real estate advertisements, including a large billboard, carried an image of her sunbathing in her backyard (Panahi, 2014). These media reports are illustrative of, and contribute to, a general disquiet among the public, raising issues of trespass and privacy. Drones have also been used for privacy-breaching criminal activity, such as reconnaissance for potential burglaries (Barrett, 2015).

In New Zealand a drone has been stomped on and damaged by an upset member of the public (Ellingham, 2015), drones have been shot at (Bradley-Smith, 2015), and a man who shot down a drone was discharged without conviction on the basis that the drone should not have been over his property without his consent (Hunt, 2019). In the United States drones have been shot at or shot down in New Jersey (The Smoking Gun, 2015), Kentucky (Cummings, 2015), California (Farivar, 2015), Virginia (Farivar, 2016), and in two separate incidents in Tennessee (Farivar, 2017; Flowers, 2016). In the New Jersey, Kentucky, and California cases the shooter claimed a right to privacy, while in the Virginia case the shooter claimed to be defending another person's right to privacy. The legal outcome for each of these cases is discussed in Section 2.5 of this chapter. The diversity of outcomes highlights the conflict between privacy and trespass on the one hand, and various issues of endangering the public, damage to property and damage to aircraft on the other.

Drone technology provides an avenue for surveillance by both private parties and State agencies. Private entities utilising drones for legitimate productive activities, such as pizza delivery or responding to burglar alarm activations, could collect significant surveillance imagery. The police in Baltimore have already engaged a private contractor to undertake citywide surveillance using manned aircraft (Friedersdorf, 2016), and the low cost of drones make this more likely to occur in the future.

In Helsinki, researchers demonstrated in a six-month study that even individuals who consent to surveillance will actively alter their behaviour in order to regulate what the surveillants see, and that the surveillance system was "a cause of annoyance, concern, anxiety, and even rage" (Oulasvirta et al., 2012). While the Helsinki researchers found that the overt negative emotions reduced over time, there was also evidence that there is a longer-term insidious effect from surveillance. A study conducted in former East Germany found that those counties that had higher levels of Stasi informers during the communist era had lower rates of economic growth and higher unemployment during the 1990s and 2000s (Lichter, Loeffler & Siegloch, 2015). The research suggests that surveillance results in individuals having lower levels of trust in institutions and other people, making it more difficult to make agreements and engage in wealth-enhancing activity.

There are, thus, potentially significant costs offsetting the many benefits of using drones, both as regards short-term emotional responses and long-term trust and economic functioning. If operators of drones do not face the costs induced by this activity, they are unlikely to take sufficient precautions and are likely to have a higher than socially optimal activity level (Shavell, 1980). An efficient level of drone activity can only be achieved if these costs are taken into account by drone operators. The role of the legal and regulatory system is to balance the costs and benefits, and, where possible and practicable, to facilitate the transfer of cost to the operator so that efficient decisions may be made.

This chapter considers from a law and economics perspective the ability of existing law to address the potential costs imposed by drones, and those characteristics of drones that require new legal rules. Section 2.2 summarises relevant aspects of the New Zealand Civil Aviation Rules, including a default prohibition from flying above persons without their permission (and a prohibition from flying above property without permission of the occupier), unless the operator has submitted a risk management plan to the Civil Aviation Authority and has been granted authorisation to conduct such flights.

As reported by the Law Commission in its consideration of police surveillance (Law Commission, 2007), surveillance, which gives rise to privacy violations, may be trespassory or non-trespassory. Trespassory surveillance necessarily involves a trespass, so law relating to trespass may be able to prevent the surveillance activity, just as it can be used to prevent some other privacy violations (Cheer, 2016, p. 978). Section 2.3 discusses the tort of trespass together with the Trespass Act 1980, which enables prosecution for trespass, and the Civil Aviation Act 1990 which prohibits actions in trespass in certain circumstances.

Non-trespassory surveillance does not involve a trespass, so reliance must be placed on privacy regulation. Section 2.4 discusses the main elements of privacy regulation in New Zealand: the privacy torts, the Privacy Act 1993, and other relevant legislation. The tort of intrusion on seclusion is particularly relevant, although the threshold of "highly offensive" may prove to be too high to effectively address the challenges of drones. The Privacy Act 1993 creates a wrong of "interference with privacy" that is applicable to drones, although the effectiveness of the existing legislation is uncertain.

Section 2.5 discusses relevant international experience, including the United States' cases discussed above and the application of the Data Protection Directive in the European Union. Section 2.6 presents six proposals for addressing privacy concerns arising from drone use: tort reform; a Code of Practice for Drones under the Privacy Act 1993; encoded radio frequency identification, particularly for those operators with procedures by the Privacy Commissioner; amendments to the Privacy Act 1993; strengthening other relevant legislation to effect the legalisation of self-help measures; and application of criminal sanctions in appropriate circumstances.

Section 2.7 provides concluding comments.

2.2 Civil Aviation Regulation

Civil aviation regulation is concerned with the regulation of aviation safety,[2] and does not directly address other issues that may require regulation, such as trespass and privacy. While most areas of civil aviation regulation are based on rules and guidelines promulgated by the International Civil Aviation Organization, the regulation of drones is currently subject to considerable discretion by each country. New Zealand has two Civil Aviation Rules (CARs) governing drones: Civil Aviation Rules Part 101 (CAR Part 101, 2015) governs drones generally, and Civil Aviation Rules Part 102 (CAR Part 102, 2015) provides for the "certification" of operators who may be exempted from some of the requirements of CAR Part 101. A brief overview of these two rules provides context for the legal environment in which drones operate.

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[2] Aviation safety includes the safety of persons and property on the ground.

2.2.1 Part 101 Rules

The CAR Part 101 rules require drones to be operated no higher than 400 feet above ground level (AGL) (r.101.207(a)(3)), and within visual line-of-sight of the pilot (r.101.209). The operator "must take all practicable steps to minimise hazards to persons, property and other aircraft" (r.101.13), and must give way to manned aviation (r.101.213). There are also specific requirements for operating at or in the vicinity of an aerodrome (r.101.205).

Of particular relevance to this chapter, CAR rule 101.207(a)(1) provides the specific restriction that unless operating in a designated "danger area":

> A person operating a remotely piloted aircraft must ... avoid operating:
>
> (i) in airspace above persons who have not given consent for the aircraft to operate in that airspace; and
>
> (ii) above property unless prior consent has been obtained from any persons occupying that property or the property owner.

This rule was introduced to address issues related to safety, yet it is popularly perceived within the drone community as addressing concerns related to privacy (see, for example, the views expressed in Brooks, 2015; New Zealand Ministry of Transport [MOT], 2019). However, permission from one person to operate above them or above their property clearly does not address privacy concerns of others nearby.

2.2.2 Certificated Operators

CAR Part 102 enables a person to become a certificated operator of a drone. This rule provides the means for an operator to be authorised to operate a drone "other than in accordance with Part 101" (r.102.9(a)), provided that the Civil Aviation Authority (CAA) is satisfied that such an exemption from CAR Part 101 will not be detrimental to aviation safety. Persons intending to operate under CAR Part 102 must make an application on the prescribed form and provide written details of operating, maintenance and safety procedures, organisational systems, and the like. If CAA is satisfied that the procedures will adequately manage the risks of the proposed operation, then the applicant is granted a CAR Part 102 Certificate and becomes a certificated operator.

The Advisory Circular that accompanies CAR Part 102 provides guidance on how CAA intends to apply the rule (Civil Aviation Authority

[CAA], 2015). It is clear that exemptions from CAR rule 101.207(a)(1) are anticipated, enabling operators to fly over persons and property without obtaining prior permission provided that the safety risks of doing so are adequately managed (p. 10). This is not surprising: the introduction of CAR Part 102 was intended to assist the development of new drone services (Bridges & Foss, 2015), such as a "drone delivery service" where drones are used to deliver packages directly to an individual or premises. Accordingly, it would be relatively straightforward to obtain approval under CAR Part 102 for persistent surveillance over an urban area. A fixed-wing drones with back-up power supplies and radios could be operated at a height of 400-500 feet AGL, well below the minimum height of 1,000 feet for manned aircraft, for many hours at a time. Being a fixed-wing aircraft it could be piloted to glide to a safe landing area if it experienced an in-flight failure.

2.3 Trespass

Trespass generally is an act that interferes with a person's right to exclusive use and possession of something, and usually requires intent on the part of the tortfeasor. The aspect of trespass most relevant to this chapter is that of trespass against land, being an intentional encroachment on to land without the consent of the owner. The tortfeasor need not themselves intrude upon the land, but may be the direct cause of an intrusion by a person or thing.

2.3.1 Intent

Intent requires a conscious and voluntary act to be at that location, rather than an intention to trespass. Conversely, the absence of a conscious and voluntary act means there is no trespass. The operator of a drone that is intentionally flown on to a particular area of land will therefore be trespassing whether or not they intend to commit a trespass. However, a drone that has a parachute as a safety feature and drifts on to a particular parcel of land when that parachute is activated may not be committing a trespass. The key consideration in the latter case is the extent to which drifting on to the land is a direct consequence of the need to use the parachute.[3]

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[3] For a discussion of the necessity of the trespass following directly from the act of the tortfeasor see Aitkin (2016, p. 494).

Recent advances in drone technology enable an agency to fly a surveillance device to “perch” in a tree or against a building (Pope, 2016a, 2016b). This would clearly be an intentional act and likely to amount to trespassory surveillance.

2.3.2 Rights to Airspace

Drones are aerial vehicles, so a relevant question is to what extent rights to land extend into airspace. Common Law holds that the owner of property also has rights to the airspace above the property.[4] The maximum height to which this principle applies is uncertain. In *Bernstein of Leigh v Skyviews and General Ltd* (Skyviews), Griffiths J held that there is an upper limit to the airspace included in the tort (at 902):

> The rights of an owner of land in the air space above the land extended only to such height above the land as was necessary for the ordinary use and enjoyment of the land and the structures on it, and above that height the owner had no greater rights in the air space than any other member of the public.

However, contrary to Skyviews, the New Zealand High Court more recently held that property rights “are absolute ... [and] can only be diminished by creation of competing interests in the land, by contract, or most importantly by statute” (*De Richaumont Investment Co Ltd v OTW Advertising Ltd*, para. 39). The qualified prohibition against actions in trespass provided by section 97(2) of the Civil Aviation Act 1990 provides such a diminution:

> No action shall lie in respect of trespass, or in respect of nuisance, by reason only of the flight of aircraft over any property at a height above the ground which having regard to wind, weather, and all the circumstances of the case is reasonable, so long as the provisions of this Act and of any rules made under this Act are duly complied with.

This provision, and the rest of section 97, was first contained in section 7 of the Air Navigation Act 1931, which was in turn modelled on section 9 of the Air Navigation Act 1920 (UK), enacted when aviation was a very new phenomenon.[5]

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[4] For a history of the earliest development of this doctrine see Abramovitch (1962).

[5] The Air Navigation Act 1936 (UK), section 9 contains almost identical wording to the Air Navigation Act 1931. For a contemporaneous discussion of this specific clause

The section 97(2) prohibition of actions in trespass has been tested infrequently in New Zealand courts. In broad terms, the minimum height for an aircraft is 1,000 feet AGL in an urban area and 500 feet AGL in a rural area, except when conducting a take-off or landing. In both *R v Peita* and *R v Hertnon*, a flight at or above the minimum height was found to be reasonable in terms of section 97(2). These decisions have limited applicability to drones because the CARs do not specify a minimum height for flight. Rather, CAR, Part 101, specifies a maximum height of 400 feet AGL unless certain specified procedures are followed.

Collectively, section 97(2) of the Civil Aviation Act 1990 and Skyviews create a two-pronged test for trespass by a drone:

(1) the aircraft is flown below a height that is reasonable given the applicable CARs; and

(2) the height at which the aircraft is flown infringes the ordinary use and enjoyment of the land.

Accordingly, an operator flying a drone at a such a low level that it has some probability of colliding with a person is likely to be committing trespass because:

(1) the operator would not be taking all practicable steps to minimise hazards to persons and the operation would then not comply with all applicable CARs; and

(2) the drone is being flown at a height that infringes the ordinary use and enjoyment of the land. Some height above that (perhaps 10 feet AGL) might also still constitute trespass and be actionable because "all the circumstances of the case" are not reasonable.

However, there will be some height AGL at which the drone will no longer be considered to be infringing the ordinary use and enjoyment of the land, and thus be considered reasonable. In a practical sense, it is difficult for both plaintiffs and the operator of the drone accurately to assess what height that might be.

2.3.3 Remedies

There are five remedies available for trespass against land: two self-help remedies, two judicial remedies, and invoking the Trespass Act 1980 (Aitkin, 2016, p. 507).

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in the 1920 and 1936 UK Acts see Thomson (1936, p. 341).

The two self-help remedies are expulsion and distress damage feasant. Expulsion normally requires the ability physically to apprehend and forcibly remove the trespasser or trespassing object. Distress damage feasant requires the ability physically to apprehend and contain the offending object until the owner makes suitable reparation for any damage. Physical apprehension may be possible only if the drone lands. While a drone is flying, it may be possible to force it to return to its take-off location (that is expel the aircraft) or to land by a variety of radio and GPS jamming devices and techniques.[6] However, it is an offence against the Radiocommunications Regulations 2001 (New Zealand Gazette, 2011) to operate any radio jamming equipment in New Zealand without a licence, effectively eliminating the use of these devices as a legal self-help remedy for most people.

The two judicial remedies are injunction and damages. If there is a continuing or repeated trespass by an identifiable drone, such as one operated by a delivery company, then an injunction may be appropriate. As discussed above, flights by drones do not constitute a trespass so long as the flight is at a height that is reasonable given the applicable CARs. Explicit legal definition of the height extent of private property rights would enhance the possibility of successful injunctive relief. McNeal (2014) suggests a height of 350 feet AGL based on the idiosyncrasies of a particular United States legal decision, while Rule (2015, p. 187) suggests setting the upper limit of private airspace at the minimum navigable airspace height of 500 feet AGL. While both recommendations were formulated for the United

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[6] A review of the relevant literature reveals that many small unmanned aircraft may be vulnerable to “hijacking” so that the aircraft is under the control of a party other than the pilot. In 2013, a hacker developed software dubbed “Skyjack” that enabled the hijacking of an unencrypted Parrot AR Drone (Goodin, 2013). Rodday (2015) identifies two security vulnerabilities, including weak encryption, that render many relatively high-end unmanned aircraft vulnerable to hijacking. In 2015 a group of computer security researchers discovered a design flaw in the Mavlink radio protocol, used by many drone manufacturers, which enabled them to develop a low-cost system to hijack an unmanned aircraft using this protocol (Benchoff, 2015).

A further technique to gain control of unmanned aircraft is that of “GPS spoofing” where a GPS transmitter is used to override satellite GPS signals. A report in 2001 warned of the vulnerabilities of GPS to signal loss and disruption, including malicious disruption (John A. Volpe National Transportation Systems Center, 2001). Despite this warning, drone technology remains vulnerable to attack. GPS spoofing was used by Iran to commandeer and land a United States RQ-170 Sentinel surveillance aircraft (Peterson, 2011). The technique has also been demonstrated as being able to be used to commandeer and potentially crash a small unmanned aircraft (Vaas, 2012).

Another example is the Battelle Systems “Drone Defender”, which uses radio jamming to overpower the radio systems on the unmanned aircraft, forcing it to activate either “auto land” or “return to home”, depending on which option has been programmed into the aircraft (Matyszczyk, 2015).

States, where at least one state has enacted such a statute,[7] there is no reason why Rule's recommendation could not also apply in New Zealand.[8] Rule argues that such an approach could significantly reduce the economic loss associated with excessive drone flights, relative to the efficient level of flights where the costs to property owners are taken into account.

A one-off incident is not amenable to an injunction, so damages may be more appropriate. However, if trespass has been committed, but no tangible harm is done, then damages must necessarily be of only a nominal amount and may amount to as little as one dollar.[9] This means that the economic cost of bringing a suit may outweigh any benefit gained,[10] and many trespasses by drones would not be actioned, even if there would be a net benefit to society from bringing suit. Additionally, the identification of the operator is likely to be problematic.

The Trespass Act 1980 creates a number of offences related to trespass, the most relevant of which are the offences of "trespass after warning to leave" and "trespass after warning to stay off". Trespass after warning to leave occurs when a person has been warned to leave by the occupier of a place and "neglects or refuses to do so". Trespass after warning to stay off occurs when a person has been warned by the occupier of a place to "stay off" that place, and then wilfully trespasses on the place within two years of the warning. Having been warned and then committing a trespass, a trespasser can then be prosecuted in the criminal justice system rather than by civil suit, transferring the cost of litigation to the Crown. The Trespass Act 1980 complements rather than replaces the tort of trespass, with actions in tort still available.

Action under the Trespass Act 1980 would require issuance of a warning, but it is not clear what form this could take to be effective, when a

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[7] Oregon Laws 2013, Chapter 686, section 15(1) allows

> a person who owns or lawfully occupies real property" in the State to "bring an action against any person or public body that operates a drone that is flown at a height of less than 400 feet over the property if (a) The operator of the drone has flown the drone over the property at a height of less than 400 feet on at least one previous occasion; and (b) The person notified the owner or operator of the drone that the person did not want the drone flown over the property at a height of less than 400 feet.

[8] Section 97(2) of the Civil Aviation Act 1990 would require amendment to take account of this defined column of private airspace.

[9] *Dehn v Attorney-General* [1988] 2 NZLR 564 (HC) at 583; affirmed in *Dehn v Attorney-General* [1989] 1 NZLR 320 (CA) at 323.

[10] While courts may make an order for costs, such orders often cover only a portion of the actual costs and there is no compensation for the time involved in bringing suit.

landowner does not know who might fly a drone over that land. Given modern technology, it might be appropriate to post a warning on an electronic bulletin board or website,[11] but there is no compulsion for the pilot of a drone to check such a website. Another option might be to follow the example of a Justice of the Peace in New Jersey, who is described in a 1910 publication on aviation, as erecting a sign on the roof of his house warning aviators against trespass (Jackman & Russell, 1910, pp. 170–171), but this would not resolve the dual problems of privacy violations from a neighbouring or public property and the difficulty of identifying the operator of the drone.

2.3.4 Summary

Because a drone is an aircraft and therefore covered by the Civil Aviation Act 1990, actions in trespass may only arise if it is flown below a height which is reasonable having regard to all the circumstances of the case. The provisions of CAR, Part 101, mean that many drones will require permission to fly over people or property, and if this does not occur then it is hard to see how any height could be considered reasonable. Nevertheless, a drone may be flown under a CAR Part 102 certification that permits flight over property without obtaining permission.

A clearly defined property right over airspace above a property could facilitate trespass actions. However, even if this action was available, it does not solve the identified problem: unwelcome surveillance by a drone able to hover over a public right of way and conduct surveillance, or to fly over property at a height “private” airspace. It also does not solve the difficulty of trying to establish the identity of the operator of the drone.

2.4 Privacy

New Zealand has two privacy torts: wrongful publication of private facts and intrusion on seclusion. The privacy torts are heavily complemented by both civil and criminal statutes, and remain an area where further relevant development is possible. This section reviews the two privacy torts and

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[11] A suitable website is provided by the “Airshare” site ¡www.airshare.co.nz¿ run by Airways Corporation of New Zealand. Airways Corporation provides services such as air traffic control, aviation mapping, and communication services utilised by aircraft. The Airshare website has been developed to provide drone operators with a central source of information on drones, as well as providing a way for drone operators to obtain permission to fly in controlled airspace.

then gives particular consideration to how the Privacy Act 1993 might apply to drones. Other potentially pertinent statutes are briefly reviewed.

2.4.1 Privacy Torts

Wrongful publication of private facts was confirmed as a tort by the Court of Appeal in *Hosking v Runting*. Gault and Blanchard JJ held that the elements of this tort are: 1. The existence of facts in respect of which there is a reasonable expectation of privacy; and 2. Publicity given to those private facts that would be considered highly offensive to an objective reasonable person. The tort of intrusion on seclusion was subsequently found to be part of New Zealand law by Whata J in the High Court in *C v Holland*. Whata J held that the following four elements must be satisfied: (a) An intentional and unauthorised intrusion; (b) Into seclusion (namely intimate personal activity, space or affairs); (c) Involving infringement of a reasonable expectation of privacy; (d) That is highly offensive to a reasonable person. It is an open question whether wrongful publication and intrusion on seclusion are separate torts or elements of a single privacy tort, but for the analysis of drones that question is not critical. The key distinguishing factor between wrongful publication and intrusion on seclusion is that publication is not required for the latter. This may be relevant to drones when imagery is collected for the private use of the operator without necessarily an intent to publish the imagery. Some commentators have questioned whether these torts are too tightly formulated and exclude privacy violations that should be captured by the respective torts. One such question concerns the "highly offensive" threshold required by both torts. A second question concerns Whata J's acceptance of there being "no right to limit views", which potentially allows surveillance and photography from afar. The relevance of both of these areas to drone operations are discussed below.

The "highly offensive" threshold

Both privacy torts require the violation of privacy to be "highly offensive to an objective reasonable person". In *C v Holland*, the intrusion involved covert filming of a woman in the shower, so easily met the "highly offensive" threshold. In *Hosking v Runting*, the action in contention was the publication of a photograph of young children taken in a public place and this did not meet the threshold. However, quite where a drone filming a person sunbathing naked in their backyard falls on this continuum is an open question with no obvious answer. In *Hosking v Runting*, Gault and Blanchard JJ were concerned that only "publicity that is truly humiliating and distressful or otherwise harmful to the individual concerned" should give rise to legal liability (para. 126). Tipping J concurred, considering that "relatively trivial invasions of privacy should not be actionable" (para. 255), while at the same time expressing the preference that the threshold should be one of a "substantial level of offence rather than a high level of offence ... [the former being] a little more flexible" (para. 256).

Moreham (2008, p. 246) argues that the "highly offensive" test is unnecessary, noting that English law avoids the use of that test by relying on the reasonable expectation of privacy test. The close linkage between offensiveness and reasonable expectation of privacy has been recognised in New Zealand (*Faesenkloet v Jenkin*, para. 50). In the context of wrongful publication of private facts, Elias CJ has also urged the Supreme Court to "reserve its position" on the test, noting that members of the House of Lords have "doubted" the test in a decision since *Hosking v Runting* (*Rogers v Television New Zealand Ltd*, para. 25).

It could be argued that in the years since *Hosking v Runting* there has been a sufficient body of precedent in New Zealand law that the original purpose for the threshold, to deter litigation over relatively trivial matters, is now redundant. In *Hamed v R* it was held that there is no reasonable expectation of privacy on a public road (Blanchard J, para. 205; and Tipping J, para. 224), but there is a much greater expectation of privacy "in a building or an enclosed space like a hedged garden or the curtilage of a home" (Blanchard J, para. 191). It is also recognised that there may be an expectation of privacy in some public places where the plaintiff does not expect his/her actions to be viewed beyond those people in immediate view (*Peck v United Kingdom*), or words heard beyond those in immediate earshot (*Andrews v Television New Zealand Ltd*), and that disclosure of some actions in public places can amount to disclosure of personal information that is private (*Campbell v MGN Ltd*).

In *Hosking v Runting* and *C v Holland* the level of offensiveness was congruent with the expectations of privacy, but that will not always be the case. In *Andrews v Television New Zealand Ltd*, it was held that publication of an exchange of which the plaintiffs held a reasonable expectation of privacy was not offensive, not least because the plaintiffs themselves were unable to identify any aspect of the broadcast that they considered offensive.

However, the “highly offensive” test has also been criticised as being unpredictable and creating uncertainty (Moreham, 2008, p. 246). Decisions involving the news media highlight circumstances in which disclosure of private information is not considered by the courts to be highly offensive, although the individuals concerned clearly held a different view. In *Hosking v Runting*, Gault P stated that “[t]he harm to be protected against is in the nature of humiliation and distress” (para. 128), yet in *Clague v APN News and Media Ltd*, Toogood J opined that embarrassment and distress might be insufficient to be classified as offensive or objectionable (para. 38).

None of the above provides clear guidance to the operator of a drone or to a person who is observed by a drone. The law appears to recognise that a person has an increasing expectation of privacy as they move from their front yard (exposed to the street) to their backyard (potentially surrounded by high fences), but it remains entirely unclear whether or not a single overflight by a drone might be highly offensive. If it is not, then the issue rests on the duration required for a drone to hover or loiter in the general vicinity before the highly offensive test is met. It is also unclear whether the filming of ordinary activities, such as gardening or children playing games in a backyard, where there is a reasonable expectation of privacy, would be considered highly offensive, even if the individuals involved experienced considerable anxiety at potentially being observed, or whether there are only certain activities for which the intrusion would be considered highly offensive.

Further uncertainty is injected by Toogood J’s acceptance in *Faesenkloet v Jenkin* that “deliberate intrusion designed to offend might be more offensive than one which is obviously accidental and incidental to another purpose” (para. 47). Given such views, drone operators might well consider that so long as they have a legitimate purpose, such as real-estate photography or roof inspection, they do not need to be concerned with what other imagery they might incidentally capture. This increases the likelihood of conduct that could violate privacy, and, if potential plaintiffs are aware of the same uncertainties, could also simultaneously decrease the likelihood of an action being brought that would clarify the question and increase the extent to which individuals change their behaviour in an effort to maintain privacy.

No right to limit views

Whata J stated in *C v Holland* that the torts provide “no right to limit views from public places or from other private property” (para. 92), which would appear to legitimise non-trespassory surveillance however it is conducted. With drones, such surveillance could be conducted from a public right of way, above the property of a consenting neighbour, or at a sufficient height above the subject property.

Whata J cited the 1937 case of *Victoria Park Racing and Recreation Grounds Co Ltd v Taylor* in support of the proposition that there is no right to limit views. In that case, Latham CJ stated that “[a]ny person is entitled to look over the plaintiff’s fences and to see what goes on in the plaintiff’s land” (p. 494). Dixon J likewise stated that “the natural rights of an occupier do not include freedom from the view and inspection of neighbouring occupiers or of other persons who enable themselves to overlook the premises” (p. 507).

However, it is unclear whether the “no right to limit views” principle applies entirely without qualification. In his judgment, Latham CJ stated that no general right of privacy exists and that “neither this court nor a court of law will interfere on the mere ground of invasion of privacy” (p. 496). The law in New Zealand has since developed, with both Parliament and the courts recognising a variety of aspects of privacy. Given that the case was decided by a narrow majority of 3:2, and that at least some aspects of privacy are now recognised, the dissenting judgments require further consideration.

Rich J, in his dissenting judgment, stated that (p. 504):

> ... the right of view or observation from adjacent land has never been held to be an absolute and complete right of property incident to the occupation of that land and exercisable at all hazards.

and went on to hold that (p. 504):

> ... there is a limit to this right of overlooking and that the limit must be found in an attempt to reconcile the right of free prospect from one piece of land with the right of profitable enjoyment of another.

Evatt J stated (p. 517):

> The defendants also say that the law of England does not forbid one person to overlook the property of another. That also is

> true in the sense that the fact that one individual possesses the means of watching, and sometimes watches what goes on on his neighbour's land, does not make the former's action unlawful. But it is equally erroneous to assume that under no circumstances can systematic watching amount to a civil wrong ... under some circumstances, the common law regards 'watching and besetting' as a private nuisance, although no trespass to land has been committed.

And, "it is an extreme application of the English cases to say that because *some* overlooking is permissible, all overlooking is necessarily lawful" (p. 518, emphasis in original).

It may be, therefore, that "no right to limit views" is an inessential element of the tort of intrusion on seclusion. An alternative formulation could place the "reasonable expectation of privacy" at the core of the tort: where the plaintiff has no reasonable expectation of privacy then there would be no right to limit views, but where the plaintiff has a reasonable expectation of privacy then there would be a right to limit views. This formulation would appear to respect the earlier authorities, such as *Victoria Park Racing and Recreation Grounds Co Ltd v Taylor*, while allowing this area of law to develop. Until such time as there is a judgment to that effect, the privacy torts appear to allow filming and observation of individuals to be undertaken so long as it is not highly offensive. The privacy torts as currently formulated might therefore allow drone flights that violate a reasonable expectation of privacy, such as for individuals in their private backyards, and thereby impose uncompensated costs on an aggrieved party.

2.4.2 Privacy Act 1993

The privacy torts are supplemented by the Privacy Act 1993, which governs the collection, use, and disclosure of personal information. An "agency" is required to comply with a set of 12 broad information privacy principles (IPPs) specified in section 6 of the Act. A drone operator, whether an individual flying recreationally or a company utilising a drone for commercial operations, falls within the definition of an agency.[12]

While the IPPs do not directly create a legal right enforceable in a court of law,[13] section 66 creates a civil wrong of "interference with privacy"

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[12] The definition of agency in the Privacy Act 1993 also includes a number of exceptions, none of which rule out a private individual collecting information about others.

[13] Section 11 of the Privacy Act 1993 expressly provides that "the information privacy

of an individual. An interference with privacy requires that the action in question breaches an IPP (or one of four other specified breaches)[14] and, in the opinion of the Privacy Commissioner or the Human Rights Review Tribunal (HRRT), the action has caused or may cause some harm to the individual. An action in the HRRT may be at the suit of either the Director of Human Rights Proceedings (Privacy Act 1993, section 82), or the aggrieved party (Privacy Act 1993, section 83), and may be appealed to the High Court.[15] The aggrieved party may only bring suit after the Office of the Privacy Commissioner has investigated the complaint, and the scope of the HRRT's hearing is restricted to the issues investigated by the Privacy Commissioner.

The Privacy Commissioner may issue guidelines to any industry sector and has done so for CCTV cameras (Privacy Commissioner, 2009). The CCTV Guidelines apply to drones, even though this is not explicitly stated in the Guidelines themselves (Mabbett, 2015). This is consistent with practice in the United Kingdom, where the equivalent guidelines issued by the Information Commissioner's Office explicitly include consideration of drones (Information Commissioner, 2015).

In *Armfield v Naughton*, the HRRT considered issues related to a CCTV system that in part surveilled the front yard of a neighbouring property. Naughton had set up a number of CCTV security cameras around his house, one of which had an unobstructed view of Armfield's lawn and of the swing used by Armfield's children. The Tribunal held that Naughton had failed to comply with the privacy principles specified in the Privacy Act 1993, and specifically that the camera recording part of the front yard collected personal information in a way that intruded to an unreasonable extent on the personal affairs of Armfield and the other persons living at that property (*Armfield v Naughton*, para. 65). Whether the surveillance was "highly offensive" was not considered by the HRRT as its jurisdiction is limited to the Privacy Act 1993 and the issues investigated by the Privacy Commissioner (*Armfield v Naughton*, para. 29).

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principles do not confer on any person any legal right that is enforceable in a court of law", with the exception to obtain confirmation from a public sector agency of whether information is held and to have access to that information.

[14] The other breaches specified in section 66 of the Privacy Act 1993 are a breach of: (a) a code of practice relating to public registers, (b) an IPP or code of practice related to information sharing agreements, (c) an information sharing agreement, and (d) provisions relating to information matching.

[15] Appeals to the High Court are made under section 123 of the Human Rights Act 1993.

The decision in *Armfield v Naughton* affirmed previous decisions that "injury to the feelings" includes negative feelings such as anxiety, stress, fear and anger (feelings associated with unwelcome surveillance) (para. 82). It was held that the facts of this case established "both significant loss of dignity and significant injury to the feelings" of the plaintiffs (para. 82), and that an interference with privacy was established (para. 87). A benchmark of $15,000 in damages was noted by the HRRT (para. 105), although a lesser amount was awarded effectively at the request of the plaintiff.

Butler (2013, p. 222) cautions that the requirement in section 66(1)(b)(iii) for the humiliation, loss of dignity, or injury to feelings to be "significant" sets a high threshold: "mere misuse or dissemination of personal information is insufficient for a complaint to be upheld." On the other hand, section 66(1)(b)(i) only requires that the action "has caused, or may cause, loss, detriment, damage, or injury to that individual." This clause seems broader and sets a far lower threshold than that required by section 66(1)(b)(iii).

Personal information is defined in section 2 as "information about an identifiable individual". Whether an individual can be clearly identified from drone imagery depends on the quality of the camera on board the drone, and the distance between the drone and the person. The person on the ground is not always able to determine whether the drone is carrying a camera, or whether they can be identified from any imagery that might be collected. Drone advocates argue that a conventional camera with a telephoto lens is capable of providing much clearer imagery from a distance and thereby provide a greater threat to privacy (Derewecki, 2015). However, technology continues to improve, and some drone cameras now rival the performance of a telephoto camera (Cooke, 2017). Even with lower-resolution images it can be possible to identify the individual from characteristics such as build and hair colour, particularly when the address at which imagery is taken is known. This would seemingly satisfy the requirement in *Andrews v Television New Zealand Ltd* (para. 52) that the plaintiff is identified "either directly or by implication". Thus, even when the imagery is at a relatively low resolution, it may be reasonable to assume that personal information is being gathered.

We can therefore conclude that: first, a drone that flies in the vicinity of a property and takes photos of that property is potentially collecting personal information; and secondly, that a person who is in some way upset, anxious or angry about such an action has suffered an "injury to feelings". Having satisfied the second limb of section 66, the only remaining requirement to prove an interference to privacy is whether the personal information collected breaches an IPP.

IPP 1 requires that "the information is collected for a lawful purpose connected with a function or activity of the agency, and the collection of information is necessary for that purpose." Flying a drone is not an unlawful purpose. However, personal information may be unintentionally but unavoidably collected when a drone is collecting imagery of an intended "target", such as when a real-estate photographer using a drone unintentionally captures imagery of people in neighbouring properties. It is unclear whether personal information collected in such a manner is contrary to this principle.

IPP 4 requires, among others, that personal information shall not be collected by an agency "by means that, in the circumstances of the case ... intrude to an unreasonable extent upon the personal affairs of the individual concerned." Whereas intrusion on seclusion requires the intrusion to be "highly offensive", the Privacy Act 1993 merely requires the collection of information (that is, capturing of video or still photographs) to intrude to "an unreasonable extent". The CCTV Guidelines note that it is almost certainly unreasonably intrusive to capture imagery of "a person's private front or backyard or any other places where people are likely to expect privacy" (Privacy Commissioner, 2009, p. 13), and this was confirmed in *Armfield v Naughton* (para. 65). It is unclear whether footage captured incidentally while the drone is capturing imagery of a neighbouring property is unreasonably intrusive. However, there may be an arguable case for an unreasonable intrusion when imagery is deliberately collected about an individual but consent has not been obtained.

IPP 6 requires that where an agency holds personal information in a form that can be readily retrieved, the individual concerned has a right to obtain confirmation of whether information is held and to access that information (that is, view the footage that pertains to the individual). However, short of involving the Privacy Commissioner, enforcing that right may be difficult, and the holder concerned has the incentive to deny that personal information is held.

In sum, footage deliberately collected without permission of someone's front or back yard is likely to breach at least one IPP, but the status of information collected incidentally to a lawful purpose is unclear. Information collected by a drone thus might be an "interference with privacy".

2.4.3 Uncertainty over Privacy Violation

Two problems arise that reduce the expected damages cost to the drone operator. The first problem is one of asymmetric information: only the drone operator knows with a high degree of certainty whether their actions are interfering with the privacy of person(s) on the ground, but the person(s) on the ground lack this information. This asymmetry creates uncertainty whether it is worth the opportunity cost of initiating an action or making a complaint to the Privacy Commissioner.

The second problem is that there is no guaranteed cause of action: an intrusion into seclusion must be highly offensive for an action in tort and yet that standard is undefined in respect of drone imagery; an intrusion into seclusion must also be intentional, and the drone operator always has the opportunity to argue it was unintentional or even negligent.

An interference with privacy requires one or more of the IPPs to have been violated, which likely requires the gathering of imagery to have intruded to an unreasonable extent.[16] The Privacy Commissioner has previously held that if a drone is not recording then there is no information collected, so no IPP can be violated (Privacy Commissioner, 2015). A drone is typically configured so that the video is broadcast back to the ground station, and this is certainly the case for any drone utilised for filming as the operator needs to ensure that the drone is filming the desired target. Given this factual background, the Privacy Commissioner's decision is questionable, as it would allow the continuous visual monitoring of private locations so long as none of the imagery was recorded. The Privacy Commissioner's decision also incentivises a drone operator to claim that no imagery was recorded if any complaint is made.

Faced with such uncertainties, a smaller proportion of cases will be pursued than would be the case if there was certainty about the filming, and some of the cases that are pursued will fail. Just what proportion of cases will be pursued and what proportion will be successful is unknown. These uncertainties will have the effect of reducing the expected cost of a penalty, and therefore reducing the incentive for a drone operator to avoid privacy violations.

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[16] Note that this does not require the physical device, whether CCTV camera or UAS, to have intruded.

2.4.4 Crimes Act 1961 and Summary Offences Act 1981

Part 9A of the Crimes Act 1961 creates a number of "crimes against personal privacy", including interception of private communications, disclosure of private communications unlawfully intercepted, and making, possessing, and distributing intimate visual recordings. The tort of intrusion on seclusion was developed in a case where the defendant had been convicted of making and possessing an intimate visual recording (i.e., *C v Holland*). Distribution of an intimate visual recording would seem to cover the same grounds as wrongful publication of private information, and interception of private communications addresses any instances where electronic communications are intercepted by a drone.

Section 30 of the Summary Offences Act 1981 creates an offence punishable by a fine of not more than $500 for "peeping or peering into a dwelling house" at night. This offence would be of little help to those concerned about a drone hovering over their house or property because most surveillance is likely to occur during the day rather than at night.[17] In addition, the fine is of a level that is unlikely to pose a significant deterrent to those with a criminal purpose.

2.4.5 Law Commission Privacy Project

From October 2006 to August 2010, the Law Commission conducted a thorough review of New Zealand privacy law. The review was conducted in four stages: Stage 1 provided an overview of privacy values, technology trends and international developments; Stage 2 considered public registers; Stage 3 considered the adequacy of New Zealand's law to deal with invasions of privacy; and Stage 4 reviewed the Privacy Act 1993. Although drones were not widespread at the time of the Law Commission's Stage 1 study, the concerns the Commission considered about CCTV and camera phones are relevant to them (Law Commission, 2008, pp. 140–142).

In the Stage 3 report, the Law Commission recommended the introduction of a Surveillance Devices Act which "would provide for both criminal offences and a right of civil action in relation to use of visual surveillance, interception and tracking devices" (Law Commission, 2010, para. [1.7]). The proposed Act was seen as a complement to the Search and Surveil-

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[17] The Law Commission (2010, para. [5.39]) suggests that "the restriction to night time is irrational."

lance Act 2012,[18] which applies solely to law enforcement officers. The Law Commission (2010, para. [3.37]) was particularly concerned about surveillance of the interior of a dwelling, and considered that:

> ... the offence [of visual surveillance of a private dwelling] should not apply to visual surveillance of the curtilage of a dwelling, such as a yard, garden or deck. The expectation of privacy outside the walls of a dwelling is lower than within it, and not so high as to justify criminal charges for infringing it.

The Law Commission considered surveillance outside of the dwelling to be adequately regulated by the Privacy Act 1993, with some minor modifications proposed. In particular, the Law Commission considered that the Privacy Commissioner should be able to undertake self-initiated audits of agencies using CCTV or other surveillance systems (Law Commission, 2010, para. [4.8]). Such audits are likely to be appropriate for drone operators and may be essential for ensuring that the IPPs are being complied with.

The Stage 3 report also recommended that the tort of invasion of privacy be left to develop at Common Law. Whata J's subsequent finding in *C v Holland* that the tort of intrusion on seclusion forms part of the law of New Zealand is in accord with the Law Commission's recommendation.

The Stage 4 report provided a focused review of the Privacy Act 1993 (Law Commission, 2011). A large number of recommendations were proffered, including the introduction of a new Privacy Act, but in large part the underlying principles would remain as discussed above.

2.4.6 Summary

The privacy torts require the publication or recording of information to be "highly offensive", a threshold that is unclear for observation of people undertaking normal activities in their backyards. The Privacy Act 1993 provides an alternative cause of action for an "interference with privacy". Imagery collected from CCTV of private front and back yards has been held to intrude to an unreasonable extent on privacy, and thus constitute an interference with privacy. It is unclear whether a single flight collecting the same imagery would necessarily constitute an unreasonable intrusion. In addition, the Privacy Commissioner has held that if a drone is not re-

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[18] When the Stage 3 report was released, the Search and Surveillance Act 2012 was still a Bill before Parliament.

cording then collection of personal information does not occur and there is no interference with privacy. In sum, there are sufficient uncertainties in the current body of tort and statute law that a person upset by unwelcome surveillance cannot be sure of an acceptable resolution, even when that surveillance takes place in a location where they have a reasonable expectation of privacy. From an economic perspective, this imposes uncompensated costs on the aggrieved party. If these costs remain uncompensated, the outcome can only be efficient if those costs would be exceeded by the cost of enforcement.

2.5 International Experience

The introduction noted six cases from the United States where drones had either been shot at or shot down, with privacy concerns claimed in four of those cases. In the New Jersey case, the shooter, Russell Percenti, was indicted on charges of criminal mischief and possession of a firearm for an unlawful purpose (The Smoking Gun, 2015). Percenti pleaded guilty to the lesser charge of criminal mischief, avoiding a potential prison sentence for the firearms charge (News, 2016). In the California case, a small claims court found that the shooter "acted unreasonably in ... shoot[ing] the drone down, regardless of whether it was over his property or not" and was ordered by a small claims court to pay $850 for damage to the drone (Farivar, 2015). There were no criminal charges. In the Virginia case, the operators of the unmanned aircraft fled when the shooter threatened to call the police, but no one has filed a criminal complaint (Farivar, 2016), and no charges have been laid. In the 2016 Tennessee case, it appears that police were called, but no charges were laid because "the responding deputy could not identify a law that had been broken" (Flowers, 2016). No charges have been laid in the 2017 Tennessee case.

In the Kentucky case, the shooter (William Meredith) was charged with first degree wanton endangerment and first degree criminal mischief (WDRB News, 2015a). Those charges were dismissed, with the Judge hearing the case finding that the overflight of the drone was an invasion of privacy and that Meredith "had the right to shoot at this drone" (WDRB News, 2015b). The owner of the drone (John Boggs) subsequently filed proceedings in the United States District Court for declaratory rulings on a number of matters, including that the operating the drone "did not violate [Meredith's] reasonable expectation of privacy", that it is not legal to shoot at a drone operating in navigable airspace, and a claim for $1,500 for damage to the drone under trespass to chattels (*Boggs v Meredith*, Complaint for Declaratory Judgment and Damages, 2016).

Part of Boggs' argument rests on the proposition that he was operating his drone in "Class G" airspace, which is defined as the airspace between the surface and the lower level of controlled airspace, and therefore the operation was legal and falls entirely under the jurisdiction of the Federal Aviation Administration. This proposition appears to ignore the leading United States authority on aviation trespass, in which the United States Supreme Court held that although the cujus est solum doctrine had been substantially and necessarily modified by the advent of aviation, low-level flight could amount to trespass (*United States v Causby* 328 US 256 (1946), p. 265):

> The superadjacent airspace at ... low altitude is so close to the land that continuous invasions of it affect the use of the surface of the land itself. We think that the landowner, as an incident to his ownership, has a claim to it and that invasions of it are in the same category as invasions of the surface.

Another argument proffered by Boggs is that Meredith does not have a reasonable expectation of privacy, relying on the majority opinion in *California v Ciraolo* that an expectation that a garden is protected from observation from publicly navigable airspace "is unreasonable and is not an expectation that society is prepared to honor" (p. 213).

The United States District Court dismissed the case for lack of subject matter jurisdiction and found that the claim for trespass to chattels was properly one for a state court to decide rather than a federal court (*Boggs v Meredith*, Memorandum Opinion, 2017). This leaves unresolved the question of the height at which the flight of an unmanned aircraft becomes a trespass: above that height *California v Ciraolo* would seem to be the controlling case, and below that height *United States v Causby* would be the controlling case.[19]

European Union (EU) member states are subject to the 'Charter of Fundamental Rights of the European Union' (European Union, 2000), which includes a "right to respect for ... private and family life, home, and communications" (Article 7) and a "right to the protection of personal data" which "must be processed fairly for specified purposes and on the basis of

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[19] For further analysis of the unresolved US legal position see McNeal (2014).

the consent of person concerned or some other legitimate basis laid down by law" (Article 8). Article 8 is expanded by the 'Data Protection Directive' (European Union, 1995), which provides additional detail on how personal data is to be protected. EU member states are required to implement their own national legislation to comply with the 'Data Protection Directive'. National legislation will be similar in effect to our Privacy Act 1993, which has been recognised by the EU as complying with the principles of the 'Data Protection Directive'. As such, EU member states will generally face the same issues as New Zealand with respect to drones and privacy.

Under Swedish law, a camera that is operated remotely and can surveil public areas is considered a surveillance device and a surveillance licence is required. In October 2016, the Supreme Administrative Court of Sweden ruled in *AA v Data Protection Authority* that drones with cameras meet both requirements (remote operation and the ability to surveil public areas) and are therefore surveillance devices. It is notable that the Swedish treatment of surveillance devices provides specific protection of privacy in public places, in contrast to the law in New Zealand which holds there is only a limited expectation of privacy in public places.

In December 2016, the United Kingdom's Department for Transport issued a consultation on the regulation of drones (Department for Transport, 2016). That consultation acknowledges the range of safety, privacy, and security issues associated with drones, but does not offer any proposals directed specifically at privacy. However, the consultation paper includes proposals for registration and electronic identification of drones to "aid enforcement".

2.6 Reform Proposals

Although the Law Commission's recommendations represent a comprehensive package of reforms that would strengthen New Zealand's privacy laws, there is gap that allows for privacy violations by drones, and for which a civil remedy is appropriate. Drawing on drone characteristics and the foregoing analysis of the status quo, the following options for statutory reform are worth consideration: (i) amending the privacy torts by statute; (ii) the issuance of a Code of Practice under the Privacy Act 1993; (iii) an encoded radio frequency beacon for those drones piloted by an operator approved by the Privacy Commissioner; and (iv) strengthening the application of the Privacy Act 1993 to drones.

Even with these changes in place, a significant problem with drones remains: identification of the operator (Aldworth, 2014). In such circumstances judicial remedies will be ineffective. Consequently, it may be more appropriate to enable forms of self-help. This would enable a potential victim to take immediate action against a drone in order to prevent an actual or potential privacy violation.

Finally, some privacy-violating conduct is sufficiently egregious that criminal sanction is warranted, hence the final option proposed is the extension of criminal law.

2.6.1 Tort Reform

The first option I propose for addressing the privacy concerns generated by modern imaging technologies, including drones, is that of tort reform. In particular, the privacy torts could be amended by statute to rely primarily on the reasonable expectation of privacy. This could include Moreham (2008)'s proposal to dispense with the "highly offensive" threshold, or alternatively, to clarify the range of circumstances which should be considered highly offensive. I also propose that the reasonable expectation of privacy should be given explicit precedence over the existing principle of no right to limit views, effectively rendering the latter redundant.

2.6.2 Code of Practice for Drone Operation

One option that could be implemented relatively quickly is the creation of a privacy code of practice associated with drone operator certification.[20] Under Part 6 of the Privacy Act 1993, the Privacy Commissioner may issue codes of practice for an industry or activity which may modify one or more of the IPPs or specifies the means of compliance with an IPP. This provides clear means by which the activities of drones could be regulated in regards to privacy, making use of existing dispute resolution and enforcement mechanisms within a coherent privacy framework.

The creation of a separate code of practice is more appropriate than revising the CCTV Guidelines or issuing new guidelines because violating a code of practice amounts to a breach of the IPPs, but a violation of guidelines does not. Such a code of practice could reduce the uncer-

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[20] Note also that the Law Commission (2010, para. [4.14]) considered the possibility of a CCTV code of practice as "the logical next step" if "guidance alone does not prove effective in controlling CCTV surveillance and ensuring that privacy is protected".

tainty around what activities intrude to an unreasonable extent, and thus reduce the uncertainty over whether a particular use of drones constitutes an interference with privacy.

I propose that the “Code of Practice for Drone Operations” should contain the following provisions:

- Unless expressly exempted by the Privacy Commissioner or permission has been obtained from the occupiers of the affected properties, a drone must not be operated over residences, residential areas or other locations where people have a reasonable expectation of privacy. Operation in contravention of this provision would be deemed to intrude to an unreasonable extent into the personal information of the affected individuals.
- Affected properties are all properties that might reasonably be expected to be included in photographs or imagery captured by the drone.
- The Privacy Commissioner may grant an exemption to a drone operator that has undertaken appropriate training, and has adopted procedures approved by the Office of the Privacy Commissioner for protection of personal information.
- An exemption carries with it the requirement to be subject to audit.

The first of the proposed provisions is the analogue of CAR Part 101, Rule 101.207(a)(1), but in relation to privacy rather than safety. The third and fourth of the proposed provisions are the analogue of CAR Part 102.

The Law Commission (2010, para. [4.15]) rejected the blanket licensing of CCTV systems as “impractical and overly bureaucratic”. My proposals for exemptions granted by the Privacy Commissioner are, in effect, a form of licensing. However, the exemptions would only be sought by those drone operators that have a genuine need to conduct operations that might be viewed as interfering with privacy, and thus would not amount to blanket licensing. Those operators who do not seek an exemption would instead need to ensure that they communicated with all affected persons regarding the purpose of their flight.

2.6.3 Encoded Radio Frequency Identification

A privacy exemption to operate over residential areas should be associated with a means of identifying both the drone and the operator. To that end, certification under CAR Part 102 already requires the operator to provide

CAA with a list of the drone that the operator intends to fly, including a serial number or other unique identifier. CAA's standard practice with manned aircraft is to publish a register of aircraft listing the registration, make, model, serial number and registered operator.[21] There may be considerable benefit in requiring registration of drones and that register being available to the public.

One potential problem is the small size of drones and the consequential difficulty of having a visible identifier. Similar to the proposal advanced by Department for Transport (2016), it might be possible to have an encoded radio frequency beacon on all properly authorised drones, with transmissions occurring on a frequency that can be received by smartphones (possibly on the 2.4 GHz "WiFi" frequency band already utilised by most drones); an app would be required to determine the aircraft's registration and whether the drone has been authorised by the Privacy Commissioner.[22] Drones without such a beacon, or with a malfunctioning beacon, would be presumed to lack a privacy exemption. People could then have confidence that an authorised drone is not violating their privacy, and the police and other enforcement officials would have greater confidence in intervening when a drone is potentially photographing without approval.

This option directly reduces both sources of uncertainty: at least some drones will be registered and carry an identification beacon, and people on the ground may be able to ascertain that such aircraft are operating with procedures approved by the Privacy Commissioner, and are therefore unlikely to be breaching privacy. The drones operating under this scheme would also be traceable back to a specific operator. Drones operating outside this scheme (not carrying an identification beacon), would be presumed to be operating outside of the Privacy Commissioner's regime, and therefore potentially committing a privacy breach. Operator identification then

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[21] The aircraft register is available at http://www.caa.govt.nz/script/air-reg-query/. Selecting an aircraft classification (for example: aeroplane, glider, helicopter) provides a list of all aircraft of that classification.

[22] The Department for Transport (2016, para. [6.16]) comments:

> We envisage a digital identification system embedded in all drones over a certain weight, which will identify the drone in the air to drone traffic management systems, other drones flying around it and other airspace users, as well as anyone 'scanning' the drone from within a certain distance equipped with appropriate 'scanning' technology. Scanning a drone would release its unique identifying number. If the drone operator was perceived to be breaking the law, this number could then be used by the Police to track the owner of the drone down via the drones registry.

remains problematic. The drone operators most likely to breach privacy might also be the operators most likely to remain outside the scheme, and this option does not provide an adequate approach for controlling those operators.

2.6.4 Strengthening the Privacy Act 1993

The Privacy Act 1993 could be strengthened to better address privacy issues raised by drones. In particular, improvements are required that reduce or eliminate existing uncertainties. This could be achieved by specifying that the gathering of still or video imagery by any broadcast or closed-circuit television system of a location where a person has a reasonable expectation of privacy constitutes an unreasonable intrusion. Using the phrase "reasonable expectation of privacy" in the formulation of the civil offence would also have the effect of harmonising the civil offence with the privacy torts. The current definition of an "interference with privacy" is quite different from the definition of the two privacy torts.

This option would reduce uncertainties about the conduct legally considered to be an interference with privacy. This option would not address the first source of asymmetric information, as it would not include a provision for the Privacy Commissioner to approve or audit the practices of drone operators, nor a means of determining whether a drone is likely to be operating in a manner that does not violate privacy. However, it would apply to all operators, so any uncertified operators that breach privacy and can be identified could be sued.

2.6.5 Self-Help

A further option proposed for addressing drone-related privacy violations is the doctrine of self-help, allowing the victim to take immediate steps to halt a potential privacy violation. This may be particularly important when it is difficult to identify the drone operator and/or an optimal fine is unlikely to be levied. Froomkin and Colangelo (2015) observe that the law allows self-help remedies against both crime and torts. While originally derived from Common Law, many of these self-help remedies have been codified in statute. The Crimes Act 1961 allows the use of reasonable force to protect both oneself and others from assault (s. 48). The Impounding Act 1955 provides that trespassing stock may be seized and restrained or impounded (Part 5), although trespass damages can only be recovered if the occupier of the land has taken reasonable precautions, such as fencing the land (s. 26). The Dog Control Act 1996 provides that any person may seize or destroy a dog attacking any person or animals (s. 57), and even a dog simply "at large" among stock or poultry may be seized or destroyed (s. 60). Froomkin and Colangelo (2015) argue that the practical problems associated with drones mean that self-help remedies may be appropriate too: if the operator of the drone cannot be identified then the law is not going to be able to ensure a just outcome, and self-help may be the only practical means of protecting oneself from a wrong.

An argument in favour of allowing self-help in relation to privacy violation by drones can be drawn by analogy with self-help remedies allowed in relation to dogs. Davis (2011, p. 170) argues in the context of physical harm that, just as a strict liability is placed on dog owners for any damage caused, there should also be strict liability placed on the operators of drones for any damage caused. This analogy can be readily extended from physical harm to a broader notion of mental and emotional harm. Stock worrying – which occurs when a dog is roaming at large among stock without actually attacking them – is a result of the fear response of prey animals to a predator (the dog).[23] Drones have been shown to induce physiological stress responses in large mammalian predators (Ditmer et al., 2015), and the adverse human responses to drones described in the introduction to this chapter are clear examples of stress. If the law allows that a dog may be seized or destroyed for stock worrying, logically applying this same principle to drones suggests that an aircraft worrying stock or people should also be liable to be seized or destroyed, even if the person concerned is not certain that the drone is engaged in a privacy breach.

The law is silent on the destruction of illegal surveillance devices. But, it is not surprising that the courts have not seen claims for compensation for the destruction of such devices, as their very existence is the result of a criminal or tortious act. Destruction of the devices is the use of reasonable force to prevent a greater harm from occurring. The Crimes Act 1961 provides for forfeiture of interception devices if a person is convicted of intentionally using such a device to intercept communications (s. 216E), and equipment used for making intimate visual recordings may also be subject to forfeit (s. 216L(2)).

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[23] Even domestic farmed sheep that are relatively familiar with the presence of dogs show behavioural and physiological responses to dogs that are characteristic of fear (Beausoleil, 2006).

There are some obvious limitations to the proposition that an individual should be able to seize or destroy a drone without evidence that it is actually breaching privacy. In the first instance, a person in a location with no reasonable expectation of privacy should not be able to exercise such a self-help remedy. Second, various offences under the Arms Act 1983 limit the ability to shoot down a drone if doing so would present risks to persons or property.[24] Third, as noted earlier, while a drone could be disabled by radio or GPS jamming radios, it is an offence against the 'Radiocommunications Regulations (Prohibited Equipment - Radio Jammer Equipment) Notice 2011' to operate any radio jamming equipment in New Zealand without a licence (New Zealand Gazette, 2011). Fourth, if a drone is disabled in flight, it may crash on another's property causing either harm to people or damage to property, particularly if non-trespassory surveillance is involved. These limitations collectively suggest that the self-help option is feasible and desirable only when trespass occurs, with the proviso that the person disabling the drone may be liable for damage caused to any other property.

It is also relevant to note the relationship between the size of a drone and its purpose. Most, if not all, drones carrying out a legitimate commercial purpose will be designated as "small" or larger.[25] High-quality photography requires a stable platform and larger machines will have greater stability in a breeze. Applications such as parcel delivery, when that eventuates, will require drones of a significant size capable of lifting a package of moderate size and weight. The size and design of the drone will be an indication that the aircraft has a legitimate purpose. Very small drones, on the other hand, are unlikely to have a legitimate purpose other than recreational use. The smallest drones are typically intended specifically for surveillance,[26] and may also be the easiest to seize and destroy if they are found to be trespassing.

Problems may arise from the prohibitions in the Aviation Crimes Act

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[24] It is offence against section 53 of the Arms Act 1983 to carelessly use a firearm or to discharge a firearm with reckless disregard for the safety of others, and against section 48 to discharge a firearm near a dwellinghouse or public place "so as to endanger property or to endanger, annoy, or frighten any person".

[25] Within the literature, drones may be described in terms of the adjectives "nano", "micro", "small", and so forth (see, for example, John A. Volpe National Transportation Systems Center, 2001). There is general agreement that those with a maximum take-off weight of 25kg or less are "small", although it is unclear how 25kg became the relevant break point. Small drones can be further classified into "micro" with a maximum weight less than 2kg, and nano with a maximum weight less than 500g.

[26] For example, the manufacturer AeroVironment has developed a "Hummingbird Nano Air Vehicle" that looks like a hummingbird, flies with flapping wings like a hummingbird, and is designed specifically for surveillance purposes (Ackerman, 2011).

1972 against destroying an aircraft in service or causing damage to an aircraft in service which renders the aircraft incapable of flight; these offences carry a term of imprisonment of up to 14 years (s. 5). These prohibitions were framed in an era when aircraft were always manned, so destroying or damaging an aircraft would necessarily put human life at risk. There is no direct risk to human life with a small drone which by virtue of their size are incapable of carrying passengers, and on that basis, it can be argued that the provisions in the Aviation Crimes Act 1972 should be revised to reflect the new technology.

Legalising self-help would require amendments to both the Aviation Crimes Act 1972, providing a defence in the event that a drone was committing aerial trespass and the Civil Aviation Act 1990, providing a broader range of circumstances in which a drone could be held to be committing aerial trespass.

If adopted, this potential option would ensure that drone operators obtained permission from every property over which they were going to fly, or otherwise risk having their drones somehow disabled or destroyed. This requirement to obtain permission would be separate from, and take precedence over, the requirement in CAR 101.207(a)(1), and thus could not be circumvented by obtaining operator certification under CAR Part 102. This would significantly reduce the costs associated with privacy violations, substituting for them the costs of either damaged or destroyed drones, or the effort of obtaining permission from all parties potentially affected by a drone operation. This would provide the drone operator with the incentive to ensure that the benefits of each drone flight were at least equal to the costs incurred, and ultimately to optimise the number and characteristics of flights.

There may be some situations where this option by itself could result in the destruction of some drones that were carrying out legitimate activities and were not engaged in a privacy breach. For that reason, a better outcome is likely to be achieved by a combining this option with a privacy code of practice, certification, and radio frequency identification: drones engaged in legitimate activity would be registered and identifiable and therefore less likely to be seized and/or destroyed if trespassing. It may also be appropriate to define aerial trespass as occurring up to a certain height (such as 500 feet AGL) so that a corridor of airspace can be preserved for drones that must traverse airspace as part of legitimate activity.[27] A gap will poten-

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[27] Note that the minimum height for manned aircraft over urban areas is 1,000 feet

tially remain for non-trespassory surveillance by unregistered drones, but this gap also exists with the "no right to limit views from public places or from other private property" under tort (*C v Holland*, para. 92).

2.6.6 Criminal Sanction

The low probability of detection means that damages in either tort or under statute would need to be very high in order to provide optimal deterrence (Polinsky & Shavell, 1992). Posner (1985) views criminal law as deterring people from bypassing "the market" when the optimal damages required for deterrence in tort are so high that they would exceed the offender's ability to pay, and therefore suggests that criminal law may be more appropriate. There is also a class of offence where civil privacy law is not the best option, such as when a drone is used for reconnaissance purposes in the commission of a crime.

In the first instance, the offence of peeping into a dwelling house at night should be amended to remove the restriction to night time, and to increase the fine from $500 to a maximum of at least the benchmark of $15,000 adopted by the HRRT.[28] These measures would provide a more effective deterrent against what might be the most egregious use of drones, the deliberate observation inside a house.

The second suggestion is the introduction of a new crime of using surveillance technologies in the commission of another crime. This would create a new offence covering the use of drones for reconnaissance in the commission of a burglary. This should attract at least the same sentence as the amended "peeping" crime or the Law Commission's proposed crime of "visual surveillance of a private dwelling".

While fines and monetary reparations under criminal law may be relatively low, transferring a wrong from tort to criminal law creates additional costs to the wrongdoer. If a suit is successful, a tortfeasor must pay damages and costs, but has no equivalent of a criminal "record" that can act to exclude the individual from future opportunities.

Counterbalancing the costs imposed by a criminal conviction, conviction of a crime requires both mens rea and a higher evidentiary standard than required for any of the other proposed options. The lowest evidentiary

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AGL or any obstacle, so allowing aerial trespass up to 500 feet AGL provides a "slice" of airspace 500 feet high that can be used for applications such as delivery services.

[28] This could also be achieved by adopting proposed crime of "visual surveillance of a private dwelling" proposed by the Law Commission (2010, para. [3.33]).

standard is associated with the proposed self-help remedy, where a concern that privacy is being breached may be sufficient for action. A breach of the Privacy Act 1993 or an associated code of practice may be unintentional, but is nonetheless still an actionable breach, and being a civil statute only requires a breach to be proved on balance of probabilities. A crime, however, must be proven beyond reasonable doubt. When a drone operator can simply delete any recording, and deny that footage was being taken, it may be very difficult to prove a crime unless an operator is caught "in the act" by law enforcement officials. Publication of material that involved a privacy breach will also not always be conclusive evidence, as it will still be necessary to prove intent.

2.7 Conclusion

The general public is concerned about drones violating their privacy and being subjected to surveillance in spaces where they might have a reasonable expectation of privacy. Experimental evidence clearly demonstrates that even individuals who consent to surveillance experience a range of negative emotions including fear, anxiety and anger, and change their behaviours in response to the surveillance. Over the longer term, these negative emotions and the behaviour changes can result in reduced trust and lower economic growth. In this chapter, I have proposed six reforms that would enhance the effectiveness of existing privacy law in addressing privacy breaches by drones.

The mind of the public frequently equates privacy and trespass, yet the two are manifestly different. However, trespass could be used to prevent some forms of privacy violation. Amending the Civil Aviation Act 1990 to provide for aerial trespass by unmanned aircraft would enable the law of trespass to be invoked when such an aircraft is operating at low level over a property without authorisation. Given the difficulty of identifying or apprehending a drone or its operator, I also propose that the law is amended to allow destruction of aircraft committing aerial trespass. These proposals are consistent with those advanced for the United States by Froomkin and Colangelo (2015).

Clarifying what conduct constitutes aerial trespass does nothing to solve the problem of non-trespassory surveillance, which can be conducted using a drone located over a neighbouring property or public way, such as a road, footpath, or walkway.

The general problem of non-trespassory surveillance by drones can only be addressed through the development of privacy law. New Zealand's privacy torts may set too high a standard ("highly offensive"), and should arguably be reformed to rely solely on the reasonable expectation of privacy as suggested by Moreham (2008). Tort law reform may be too slow given the pace of technological change unless implemented by statute. An alternative approach is for the Privacy Commissioner to promulgate a "Code of Practice for Drone Operations", issued under the Privacy Act 1993. The Code would be able to clarify exactly when a drone would constitute an unreasonable intrusion and likely to result in an "interference with privacy", a civil wrong that can be pursued in the HRRT. I propose that the Code of Practice would prohibit flights over residences, residential areas and other areas where persons would have a reasonable expectation of privacy unless either permission is obtained from all affected properties (including those not directly under the flight path) or an exemption has been obtained from the Privacy Commissioner on the basis that the applicant has demonstrated good privacy systems. A privacy exemption to operate over residential areas should be associated with a means of identifying both the drone and the operator, which might be best achieved by use of an encoded radio frequency beacon as proposed by Department for Transport (2016).

The proposed Code of Practice would sit alongside the CARs in being an instrument to regulate the use of drones, and may be most effectively implemented by requiring the drone operator to hold a CAR Part 102 certificate. There may, however, need to be a minor amendment to the Civil Aviation Act 1990 to allow this.

I also propose amending the Privacy Act 1993 to clarify what constitutes an unreasonable intrusion into privacy for still or video imagery by any broadcast or closed-circuit television systems. The reduction in uncertainty would improve efficiency in the application of the law.

Finally, I support the extension of the existing crime of peeping into a dwelling house to include peeping during daytime; and propose a new crime to capture the use of unmanned aircraft in the commission of any other crime. Collectively, these proposals would enable New Zealand's privacy law to better address the challenges posed by drones.

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Chapter 3

A Model of Self-Defence against Drones

Synopsis

This chapter considers when a bystander should be allowed to exercise a right to self-defence and take action to destroy a drone. The analysis considers simultaneous interaction between the drone operator and a bystander, as well leader-follower variants with the drone operator as leader and with the bystander as leader. I show that it can be efficient to destroy a drone whenever the operation of the drone reduces welfare, assuming that the expected liability of the drone operator is low. The analysis also suggests that it is never efficient to allow the destruction of manned aircraft, a conclusion which reflects existing law.

3.1 Introduction

Like many, if not most, other technologies, drones have many beneficial uses but can also cause harm. That harm may arise as an externality associated with a beneficial use, or it may arise where the operator acts maliciously and intends to cause harm.

The absence of a person on board a drone means that the aircraft can be significantly smaller, lighter, and cheaper than a manned aircraft. This in turn means that drones can be used for many purposes that are uneconomic with manned aircraft. Consulting research suggests that there are significant economic benefits to be gained from the utilisation of drones, even when just a small selection of economic activities is considered (see, for example, Andrews & Shelley, 2015).

The same features that enable the attainment of these benefits also make it easier and cheaper for a variety of harm to arise as a consequence of the operation of a drone. The various sources of harm that might arise from drone use include privacy violations (Shelley, 2016b), surveillance (Shelley, 2016c), physical injury to bystanders (Shelley, 2016a), as well as physical injury to larger numbers of people in a collision with a manned aircraft, damage to critical infrastructure, and threats to national security (Shelley, 2018; Wright & Jenzen-Jones, 2018). Furthermore, drones can be flown from afar, making it difficult to identify the operator (Aldworth, 2014) and attribute liability.

Drones are classified by regulatory authorities as aircraft and hence subject to the same regulatory arrangements as all other aircraft. The Montreal Convention (United Nations, 1975) prohibits any person from destroying an “aircraft in service” or causing “damage to an aircraft in service which renders the aircraft incapable of flight”. In New Zealand, these prohibitions are codified in the Aviation Crimes Act 1972, with the offences which carrying a term of imprisonment of up to 14 years. These prohibitions were framed in an era when an aircraft always had a person on board, so destroying an aircraft or rendering it incapable of flight while in service would necessarily put human life at risk. An important area of policy research is the extent to which existing legal and regulatory frameworks designed for manned aircraft might require amendment to better address the characteristics of drones.

At a high level of abstraction, it could be argued that drones are little different to any other new technology and that the law is well able to adjust to meet the challenges posed by the technology. Some also argue that tort law can respond to the challenges of new technology when legislatures and regulators cannot (see, for example, Lyndon, 1995, p. 176). This chapter adopts a contrary position and argues that drones have unique characteristics which render the standard law and economics prescriptions ineffective and that there will, therefore, be situations in which it is most efficient for parties to act in self-defence against drones, including potentially destroying the drone. Section 2 of this chapter considers the extent to which existing legal, regulatory, and policy instruments are capable of providing incentives for an efficient level of drone activity and drone-related harm. I conclude that the characteristics of drones are such that a self-defence remedy may be appropriate.

In section 3.3 I present a formal model of self-defence against drones to analyse the conditions under which self-help to prevent harm from a drone is efficient given an exogenously specified level of harm. Section 3.4 then presents a numeric example to analyse the predictions of the model for both manned and unmanned aircraft, clarifying the policy responses that are appropriate for each. Section 3.4 also addresses several questions that could not be answered by the formal analysis.

I derive the general result that destruction of drones is likely to be efficient when harm is relatively high, the operator of the drone bears a relatively low proportion of liability, and the social cost of destruction is low. Conversely, the analysis also suggests that it is not efficient to destroy manned aircraft, confirming the principles embodied in the Montreal Convention.

3.2 Literature Review

Harm from the use of drones can arise via three primary channels: as an externality associated with a beneficial activity; as a consequence of negiligence when the drone operator is undertaking an otherwise socially beneficial activity; or as a consequence of the drone operator's intent to cause harm. The appropriate means of addressing harm caused depends in part on which of the three channels is active.

3.2.1 Externalities and Negligence

Consider, first, harm that arises by way of an externality associated with the operation of a drone. In a first-best world, the drone operator and bystander could negotiate a Coasian bargain that would ensure that the efficient level of flights, and the efficient level of harm from those flights, would occur. However, as is well accepted, a Coasian bargain is not possible if there are high transaction costs, such as when there are a large number of people potentially affected by the harm (Coase, 1960). Thus, when there is only a few drone operators and a few bystanders then the approach of direct negotiation may be appropriate, but if there are a large number of drone operators and/or a large number of bystanders then the transaction costs of negotiations becomes prohibitively high and the Coasian solution is unobtainable. However, an efficient outcome may still be attainable if individual drone operators can be identified and liability for harm can be imposed via tort.

Consider now harm that arises as a result of negligence on the part of the drone operator. The standard economic prescription for negligence is tort liability, which causes the (potentially) negligent party to internalise the potential cost of their actions by way of the expected cost of liability that they might bear in the event of negligent actions. The same approach is applicable to externalities when private contracting is not practicable.

Tort Liability

The most common liability standards imposed under tort can be broadly characterised as negligence and strict liability. Negligence requires proof that harm to the plaintiff was caused by an act of the liable party, and that the liable party failed to meet a reasonable standard of care. Strict liability only requires proof that harm to the plaintiff was caused by an act of the liable party. Strict liability is an appropriate legal standard when the victim is unable to readily take precaution, or the cost of the victim taking precaution is much higher than the cost of the injurer taking precaution (Feldman & Frost, 1998; Shavell, 1980).[1]

It is difficult if not impossible for the (potential) victim to know the level of care of any aircraft operator and therefore how much precaution to take, but it is straightforward for the aircraft operator to exercise a reasonable standard of care. Appropriately, therefore, aviation typically imposes strict liability for damage caused by an aircraft or by an object falling from an aircraft. Jakubiak (1997) summarises the liability regime that applies to commercial aviation in the United States, concluding that the various doctrines of liability "appear strikingly similar to common-law imposed strict liability". In New Zealand, s97 of the Civil Aviation Act 1990 imposes strict liability with contributory negligence. The allowance for contributory negligence means that where a person on the ground takes some action that contributes to the crash of an aircraft, or does not reasonably avoid

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[1] More generally, negligence and strict liability are equivalent in the case of unilateral accidents if injurers are homogenous, the volume of the injurer's output is exogenously fixed, and parties are risk neutral (Schäfer & Schönenberger, 2000). Strict liability is preferred when the injurer's output levels depend on the liability for harm, both in the single firm scenario (Shavell, 1980) and in long-run equilibrium in a market (Polinsky, 1980). Strict liability is also superior if injurers differ in their ability to take precaution and the standard of care under negligence does not take account of this difference (Klevorick, 1985). Relaxing the assumption of risk neutrality has ambiguous effects on which rule is preferable: Lee (2015) shows that risk aversion may increase or decrease the efficient standard of care under negligence, and that strict liability may result in a higher or lower social welfare than the negligence rule, with both effects depending on the relative wealth levels of the two parties.

an aircraft, then they will also bear liability.

Even though strict liability may apply to physical harm, it typically does not apply to harm caused by potential privacy violations. For example, New Zealand's Privacy Act 1993 requires that information collection intrudes to an "unreasonable extent" for an actionable "interference with privacy" to occur. However, the practical interpretation of this standard is currently unclear for drones (Shelley, 2016c). The Privacy Commissioner has previously held that if a drone is not recording then there is no information collected, so there is no interference with privacy (Privacy Commissioner, 2015). It is not possible for a bystander to know whether or not a drone is recording, so they also cannot know whether to take precaution or whether it is worth the cost of initiating a complaint with the Privacy Commissioner. The Privacy Commissioner's ruling also creates an obvious incentive problem, providing an incentive for drone operators to simply claim that they were not recording any information. There may, therefore, be insufficient attribution of liability for privacy violations under existing New Zealand law, and it may be necessary to utilise an alternative means to provide sufficient incentives for an efficient level of privacy violations.

Probability of Identification and Enforcement

While the various types of harm described above can also be perpetrated with a manned aircraft, manned aircraft are large and prominently marked with registration codes, enabling relatively easy identification of the registered operator of an aircraft that is engaged in an activity potentially causing harm. A drone, on the other hand, is small and cannot be readily identified (Patterson, 2017). Commonly available drones have the capability to stream live video back to the pilot, who may be located some considerable distance away from the subject being observed. There is therefore much less likelihood of any given regulation or legal right being enforced with drones than with manned aircraft.

Statistics released by the Civil Aviation Authority confirm that this is indeed the case: of 696 complaints about drones, only 11 resulted in warning letters, 15 in infringement notices and one person was prosecuted (Lawrence, 2018). Thus only 2% of complaints resulted in an enforcement action that would impose a cost on the operator of the drone. While it can be expected that some proportion of complaints concerns drone activity that is not contrary to the relevant rules, this does suggest that there is a very low probability of enforcement action being taken.

Optimal Damages and the Judgment Proof Problem

Even with a low the probability of successfully attributing liability through the legal system, an efficient outcome can be attained with sufficiently large penalties reflecting the damage cost adjusted for the probability of successful attribution of liability (Polinsky & Shavell, 1992). Damages in tort normally reflect the cost of harm actually caused, and thus are insufficient to provide efficient incentives when the probability of identifying the tortfeasor is low. Punitive damages are possible, but they are only awarded when the court considers that the tortfeasor is guilty of “outrageous wrongdoing” (Aitkin, 2016, p. 1332). It seems likely, therefore, that tort liability will be generally insufficient to provide efficient incentives to constrain harmful operation of drones.

The New Zealand Ministry of Transport estimates the value of a statistical life (VOSL) as $4.21 million (MOT, 2017). If the courts did award a sum reflective of the VOSL, properly adjusted for probability of detection (Polinsky & Shavell, 1992), the amount would be so high that perpetrators would be judgement proof (Shavell, 1986) and there would still be insufficient deterrence against operating a drone in a dangerous manner. In such circumstances some form of ex-ante regulation is appropriate to reduce the likelihood of harm occurring (Shavell, 1984).

3.2.2 Ex Ante Regulation

Two common forms of ex ante regulation are the promulgation of conduct rules and licensing. Conduct rules specify actions that must or must not be taken, and may also specify general standards of conduct. Licensing may be adopted in situations when welfare is enhanced by ensuring that practitioners meet a minimum standard of knowledge or skill. Neither approach is sufficient to address the harm that can be caused by drones.

Conduct Rules

Within New Zealand, drones are regulated as aircraft under the Civil Aviation Act 1990, and subject to the provisions of the Civil Aviation Rules 2015, Part 101 (“Part 101”). Part 101 can be characterised as containing both rules and standards (Kaplow, 1992). The rules in Part 101 includes restrictions such as not flying higher than 400ft above ground level, not flying over people without their consent, not flying over property without the consent of the occupier or owner, not flying within 4km of an aerodrome without the agreement of the aerodrome operator, and not flying in controlled airspace without the approval of air traffic control. The most significant standard specified in Part 101 is to "take all practicable steps to minimize hazards to persons, property, and other aircraft".

Research conducted for the Civil Aviation Authority indicates that there is a significant knowledge deficit in relation to the rules governing drones. Colmar Brunton (2017) found that 56% of New Zealand resident drone users and 55% of overseas resident drone users in New Zealand self-identified as being aware of the rules and having at least a basic knowledge of those rules. For New Zealand resident drone users awareness of specific rules ranged between 56% and 78% of drone users.

In addition to the low awareness of the Part 101 rules, only 35% to 59% of New Zealand resident drone users stated that they always comply with those rules (Colmar Brunton, 2017). This relatively low rate of compliance even amongst those that claim awareness of the rules may be a consequence of the low probability of enforcement discussed earlier.

Licensing

Licensing is common to a number of activities that are considered to pose a hazard to third parties. For example, licenses are required to drive cars, fly aeroplanes, and possess firearms, even if the relevant activities are to be performed privately. A pilot of a manned aircraft is also required to undergo significant training, usually at considerable personal expense, before gaining a licence that enables them to fly an aircraft. The operator of a drone, on the other hand, can purchase a drone relatively cheaply from a consumer electronics store, is not required to hold a licence, and within a matter of minutes from the purchase can fly the drone. Licensing is typically coupled with a knowledge test, and consequently could be assumed to eliminate the knowledge deficit evident in the Colmar Brunton (2017) survey.

However, licensing, even when coupled with surveillance and enforcement, does not prevent unlicensed individuals from engaging in the activity, or licensed individuals from undertaking the activity in an unsafe manner. For example, both cars and drivers are licensed. In a random survey of 746 vehicles being driven in Auckland, 79% of drivers elected to participate in the survey, and of those drivers 1.1% were unlicensed (Blows et al., 2005). Notwithstanding the prohibition on using a hand-held cellphone while driving, in the 2017 calendar year the New Zealand Police recorded 23,412 offences of using a hand held device for calling or texting while driving (New Zealand Police, 2018). Licensing has not prevented people from using their devices in a manner that creates a potentially serious safety risk to third parties.

Thirty five percent of New Zealand drone users do not consider that drones pose a risk to aviation safety (Colmar Brunton, 2017), which suggests that they would also view enforcement of relevant Part 101 rules as lacking legitimacy, in the sense that there is no valid safety basis for the rules. Watling and Leal (2012) report statistically significant negative correlations between the likelihood of violating specific driving laws and the perceived legitimacy of enforcement of that particular law. It therefore seems likely that licensing of drone operators would not solve the problem of compliance.

In addition to the issues discussed above, licensing does not change the fact that the casual bystander will not be able to determine who is flying a particular drone, let alone whether the pilot is licensed or unlicensed. A remote identification scheme, whereby drones are required to carry electronic identification, may at least partially address this problem, but compliance will depend on perceptions of the likelihood of enforcement.

There is, therefore, likely to be an ongoing problem of potentially hazardous use of drones, and this problem is likely to persist regardless of any licensing.

3.2.3 Malicious and Reckless Action

Consider now the malicious and reckless use of drones. The difference between the two is subtle: a malicious operator intends to operate the drone in a manner that causes harm; whereas the reckless user may intend to use the drone for a valid purpose but does so in a manner that creates a risk to others, is aware of that risk, and continues anyway.

We could hypothesise a range of motivations for these behaviours. The operator may derive utility from the harmful activity, such as pleasure from voyeuristic observation.

Posner (1985) suggests that all crime can be construed as an attempt to bypass the market. The expected cost of the criminal behaviour to the perpetrator is less than both (a) the value that the perpetrator receives from the "property" that they have criminally acquired, and (b) the cost that would be incurred for acquiring the property via the market, so the decision to commit the crime is rational.

In both of these cases any policy intervention that increases the cost of the harmful behaviour via expected punishment costs - whether fines or incarceration - will reduce the incidence of that behaviour. If expenditure on crime prevention, broadly defined, is efficient then the incidence of the behaviour will not reduce to zero (Becker, 1974).

Terrorists, seeking to achieve a political objective, make their decision to act given the existing regime of legal sanctions in place. They can be assumed to be rational (Sandler & Enders, 2004), weighing the expected value of the gains in furtherance of their political objective against the personal cost of criminal sanction. When the probability of identifying the drone operator is low, the expected cost of punishment is commensurately lower and terrorist action may be undertaken at a lower threshold.

3.2.4 The Need for Self-Defence

The harm caused by malicious use is potentially very large. If a drone was used to bring down an airliner or drop an improvised explosive device over a public event then there could be significant harm in the form of multiple causalties. No legal sanction, whether civil or criminal, can reverse the harm, and it may be more efficient to have a means of preventing harm from occurring. Similarly, even if there was an education campaign or a licensing regime for non-malicious drone operators, the potential harm from negligent use is high. Again, a multiple-casualty event from careless use around manned aircraft is possible.

The common law developed the remedy of injunction for preventing harm in circumstances where threatened or likely conduct could result in injury, particularly where damages will not adequately compensate for harm (Aitkin, 2016, p. 1348). Injunction is a court order that the defendant either does something or refrains from doing something. An injunction may be: mandatory, requiring the defendant to take an action to restore the plaintiff's position; *quia timet*, granted to forestall anticipated future harm; or interim, to prevent imminent or recurring harm until the matter can be heard in full by the court. However, injunctive relief is not appropriate or effective where the harm is so immediate that there is no time to lodge proceedings, or where the injurer cannot be readily found or identified. Both of these constraints apply with drones.

In the United States drones are reported as having being shot at or shot down in New Jersey (The Smoking Gun, 2015), Kentucky (Cummings, 2015), California (Farivar, 2015), Virginia (Farivar, 2016), and in two separate incidents in Tennessee (Farivar, 2017; Flowers, 2016). In the New Jersey, Kentucky, and California cases the shooter claimed a right to privacy, while in the Virginia case the shooter claimed to be defending another person's right to privacy. The legal issues in these cases have provoked debate over whether there should be a right to take action against drones that are perceived as threatening the physical safety or privacy of an individual. Froomkin and Colangelo (2015) argue in favour of "violent self-defence against drones" (i.e. destroying them) if they are trespassing as one means of addressing privacy concerns, but their argument is one of legal theory rather than the result of analysis within a formal economic framework. Similarly, Shelley (2016c) proposes destruction of drones as part of a package of legal and regulatory measures to address privacy and surveillance by drones.

While there may be cogent legal arguments as to why self-defence against drones should be allowed, those arguments lack the economic analysis to identify whether such action would be welfare-enhancing. The purpose of the present chapter is to analyse self-defence against drones within a formal analytical framework in order to identify the circumstances in which self-defence would be welfare-enhancing and those in which it would be inefficient.

The destruction of a drone is a form of self-help, in which a person who suffers a loss as a consequence of the actions of another can take steps to prevent, minimise, or remedy the loss without resort to the courts. Self-help can be thought of as having three dimensions. First, precaution is actions taken to prevent an undesirable outcome from occurring. Second, self-defence is actions taken to stop an undesirable event while it is occurring. And third, actions may be taken after the undesirable event to obtain remedy without resort to the courts.

The first dimension of self-help, that of precaution, is an integral feature of Shavell (1980)'s analysis of liability rules in a framework where both the injurer and victim can take precaution. Shavell demonstrates that a liability rule that provides optimal incentives for one party to take precaution fails to provide an incentive for the other party to take precaution. As a consequence, the assignment of liability may depend on which party is best able to take precaution.

The second dimension of self-help, that of taking direct action to prevent losses, is well recognised by the law but not studied extensively in the literature. The law allows self-defence remedies against both crime and torts, generally in situations where it is important to stop a significant loss or harm from occurring. While originally derived from common law, many of these remedies have been codified in statute. In New Zealand, the Crimes Act 1961 allows the use of reasonable force to protect both oneself and others from assault (s48). The Impounding Act 1955 provides for trespassing stock to be seized and restrained or impounded (Part 5), although trespass damages can only be recovered if the occupier of the land has taken reasonable precautions such as fencing the land (s26). The Dog Control Act 1996 provides that any person may seize or destroy a dog attacking any person or animals (s57), and even a dog simply "at large" among stock or poultry may be seized or destroyed (s60).

The third dimension of self-help, that of post-event actions, is analysed by Badawi (2012) in the context of a game of a creditor recovering a debt from a debtor. The creditor can seek recovery of the debt in court or seek to recover the debt directly (e.g. by way of repossession). If the creditor seeks to recover the debt directly then the debtor can choose to acquiesce, in which case the game ends, or can resist. If the debtor resists then the creditor proceeds to court, recovers the debt, and incurs certain costs. In this game the prospect of recovery through the courts is certain, the court process incurs administrative costs, and there is a known probability of the debtor resisting violently. In Badawi's model, self-help is efficient if the probability of violence is low and the expected costs of self-help are less than the certain costs of going to court.

3.2.5 Counter-UAS Technology

While drone shootings, mentioned above, capture media attention and highlight some of the legal issues involved with self-defence against drones, there is a much greater range of counter-drone technologies available, such as GPS spoofing, radio jamming, physical capture, electronic hijacking and "protocol manipulation". Each of these technologies is briefly discussed below. Using the more technical description of a drone as an "unmanned aerial system" or "UAS", the technologies are collectively known as "counter-

UAS" (C-UAS).

GPS Spoofing

Drones typically use GPS signals to navigate to waypoints. "GPS spoofing" occurs when a GPS transmitter is used to overpower the weak signals received from GPS satellites. A report in 2001 warned of the vulnerabilities of GPS to signal loss and disruption, including malicious disruption (John A. Volpe National Transportation Systems Center, 2001), yet drone technology remains vulnerable to attack. GPS spoofing was used by Iran to commandeer and land a United States RQ-170 Sentinel surveillance drone (Peterson, 2011), and the technique has been demonstrated as being able to be used to commandeer and potentially crash a small unmanned aircraft (Vaas, 2012). Drug Traffickers are reportedly using GPS jamming and spoofing technologies to disrupt unmanned aircraft surveillance of the US-Mexico border (Tucker, 2015), surveillance which is conducted using military-grade unmanned aircraft.

Radio Jamming

Radio jamming involves the use of "a radio transmitter ... to disrupt or prevent the reception of radiocommunications" (New Zealand Gazette, 2011). This basic principle can be applied to disrupt the control signal from a transmitter or ground control station to a drone. A number of commercial jammers are available for drones; several of these are outlined below.

The Battelle Systems "Drone Defender" is a shoulder-mounted radio "gun" which uses radio jamming to overpower the radio systems on the drone, forcing it to activate either "auto land" or "return to home", depending on which option has been programmed into the aircraft (Matyszczyk, 2015). A similar system is the hand-held "Dronebuster" by Radio Hill Technologies, which jams both common radio frequencies (RF) and GPS frequencies (Blighter Surveillance Systems, 2016).

The Blighter Surveillance Systems "Anti UAV Defence System" ("AUDS") is a much larger military-grade C-UAS system that utilises radar to detect drones at a range of up to 10km for larger drones, and smaller drones at a range of up to 3.6km. After radar detection an electro-optical and infrared system is used to track the drone and a directed radio beam is used to "inhibit" the drone (Blighter Surveillance Systems, 2017). The literature does not state about this system whether the AUDS is a radio-frequency jamming device or whether it uses a different technique to “inhibit” the drone. However, the literature states that the “response of a [drone] to RF inhibition is dependent upon its design and manufacture, including the programming of any auto-pilot function and the actions of the [done] operator,” which suggests a technology based on jamming. Another large-scale detection and jamming system has been developed by Airbus Defense & Space (Airbus, 2015).

Radio- and GPS-jamming is illegal in most jurisdictions. For example, in New Zealand it is an offence against the Radiocommunications Regulations 2001 to operate any radio jamming equipment in New Zealand without a licence (New Zealand Gazette, 2011), effectively eliminating the use of these devices as a legal self-help remedy for most people.

Physical Capture

A number of alternative methods of drone interdiction have been developed which neither knock the drone out of the sky nor utilise jamming. Eagles have been trained to hunt small drones in both the Netherlands (Cade, 2016; Zhang, 2016) and France (Roberts, 2017; Samuel, 2016).

French firm Malou Tech has developed a drone-based net system that uses a large drone to entangle a small drone in a rectangular net draped below the large drone (Economist, 2015). English firm OpenWorks has developed a shoulder-launched system called “SkyWall” that uses compressed air to fire a net to capture a drone up to 100m away (OpenWorks, 2016). SkyWall projectiles may also include a parachute to reduce damage on landing, and may also include electronic counter-measures. Horiuchi et al. (2016) describe a drone-based system with a drone that autonomously tracks and pursues the target drone and fires a net when in range. A similar system designed by researchers at Michigan Technological University consists of a large drone that fires a net at the target drone from a distance of up to 40 feet; the net remains attached to the larger drone by a string, enabling the larger drone to transport the smaller drone to a safe location (Goodrich, 2016). These drone-based net systems typically require human control. In contrast, Goppert et al. (2017) describe a fully autonomous system utilising a ground-based radar to direct a “hunter” drone to intercept and fire a net at a hostile drone.

“Hijack” and “Protocol Manipulation”

Many unmanned aircraft may be vulnerable to “hijack” so that the aircraft is under the control of a party other than the *bone fide* pilot. In 2013 a hacker developed software dubbed “Skyjack” that enabled the hijacking of an unencrypted ”Parrot AR Drone” (Fincher, 2013; Goodin, 2013; Scharr, 2013). Rodday (2015) identifies two security vulnerabilities including weak encryption that render many relatively high-end unmanned aircraft vulnerable to hijacking. In 2015 a group of computer security researchers discovered a design flaw in the Mavlink radio protocol, used by many manufacturers of small drones, which enabled them to develop a low cost system to hijack an unmanned aircraft using this protocol (Benchoff, 2015; ‘Drone Code Execution (Part 1)’, 2015).

US/Australian firm Department 13 has developed a radio-based system called “Mesmer” that does not utilise jamming (Department 13, 2017). This system relies on what Department 13 describes as “protocol manipulation” (Department 13, 2016), which involves intercepting the radio signals used to control the drone, identifying the protocol being used, then transmitting commands to completely take over control of the drone. The drone can then be instructed to leave the area or to land in a safe zone.

3.2.6 Legal Issues

Drones are classified by regulatory authorities as aircraft and hence subject to the same regulatory arrangements as all other aircraft. The Montreal Convention (United Nations, 1975) prohibits any person from destroying an “aircraft in service” or causing “damage to an aircraft in service which renders the aircraft incapable of flight”. In New Zealand, these prohibitions are codified in the Aviation Crimes Act 1972, with the offences which carrying a term of imprisonment of up to 14 years. These prohibitions were framed in an era when an aircraft always had a person on board, so destroying an aircraft or rendering it incapable of flight while in service would necessarily put human life at risk.

Most of the C-UAS technologies reviewed involve rendering the drone incapable of flight, and thus might be prohibited by the Montreal Convention. The “Mesmer” system involving protocol manipulation is an exception to this, taking control of the drone but not damaging it. However,as noted, protocol manipulation requires that the drone is actively being flown rather than relying on autopilot, and thus is not capable of providing a complete self-defence solution.

Notwithstanding this general legal framework that would appear to prevent self-defence actions against drones, the United States has passed legislation that explicitly allows actions to be taken against drones that potentially threaten the safety or security of a broad range of assets or facilities related to national security (National Defense Authorization Act for Fiscal Year 2018, 2017). Importantly, these provisions relate to assets or facilities located in the United States or its territories, and is thus focussed on domestic security rather than security during war or war-like situations. The Preventing Emerging Threats Act (2018) also enables the Department of Homeland Security, the Department of Justice, and the United States Coast Guard to also take action against drones in a wide range of circumstances. The actions allowed by both pieces of legislation include warning the operator, seizing control of the drone, destroying the drone, and the like.

3.3 Model

I now consider potential strategic games between a drone operator and a generic “bystander” or otherwise affected party who is able to exercise self defence against drones. There are three potential games that could arise from the interaction between the two parties. In the first game, the drone operator and the bystander simultaneously make their strategic choices. In the second game the drone operator is the leader, choosing the quantity of drone activity and committing to this strategy by actually flying. In the third game the bystander is the leader, choosing a level of self-defence and credibly committing to this via, for example, a visible C-UAS system. Each of these games represents a plausible real-world scenario.

The objective of my analysis is to identify the circumstances in which allowing self-defence and the potential destruction of drones is more efficient than prohibiting such action. Each of the three games represents an alternative equilibrium, so may also result in a differing policy prescription. For that reason I analyse all three games.

Section 3.3.1 below introduces the general assumptions for the three games, including the utility function for the operator and the cost function for the bystander.

The strategic games can be characterised as either Cournot-like or Stackelberg-like games. While Cournot and Stackelberg games are conventionally presented in terms of firms competing on the quantity of a homogenous good, in the current context the strategic choice variables are quantity for the drone operator and the level of effort towards self-defence for the bystander.

The defining characteristics of the Cournot-like game are that the two players have perfect knowledge of the other's best response function and choices are made simultaneously. These are characteristics of the first, simultaneous, game analysed in section 3.3.2. A Stackelberg-like game requires that one player is the leader, that the leader can credibly commit to a strategy, and that the strategy is observable by the follower. In the second game, analysed in section 3.3.3, the operator is the leader and commits to an observable level of drone activity. In the third game, analysed in section 3.3.4, the bystander is the leader and commits to an observable level of self-defence.

3.3.1 General Setup

There is a drone operator and a bystander. Let v denote the unit value received by the operator from flying her drone, H denote the unit harm to the bystander, and $m \in (0, 1)$ denote the proportion of liability borne by the drone operator. Nature chooses v, H, and m.

The drone operator chooses an activity level, $q \in \mathbb{R}_+$. The bystander chooses a level of effort toward self-defence, $s \in \mathbb{R}_+$. These choices may either be simultaneous or sequential.

Although m and H are known with certainty, and q and s are either known with certainty or perfectly anticipated, the outcome of the bystander's effort to destroy the drone is not deterministic. Just as an effort to swat a fly is not certain to hit the fly, much less kill it, I assume that the effort to destroy the drone is not certain of success. A higher level of effort increases the probability that the drone is destroyed. The probability that the drone will *not* be destroyed is denoted by $0 \leqslant \rho(s) \leqslant 1$, which is strictly decreasing and strictly convex.

Let $c(q)$ denote the cost of operating the drone, which is strictly increasing and strictly convex. The costs associated with destroying the drone are $\kappa \in \mathbb{R}_+$, which includes the value of the drone including future earnings, and the cost of harm to any person that is on-board the aircraft. Although small drones are not capable of carrying a person, larger unmanned aircraft are likely to be capable of this in future. Allowing for the possibility of an aircraft being “manned” also facilitates the predictions of this model being validated against existing regulation for manned aircraft.

The cost of harm to a person on-board the aircraft is assumed to be borne by the operator. For example, in the case of an aircraft carrying a single pilot, the aircraft operator (being the pilot) bears the cost of a fatality. No matter what legal system is in place, a dead pilot cannot be resurrected so the cost is always borne by the operator.

Assuming risk-neutrality the expected utility of the operator is:

$$U(q; s, mH) = \rho(s)(v - mH)q - c(q) - (1 - \rho(s))\kappa. \tag{3.1}$$

The first term is the expected value received by the operator, net of any liability for harm caused. The second term is the cost of operation. The analysis of the case where the bystander is leader requires that the cost function is at least twice continuously differentiable. The third term is the expected cost from the drone being destroyed.

The expected utility of the bystander is:

$$V(s; q, m, H) = -\rho(s)(1 - m)Hq - s. \tag{3.2}$$

The first term is the expected harm from the drone operation, net of any liability borne by the drone operator. The second term is the effort exerted in self-defence. The bystander only incurs cost so his utility is always negative.

3.3.2 Simultaneous Interaction

The drone operator and bystander observe v, H, and m and then simultaneously choose an activity level, q, and effort, s, respectively.

Operator

The operator’s FOC is:

$$U_q = \rho(s)(v - mH) - c'(q) = 0. \tag{3.3}$$

Lemma 1. *The operator’s best response is such that she will only fly if* $(v - mH) \geqslant c'(0)/\rho(s)$ *and will not fly if* $v < mH$ *or* $\rho(s) = 0$*.*

Proof. If $\rho(s) = 0$ then it is certain that the drone will be destroyed and from equation (3.3) the operator will only fly if $c'(q) = 0$. However, $c(q)$ is strictly increasing and strictly convex hence $c'(q) > 0 \; \forall \; q > 0$ and it must be that the operator does not fly.

If $\rho(s) > 0$ then rearranging equation (3.3) we have $v - mH = c'(q)/\rho(s)$. Signs are $c'(q) > 0$ and $\rho(s) > 0$ hence $c'(q)/\rho(s) > 0$. If $v - mH < c'(q)/\rho(s)$ then the drone operator will reduce activity until $v - mH = c'(q)/\rho(s)$ holds. Therefore the drone operator will fly if $(v - mH) \geqslant c'(q)/\rho(s)$. Furthermore, $c'(q) \geqslant c'(0)$, hence the operator will only fly in the region $(v - mH) \geqslant c'(q)/\rho(s) \geqslant c'(0)/\rho(s)$. The operator does not fly in the region where $v - mH < c'(q)/\rho(s)$. A subset of the region where the drone operator does not fly is provided by $v < mH$: if $v < mH$ then $v - mH < 0 < c'(q)/\rho(s)$ and the drone operator does not fly. □

Let q^* denote the operator's best response. Her best-response function is

$$q^*(s; m, H) = \max\{0, g(\rho(s)(v - mH))\} \tag{3.4}$$

where $g(.)$ is the inverse of the marginal cost function. As the bystander increases the effort expended in self-defence s, the probability $\rho(s)$ that the drone is not destroyed decreases, which in turn decreases the operator's expected unit surplus $\rho(s)(v - mH)$ from flying the drone. The operator's FOC requires that the marginal cost of activity $c'(q)$ must also reduce so that it equals the unit surplus. A reduction in marginal cost implies that the operator's level of activity q is reduced in response to the increase in s, hence this best response is downward sloped in $s \; \forall \; v > mH$.

Let ${q^*}_s$, ${q^*}_m$, and ${q^*}_H$ denote the change in the operator's best response wrt a change in the bystander's effort towards self defence, the operator's level of liability, and the level of harm, respectively. For later use, I now derive an expression for each of ${q^*}_s$, ${q^*}_m$, and ${q^*}_H$. The term q in the operator's FOC is a point on the best-response function $q^*(s; m, H)$, so equation (3.3) can be rewritten as:

$$c'(q^*(s; m, H)) = \rho(s)(v - mH). \tag{3.5}$$

Differentiating equation (3.5) wrt s yields:

$$c''(q^*){q^*}_s = \rho'(s)(v - mH) \Rightarrow {q^*}_s = \frac{\rho'(s)(v - mH)}{c''(q^*)}. \tag{3.6}$$

For an interior solution, signs are: $\rho'(s) < 0$ since $\rho(s)$ is strictly decreasing; $v - mH \geqslant 0$ from Lemma 1; and $c''(q) > 0$ since $c(q)$ is strictly convex. We therefore have ${q^*}_s \leqslant 0$: the operator reduces activity as the bystander's effort towards self-defence increases.

Differentiating equation (3.5) wrt m yields:

$$c''(q^*){q^*}_m = -\rho(s)H \Rightarrow {q^*}_m = -\frac{\rho(s)H}{c''(q^*)}. \tag{3.7}$$

For an interior solution, signs are: $\rho(s) > 0$; $H \geqslant 0$; and $c''(q) > 0$. We therefore have ${q^*}_m \leqslant 0$: the operator reduces activity as liability for harm caused increases.

Differentiating equation (3.5) wrt H yields:

$$c''(q^*){q^*}_H = -\rho(s)m \Rightarrow {q^*}_H = -\frac{\rho(s)m}{c''(q^*)}. \tag{3.8}$$

For an interior solution, signs are: $\rho(s) > 0$; $m \geqslant 0$; and $c''(q) > 0$. We therefore have ${q^*}_H \leqslant 0$: the operator reduces activity as harm, and therefore damages for harm caused, increases.

Bystander

The bystander's FOC is:

$$-V_s = \rho'(s)(1 - m)Hq + 1 = 0. \tag{3.9}$$

Let s^* denote the bystander's best response. His best-response function is

$$s^*(q; m, H) = \max\{0, e(-1/[(1 - m)Hq])\} \tag{3.10}$$

where e is the inverse of the slope of $\rho(s)$. If the operator increases her activity level q, the bystander will suffer a greater expected level of harm. The bystander's FOC requires that the marginal harm (w.r.t. s) is constant, so an increase in harm H must be offset by an decrease in the marginal probability that the drone will not be destroyed $\rho'(s)$. Recall that the probability that the drone is not destroyed, $\rho(s)$, is strictly decreasing and strictly convex, therefore $\rho'(s)$ must be negative but increasing. An increase in marginal probability $\rho'(s)$ therefore implies an increase in s. Thus, as the operator increases activity and the bystander suffers a greater level of harm, the bystander responds by increasing the effort in self-defence s. This means that the bystander's best response function is upward-sloped in q.

Let ${s^*}_q$, ${s^*}_m$, and ${s^*}_H$ denote the change in the bystander's best response wrt a change in the operator's level of activity, the operator's level of liability, and the level of harm, respectively. For later use, I now derive an expression for each of ${s^*}_q$, ${s^*}_m$, and ${s^*}_H$. The term s in the bystander's FOC is a point on the best-response function $s^*(q; m, H)$, so equation (3.9) can be rewritten as:

$$\rho'(s^*(q; m, H))(1-m)Hq + 1 = 0. \tag{3.11}$$

Differentiating equation (3.11) wrt q yields:

$$\rho''(s^*){s^*}_q(1-m)Hq = -\rho'(s^*)(1-m)H \Rightarrow {s^*}_q = -\frac{\rho'(s^*)}{\rho''(s^*)q}. \tag{3.12}$$

For an interior solution, signs are: $\rho'(s^*) < 0$; $\rho''(s) > 0$; and $q \geqslant 0$. We therefore have ${s^*}_q > 0$: the bystander's effort towards self defence increases as the operator's activity increases.

Differentiating equation (3.11) wrt m yields:

$$\rho''(s^*){s^*}_m(1-m)Hq = \rho'(s^*)Hq \Rightarrow {s^*}_m = \frac{\rho'(s^*)}{\rho''(s^*)(1-m)}. \tag{3.13}$$

For an interior solution, signs are: $\rho'(s^*) < 0$; $\rho''(s) > 0$; and $(1-m) \geqslant 0$. We therefore have ${s^*}_m < 0$: the bystander's effort towards self defence decreases as the operator's liability for harm caused increases.

Differentiating equation (3.11) wrt H yields:

$$\rho''(s^*){s^*}_H(1-m)Hq = \rho'(s^*)(1-m)q \Rightarrow {s^*}_H = -\frac{\rho'(s^*)}{\rho''(s^*)H}. \tag{3.14}$$

For an interior solution, signs are: $\rho'(s^*) < 0$; $\rho''(s) > 0$; and $H \geqslant 0$. We therefore have ${s^*}_H > 0$: the bystander's effort towards self defence increases as the harm caused by the operator increases.

Effect of Change in Liability, m, and Harm, H, on Equilibrium

Let $\hat{q}$ denote the equilibrium level of operator activity and $\hat{s}$ denote the equilibrium level of bystander self defence. Then:

$$\hat{q}(m,H) = q^*(s^*(\hat{q}(m,H);m,H);m,H) \tag{3.15}$$

$$\hat{s}(m,H) = s^*(q^*(\hat{s}(m,H);m,H);m,H). \tag{3.16}$$

Lemma 2. *A change in the cost of an aircraft being destroyed has no effect on the equilibrium level activity or self defence.*

Proof. κ does not appear in the best-response function or equilibrium function for either the operator or the bystander. □

Lemma 3. *An increase in liability m will result in a decrease in the bystander's level of self defence.*

Proof. Differentiating equation (3.16) wrt m and solving for $\hat{s}_m$:

$$\hat{s}_m = \frac{{s^*}_q {q^*}_m + {s^*}_m}{1 - {s^*}_q {q^*}_s}. \tag{3.17}$$

Signs are ${s^*}_q > 0$, ${q^*}_m \leqslant 0$, ${s^*}_m < 0$, and ${q^*}_s \leqslant 0$. The denominator is positive and the numerator is negative so $\hat{s}_m < 0$. □

Unlike the definite result obtained above, at this general level it is not possible to determine the effect that an increase in the level of liability has on the equilibrium level of activity. Differentiating equation (3.15) wrt m and solving for $\hat{q}_m$:

$$\hat{q}_m = \frac{{q^*}_s {s^*}_m + {q^*}_m}{1 - {q^*}_s {s^*}_q}. \tag{3.18}$$

Signs are ${q^*}_s \leqslant 0$, ${s^*}_m < 0$, ${q^*}_m \leqslant 0$, and ${s^*}_q > 0$. The denominator is positive but the sign of the numerator cannot be determined, so the sign of $\hat{q}_m$ also cannot be determined. Further analysis requires assumptions as to the functional form of $c(q)$ and $\rho(s)$, and is considered in section 3.3.2 below.

Lemma 4. *An increase in harm H results in a decrease in the equilibrium level of activity.*

Proof. Differentiating equation (3.15) wrt H and solving for $\hat{q}_H$:

$$\hat{q}_H = \frac{{q^*}_s {s^*}_H + {q^*}_H}{1 - {q^*}_s {s^*}_q}. \tag{3.19}$$

Signs are ${q^*}_s \leqslant 0$, ${s^*}_H > 0$, ${q^*}_H \leqslant 0$, and ${s^*}_q > 0$. The numerator is non-positive and the denominator is positive, so $\hat{q}_H \leqslant 0$. □

Unlike the definite result obtained above, at this general level it is not possible to determine the effect of an increase in harm on the bystander's effort towards self defence. Differentiating equation (3.16) wrt H and solving for $\hat{s}_H$:

$$\hat{s}_H = \frac{{s^*}_q {q^*}_H + {s^*}_H}{1 - {s^*}_q {q^*}_s}. \tag{3.20}$$

Signs are ${s^*}_q > 0$, ${q^*}_H \leqslant 0$, ${s^*}_H > 0$, and ${q^*}_s \leqslant 0$. The denominator is positive but the sign of the numerator cannot be determined, so the sign of $\hat{s}_H$ also cannot be determined. Further analysis requires an assumption as to the functional form of $c(q)$ and $\rho(s)$, and is considered in section 3.3.2 below.

Further Properties of the Equilibrium with Specific Functional Forms

It was noted above that the sign of $\hat{q}_m$ and $\hat{s}_H$ could not be determined given the general form of the model. The assumption of specific functional forms for $c(q)$ and $\rho(s)$ allows more definite conclusions to be derived.

Before analysing each of $\hat{q}_m$ and $\hat{s}_H$ we first consider the value of q and s at equilibrium. Assume that:

$$c(q) := \eta \frac{q^\alpha}{\alpha}, \qquad \rho(s) := (1+s)^{-n},$$

where $\alpha \geqslant 2$ and $n \geqslant 1$.

The closed-form expression for the operator's best response is:[2]

$$q^*(s; m, H) = \max\left\{0, \left[(1+s)^{-n}\left(\frac{v - mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}}\right\}, \tag{3.21}$$

which is independent of κ. An increase in the net value received by the operator from the drone operation, $v - mH$, increases the value of q^*. An increase in the cost of operation via the parameter η reduces the value of q^*. An increase in the bystander's effort towards self-defence, s, reduces the value of q^*. These effects are consistent with the results from section 3.3.2

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[2] $c(q) = \eta q^\alpha/\alpha \Rightarrow c'(q) = \eta q^{(\alpha-1)}$. From the operator's FOC we have $c'(q) = \rho(s)(v - mH)$. Setting the two expressions for $c'(q)$ equal we have $q = \left[\rho(s)\frac{v-mH}{\eta}\right]^{1/(\alpha-1)}$, which is positive for all $v > mH$.

that ${q^*}_s \leqslant 0$, ${q^*}_m \leqslant 0$, and ${q^*}_H \leqslant 0$, and are all as intuitively expected.

The closed-form expression for the bystander's best response is:[3]

$$s^*(q; m, H) = \max\left\{0, [n(1-m)Hq]^{\frac{1}{n+1}} - 1\right\}. \tag{3.22}$$

Let $\hat{q}$ and $\hat{s}$ denote the equilibrium level of q and s respectively. For an interior solution, $\hat{s}$ is given by:[4]

$$\hat{s}(m, H) = \max\left\{0, \left[(n(1-m)H)^{(\alpha-1)}\left(\frac{v - mH}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)+n}} - 1\right\}. \tag{3.23}$$

A corner point solution occurs when $\hat{s} = 0$. From equation (3.23), a corner point solution will arise when:

$$\hat{s} = 0 \Rightarrow (n(1-m)H)^{(\alpha-1)}(v - mH) \leqslant \eta, \tag{3.24}$$

and hence the boundary of the region for which $\hat{s} = 0$ is given by:

$$(n(1-m)H)^{(\alpha-1)}(v - mH) - \eta = 0.$$

For an interior solution $\hat{q}$ is given by:[5]

$$\hat{q}(m, H) = \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{v - mH}{\eta}\right)\right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}}. \tag{3.25}$$

Let $\hat{q}_{CP}$ denote $\hat{q}$ for a corner-point solution. Then $\hat{q}_{CP}$ is given by:

$$\hat{q}_{CP}(m, H) = \left(\frac{v - mH}{\eta}\right)^{\frac{1}{\alpha-1}}. \tag{3.26}$$

Lemma 5. *Equilibrium activity when self-defence is allowed is less than or equal to equilibrium activity when self-defence is prohibited.*

Proof. If self-defence is prohibited then self-defence is constrained to $s = 0$ and equilibrium activity is given by equation (3.26).

If self defence is allowed then we will have either a corner point solu-

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[3] $\rho(s) = (1+s)^{-n} \Rightarrow \rho'(s) = -n(1+s)^{-(n+1)}$. From the bystander's FOC we have $\rho'(s)(1-m)Hq + 1 = 0 \Rightarrow \rho'(s) = \frac{-1}{(1-m)Hq}$. Setting the two expressions for $\rho'(s)$ equal we have $\frac{1}{n}(1+s)^{(n+1)} = (1-m)Hq \Rightarrow s = [n(1-m)Hq]^{\frac{1}{n+1}} - 1$ as shown.

[4] See equation (3.61) in Appendix 3.A.1.

[5] See equation (3.62) in Appendix 3.A.2.

tion or an interior solution. For a corner point solution $\hat{s} = 0$ and again equilibrium activity is given by equation (3.26), and hence activity is the same as when self-defence is prohibited.

Equation (3.24) for the corner-point solution can be rearranged to:

$$\begin{aligned}
\left(\frac{v - mH}{\eta}\right) &\leqslant \left(\frac{1}{n(1-m)H}\right)^{(\alpha-1)} \\
\Rightarrow \hat{q}_{CP} = \left(\frac{v - mH}{\eta}\right)^{\frac{1}{(\alpha-1)}} &\leqslant \left(\frac{1}{n(1-m)H}\right) \qquad (3.27)
\end{aligned}$$

Substituting this into equation (3.25) we have:

$$\begin{aligned}
\hat{q}(m,H) &= \left[\left(\frac{1}{n(1-m)H}\right)^{n}\left(\frac{v - mH}{\eta}\right)^{(n+1)}\right]^{\frac{1}{(n+1)(\alpha-1)+n}} \\
\Rightarrow \hat{q}(m,H) &= \left[\left(\frac{1}{n(1-m)H}\right)^{n} \hat{q}_{CP}{}^{(n+1)(\alpha-1)}\right]^{\frac{1}{(n+1)(\alpha-1)+n}} \\
\Rightarrow \hat{q}(m,H) &\leqslant \left[\hat{q}_{CP}{}^{n}\,\hat{q}_{CP}{}^{(n+1)(\alpha-1)}\right]^{\frac{1}{(n+1)(\alpha-1)+n}} \\
\Rightarrow \hat{q}(m,H) &\leqslant \hat{q}_{CP}. \qquad (3.28)
\end{aligned}$$

□

Lemma 6. *An increase in liability m has an ambiguous effect on the equilibrium level of activity $\hat{q}$.*

Proof. See the calculations in Appendix 3.A.4. □

Lemma 7. *An increase in harm H has an ambiguous effect on the bystander's effort towards self defence.*

Proof. See the calculations in Appendix 3.A.5. □

Welfare

Welfare is the sum of utility of the operator and the bystander:

$$\begin{aligned}
W(q,s;m,H,\kappa) =& [\rho(s)(v - mH)q - c(q) - (1-\rho(s))\kappa] \\
& - [\rho(s)(1-m)Hq + s] \\
=& \rho(s)(v - H)q - c(q) - s - (1-\rho(s))\kappa. \qquad (3.29)
\end{aligned}$$

The first term, $\rho(s)(v-H)q$, is the expected value from the drone operation. The second term, $c(q)$, is the cost of operation. The third term, s, is the effort exerted in self-defence. The fourth term, $(1-\rho(s))\kappa$, is the expected costs if the drone is destroyed. The incidence of liability m does not directly alter total welfare; however it will indirectly influence welfare via its effect on equilibrium activity, $\hat{q}$, and equilibrium self defence, $\hat{s}$.

Lemma 8. *If $m < 1$ then at the Nash equilibrium the operator's privately-optimal level of activity always exceeds the socially-optimal level of activity.*

Proof. The FOC for welfare-maximisation wrt activity, W_q is:

$$W_q = \rho(s)(v-H) - c'(q) = 0. \tag{3.30}$$

Utilising the operator's FOC from equation (3.3), at the Nash equilibrium W_q will be:

$$W_q = U_q - \rho(\hat{s})(1-m)H \leqslant 0, \tag{3.31}$$

since $U_q = 0$ at the Nash equilibrium. It is readily apparent that the operator's FOC only coincides with the FOC for welfare maximisation ($W_q = 0$) if $m = 1$; if $m < 1$ then $W_q < 0, U_q > W_q$, and the operator's privately-optimal level of activity will be greater than the socially optimal level of activity. This result is consistent with Shavell's (1980) model of bilateral precaution. □

Lemma 9. *When self-defence is allowed, the equilibrium level of self-defence is greater than the socially optimal level.*

Proof. The FOC for welfare maximisation wrt the effort exerted in self defence, W_s is:

$$W_s = \rho'(s)(v-H)q + \rho'(s)\kappa - 1 = 0. \tag{3.32}$$

W_s does not coincide with the bystander's FOC in equation (3.9) for any values of m: W_s includes v and κ, whereas equation (3.9) does not include either of these variables. This result arises because the bystander does not receive any of the value generated by the drone activity and does not face the cost to the operator if the drone is destroyed.

In general form, the sign of W_s in equilibrium cannot be determined since v may be greater or less than H. However, given the functional forms specified in section 3.3.2, $W_s \leqslant 0$. First, note that W_s is evaluated at a point of equilibrium. Then, utilising equations (3.23) and (3.25), we have:

$$\begin{aligned} W_s = &- n \left[(n(1-m)H)^{(\alpha-1)} \left(\frac{v-mH}{\eta} \right) \right]^{\frac{-(n+1)}{(n+1)(\alpha-1)+n}} \\ &\times \left[(v-H) \left[(n(1-m)H)^{-n} \left(\frac{v-mH}{\eta} \right)^{(n+1)} \right]^{\frac{1}{(n+1)(\alpha-1)+n}} + \kappa \right] - 1 \end{aligned}$$

Note that $\partial W_s / \partial \kappa < 0$, so the maximum value of W_s occurs when $\kappa = 0$. Let $\kappa = 0$, then:

$$\begin{aligned} W_s = &- n(v-H) \left[(n(1-m)H)^{-(n+1)(\alpha-1)} \left(\frac{v-mH}{\eta} \right)^{-(n+1)} \right]^{\frac{1}{(n+1)(\alpha-1)+n}} \\ &\times \left[(n(1-m)H)^{-n} \left(\frac{v-mH}{\eta} \right)^{(n+1)} \right]^{\frac{1}{(n+1)(\alpha-1)+n}} - 1 \\ = &- n(v-H) \left[n(1-m)H \right]^{-1} - 1 \\ = &\frac{-(v-mH)}{(1-m)H} \leqslant 0 \end{aligned} \tag{3.33}$$

$W_s < 0$ means that the second FOC for welfare maximisation is not met, and that in equilibrium the level of self defence is greater than the socially optimal level.

□

Effect of Changes in Exogenous Parameters

Now consider the effect of a change in the exogenous parameters on welfare: the cost incurred if the drone is destroyed, κ; the level of liability borne by the operator for harm caused, m; and the level of harm, H. Let equilibrium welfare be:

$$W(q, s; m, H, \kappa) \equiv W(\hat{q}(m, H), \hat{s}(m, H), H, \kappa). \tag{3.34}$$

The change in welfare arising from a change in the cost when a drone is destroyed is:

$$\frac{dW}{d\kappa} = W_\kappa = -(1 - \rho(s)) \leqslant 0. \tag{3.35}$$

Thus if self defence is allowed then an increase in the cost incurred when a drone is destroyed results in a decrease in welfare, but a reduction in that cost will reduce the negative welfare impact from destruction.

The change in welfare arising from a change in liability is:

$$\frac{dW}{dm} = W_q \hat{q}_m + W_s \hat{s}_m. \tag{3.36}$$

Signs are: $W_q \leqslant 0$ (equation (3.31)); $\hat{q}_m \lesseqgtr 0$ (Lemma 6); $\hat{s}_m < 0$ (Lemma 3); and the sign of W_s is undetermined in the general case. The sign of dW/dm therefore cannot be determined in the general case.

If the specific functional forms in section 3.3.2 are adopted for $c(q)$ and $\rho(s)$, then $W_s \leqslant 0$ and $H \geqslant H_{0q} \Rightarrow \hat{q}_m \leqslant 0$. Under these assumptions $H \geqslant H_{0q} \Rightarrow dW/dm \geqslant 0$. If $H < H_{0q}$ then the sign of dW/dm cannot be determined.

That the sign of dW/dm cannot be determined under some conditions suggests that there may be a set of conditions under which an *increase* in liability for harm caused reduces welfare. This is counter to the normal presumption that an increase in liability for the person causing harm results in their privately optimal decision being better aligned with the socially optimal decision and thus increases welfare. The reason for this possibility is twofold. First, the potential destruction of the drone imposes a cost on the drone operator, so the drone operator may face expected costs equal to the social cost of her operation at less than full liability. Second, increasing the operator's liability for harm caused reduces the bystander's effort expended in self-defence ($\hat{s}_m < 0$), which increases the probability that the drone is not destroyed. The drone operator thus faces two opposite effects on the term $\rho(s)(v - mH)$: the probability increases, increasing the utility of flying, acting to increase equilibrium activity; but mH also increases, reducing the utility from flying, and acting to decrease equilibrium activity. When $H < H_{0q}$ the first of these effects dominates the second and the operator's activity level increases with an increase in m ($\hat{q}_m > 0$). This increase in activity reduces welfare ($W_q < 0$), but is offset by an increase in welfare from the lower level of self defence. Whether the increase in activity every outweighs the reduction in self defence (and hence whether $dW/dm < 0$) must be established numerically.

The change in welfare arising from a change in the level of harm is:

$$\frac{dW}{dH} = W_q \hat{q}_H + W_s \hat{s}_H + W_H, \tag{3.37}$$

where $W_H = -\rho(s)q \leqslant 0$. The other signs are: $W_q \leqslant 0$ (equation (3.31)); $\hat{q}_H \leqslant 0$ (Lemma 4); $W_s \leqslant 0$; and $\hat{s}_H \lesseqgtr 0$ (Lemma 7).

W_H is the direct reduction in welfare due to an increase in harm. This is offset by an increase in welfare due to the operator's reduction in activity. There is also an ambiguous change in the level of self defence, which has an ambiguous effect on welfare. Even if $W_s \hat{s}_H$ has a definite sign, $W_q \hat{q}_H \geqslant 0$ and $W_H \leqslant 0$. The opposing signs coupled with the ambiguity of $\hat{s}_H$ means that the sign of dW/dH cannot be easily determined. This implies that there may be a set of conditions under which a reduction in harm caused reduces welfare or, equivalently, that an increase in harm caused increases welfare. The direction of the change in welfare must be established numerically.

Optimal Policy

From lemmas 8 and 9 we have the general result that the FOCs for both the bystander and the operator do not coincide with the FOCs for welfare. Whether it is efficient to allow the destruction of drones depends on whether allowing or preventing destruction is the second-best option. Let W^A denote welfare if destruction of drones is allowed, and W^P denote welfare if destruction of drones is prohibited. The optimal policy is to allow destruction of drones if $W^A > W^P$, but to prohibit destruction of drones if $W^A < W^P$.

If the destruction of drones is allowed then from equation (3.29) welfare is:

$$W^A = \rho(\hat{s})(v - H)\hat{q} - c(\hat{q}) - (1 - \rho(\hat{s}))\kappa - \hat{s} \tag{3.38}$$

If the destruction of drones is prohibited then the bystander does not exert any effort in self defence ($s = 0$), the drone is not destroyed ($\rho(0) = 1$), and the operator's activity level is the same as for a corner point solution, $\hat{q}_{CP}$. Welfare is therefore:

$$W^P = (v - H)\hat{q}_{CP} - c(\hat{q}_{CP}) \tag{3.39}$$

The destruction of drones is welfare-enhancing if:

$$\begin{gathered} W^A - W^P > 0 \\ \Rightarrow (v - H)\left[\rho(\hat{s})\hat{q} - \hat{q}_{CP}\right] - \left[c(\hat{q}) - c(\hat{q}_{CP})\right] > (1 - \rho(\hat{s}))\kappa + \hat{s} \end{gathered} \tag{3.40}$$

The left-hand side of the inequality in equation 3.40 is the benefit (or) cost from any reduction in drone activity. The right-hand side of the inequality is the cost from destruction of drones, being the expected cost of the drone being destroyed plus the cost of the effort towards self-defence. Signs are as follows: $(v - H)$ may have either sign; the first term in square brackets is negative since $\hat{q} \leqslant \hat{q}_{CP}$ (lemma 5) and $\rho(\hat{s}) \leqslant 1$; the second term in square brackets is negative since $\hat{q} \leqslant \hat{q}_{CP}$ (lemma 5) and costs are strictly increasing; and the right-hand side of the inequality is positive. If $H > v \Rightarrow v - H < 0$ then the left-hand side of the inequality is positive and destruction of drones will be welfare enhancing if the benefit from the reduction in drone activity is greater than the expected cost of the drone being destroyed plus the cost of the effort towards self-defence. If $H < v \Rightarrow v - H > 0$ then the sign of the left-hand side may be positive or it may be negative: if it is negative then destruction is welfare reducing.

If an analytical solution of equation (3.40) was possible, it would yield an expression for the value of H at which we are indifferent between allowing and prohibiting destruction, with H expressed as a function of $v, m, \alpha, \eta,$ and κ. However, given the functional forms for $\rho(.), \hat{s}, \hat{q},$ and $\hat{q}_{CP}$, an analytical solution is not possible and a numerical solution is required.

3.3.3 Drone Operator as Leader

In the analysis of the previous section it was assumed that the operator and bystander simultaneously choose the activity level, q, and effort toward self-defence, s. I now assume that the bystander's decision to exert some effort towards self-defence is made after the operator has made the decision to fly. The operator chooses the level of activity, q, given the bystander's (perfectly) anticipated level of effort. The drone operator commits to that level of activity by visibly flying her drone. The bystander observes the level of activity and then chooses a level of effort towards self-defence, s. Self-defence by the bystander disciplines the drone operator to choose a level of activity that does not exceed the equilibrium level.

The bystander's expected costs remain as specified in equation (3.2), with FOC per equation (3.9), and best response function per equation (3.10). This means that the signs of ${s^*}_q$, ${s^*}_m$, and ${s^*}_H$ are as established in the analysis of simultaneous interaction.

The operator's expected utility remains as specified in equation (3.1). However, the operator chooses her level of activity, q, subject to the expected reaction of the bystander, which is given by the bystander's best response function.

Before attempting an analytic solution to the equilibrium $(\hat{q}, \hat{s})$, we can first establish some general properties of the equilibrium relative to the equilibrium of the simultaneous model.

Lemma 10. *Assume that self defence is permitted. Then q and s are lower in the Stackelberg-like game with the operator as leader than in the simultaneous version.*

Proof. As q decreases along the bystander's best response, the operator's utility changes by:

$$\frac{dU(q, s^*(q))}{dq} = U_q + U_s s^* q. \tag{3.41}$$

At the Nash equilibrium of the simultaneous model, $U_q = 0$ and $U_q > 0$ as q is decreased from that equilibrium. From the operator's utility function in equation (3.1) $U_s = \rho'(s)(v - mH)q + \rho'(s)\kappa \leqslant 0$, and from equation (3.12) ${s^*}_q > 0$. We therefore have $dU/dq < 0$ and the operator's utility increases as q is reduced incrementally. Therefore the drone operator will adopt a lower level of activity in the sequential model than in the simultaneous model, and the drone operator will consequently adopt a lower effort towards self defence. □

Lemma 11. *If $v \geqslant H$ then the equilibrium in the Stackelberg-like game with the operator as leader will have a higher level of welfare than the equilibrium in the simultaneous variant of the game.*

Proof. As q decreases along the bystander's best response, welfare in the Stackelberg-like game changes by:

$$\frac{dW(q, s^*(q))}{dq} = W_q + W_s {s^*}_q. \tag{3.42}$$

Note that $W_q = U_q - \rho(s)(1 - m)H$. At the Nash equilibrium of the simultaneous game $U_q = 0$ and hence $W_q = -\rho(s)(1 - m)H \leqslant 0$. From equation (3.12) it was established that ${s^*}_q > 0$. The term W_s is provided in equation (3.32): W_s will be unambiguously negative if $v \geqslant H$, and hence under the same conditions $dW/dq < 0$ and the reduction in activity by the operator increases welfare. □

Consider now the conditions under which welfare will be improved in this variant of the game relative to the simultaneous game. Noting that the drone operator reduces activity, the relevant condition is:

$$\begin{aligned}\frac{dW}{dq} < 0 &\Rightarrow W_q + W_s {s^*}_q < 0 \\ &\Rightarrow U_q - \rho(s^*)(1-m)H + W_s {s^*}_q < 0 \\ &\Rightarrow W_s < \frac{\rho(s^*)(1-m)H}{{s^*}_q},\end{aligned} \tag{3.43}$$

since $U_q = 0$ at the Nash equilibrium of the simultaneous game.

Substituting the definition of W_s from equation (3.32) into equation (3.43), the condition under which $dW/dq > 0$ is:

$$\begin{aligned}\rho'(s^*)(v-H)q + \rho'(s^*)\kappa - 1 &< \frac{\rho(s^*)(1-m)H}{{s^*}_q} \\ \Rightarrow (v-H) &> \frac{\rho(s^*)(1-m)H + {s^*}_q}{\rho'(s)q{s^*}_q} - \frac{\kappa}{q}.\end{aligned} \tag{3.44}$$

The term $\rho'(s) < 0$ and all other terms are non-negative, hence the RHS of equation (3.44) is negative. This means that $dW/dq < 0$ for $v \geqslant H$ and for a range of values $v < H$. It is apparent from equation (3.44) that as the value of κ increases, H can exceed v by an increasing amount in order for the decrease in operator activity to be welfare enhancing.

Equilibrium

Turning now to a more explicit formulation of the equilibrium, the bystander's best response function is embodied in the operator's FOC, subject to the constraint that $s \geqslant 0$. The Lagrangian for the operator is:

$$\mathcal{L} = \rho(s)(v - mH)q - c(q) - (1-\rho(s))\kappa - \lambda[\rho'(s)(1-m)Hq + 1]. \tag{3.45}$$

The operator has the FOCs:

$$\frac{\partial \mathcal{L}}{\partial q} = \rho(s)(v - mH) - c'(q) - \lambda\rho'(s)(1-m)H = 0 \tag{3.46}$$

$$\frac{\partial \mathcal{L}}{\partial s} = \rho'(s)(v - mH)q + \rho'(s)\kappa - \lambda\rho''(s)(1-m)Hq = 0 \tag{3.47}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = \rho'(s)(1-m)Hq + 1 = 0. \tag{3.48}$$

I show in Appendix 3.B that given the above FOCs, the equilibrium can be expressed as:

$$(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}q^{\left(\alpha+\frac{n}{n+1}\right)}-(v-mH)q+n\kappa=0.$$

The equilibrium is a polynomial in q. However, as expressed the polynomial has a fractional power of q. Let $t=q^{\frac{1}{n+1}}$ then the polynomial can be expressed as a whole number power of t:

$$(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}t^{(\alpha(n+1)+n)}-(v-mH)t^{(n+1)}+n\kappa=0. \tag{3.49}$$

The lowest value of $(\alpha(n+1)+n)$ is provided by $n=1$ and $\alpha=2$, with equation (3.49) becoming the quintic:

$$(n+1)\eta\left[n(1-m)H\right]^{\frac{1}{2}}t^{5}-(v-mH)t^{2}+n\kappa=0. \tag{3.50}$$

Higher values of α and n result in higher order polynomials. All polynomials higher than a cubic require numerical methods to solve.

Lemma 12. *When the drone operator is leader and self-defence is allowed, there is a maximum value of κ for which the operator will choose to fly.*

Proof. See the calculations in Appendix 3.B.2. □

Lemma 13. *When the drone operator is leader, an increase in κ reduces the operator's activity level.*

Proof. See the calculations in Appendix 3.B.3. □

3.3.4 Bystander as Leader

Now assume that the operator's decision to fly is made after the bystander has chosen his level of effort towards self-defence. The bystander chooses the effort towards self-defence, s, given the operator's (perfectly) anticipated activity level. The bystander commits to a level of effort towards self-defence, perhaps by way of investment in a visible counter-UAS system. The operator observes the level of effort towards self-defence and then chooses an activity level, q.

The operator's expected utility remains as specified in equation (3.1) with FOC per equation (3.3) and best response per equation (3.4). This means that the signs of ${q^*}_s$, ${q^*}_m$, and ${q^*}_H$ are as established in the analysis of simultaneous interaction.

The bystander's expected costs remain as specified in equation (3.2). However, the bystander chooses his level of effort towards self-defence, s, subject to the expected activity level of the operator.

Properties of the Equilibrium

As with the Stackelberg-like model with the operator as leader, before attempting an analytic solution to the equilibrium $(\hat{q}, \hat{s})$, we can first establish some general properties of the equilibrium relative to the equilibrium of the simultaneous model.

Lemma 14. *Assume that self defence is permitted. Then $\hat{s}$ is higher and $\hat{q}$ is lower in the Stackelberg-like model with the bystander as leader than in the simultaneous version.*

Proof. As s increases along the operator's best response, the bystander's utility changes by:

$$\frac{dV(s, q^*(s))}{ds} = V_s + V_q q^* s. \tag{3.51}$$

At the Nash equilibrium of the simultaneous model, $V_s = 0$. From the bystander's cost function in equation (3.2), $V_q = -\rho(s)(1-m)H \leqslant 0$, and from equation (3.6) ${q^*}_s \leqslant 0$. We therefore have $dV/ds \geqslant 0$ at the Nash equilibrium. If $dV/ds > 0$ at the Nash equilibrium then it will decrease towards zero as s increases, since $V_s < 0$ as s is increased from the Nash equilibrium. The bystander's utility increases for an incremental increase in s along the operator's best response curve and the bystander will therefore increase his effort towards self defence. Furthermore, an increase in s means that activity q will decrease since ${q^*}_s \leqslant 0$. □

Lemma 15. *For sufficiently large $H > v$, the Stackelberg-like game with the bystander as leader will have a higher level of welfare than the equilibrium in the simultaneous variant of the game.*

Proof. As s increases along the operator's best response, welfare in the Stackelberg-like game changes by:

$$\frac{dW(q^*(s), s)}{ds} = W_q {q^*}_s + W_s. \tag{3.52}$$

As before, $W_q < 0$ at the Nash equilibrium of the simultaneous game. From equation (3.6) ${q^*}_s \leqslant 0$, hence $W_q {q^*}_s \geqslant 0$. The sign of dW/ds depends on the sign of W_s. If $W_s > 0$ then $dW/ds > 0$, but if $W_s < 0$ then the sign of

dW/ds cannot be determined without more detailed analysis. The relevant condition for $W_s > 0$ is:

$$\begin{aligned} W_s > 0 &\Rightarrow \rho'(s)(v - H)q + \rho'(s)\kappa - 1 > 0 \\ &\Rightarrow H > v - \frac{1 - \rho'(s)\kappa}{\rho'(s)q} > v. \end{aligned} \tag{3.53}$$

□

Consider now the general conditions under which welfare will be improved in this version of the game relative to the simultaneous game. The relevant condition is:

$$\begin{aligned} \frac{dW}{ds} > 0 &\Rightarrow W_q {q^*}_s + W_s > 0 \\ &\Rightarrow [U_q - \rho(s)(1-m)H]\, {q^*}_s + [\rho'(s)(v - H)q + \rho'(s)\kappa - 1] > 0 \\ &\Rightarrow \rho'(s)(v - H)q > \rho(s)(1-m)H{q^*}_s - \rho'(s)\kappa + 1, \end{aligned}$$

since $U_q = 0$ at the Nash equilibrium of the simultaneous game.

Dividing both sides by $\rho'(s)$ reverses the inequality since $\rho'(s) < 0$:

$$\frac{dW}{ds} > 0 \Rightarrow (v - H) < \frac{\rho(s)(1-m)H{q^*}_s + 1}{\rho'(s)q} - \frac{\kappa}{q}. \tag{3.54}$$

We have previously established that ${q^*}_s \leqslant 0$, which means that the term $\rho(s)(1-m)H{q^*}_s + 1$ could have either sign. Consider a value of $(1-m)H$ sufficiently small that $\rho(s)(1-m)H{q^*}_s + 1 > 0$, then the RHS of equation (3.54) is negative. This means that only values of H that exceed v by an amount at least equal to the absolute value of the RHS of equation (3.54) will be associated with $dW/ds > 0$. However, if H is relatively large, then $\rho(s)(1-m)H{q^*}_s + 1 > 0$ could only hold for large m (close to 1).

Alternatively, consider $\rho(s)(1-m)H{q^*}_s + 1 < 0$. If $\kappa = 0$ then the RHS of equation (3.54) is positive. All values of $H \geqslant v$ will be associated with $dW/ds > 0$. In addition, if H is less than v by a amount not greater than the RHS of equation (3.54) then dW/ds will also be > 0. That margin reduces as κ increases, and for large κ the RHS of equation (3.54) will be negative and the analysis of the previous paragraph applies.

Equilibrium

Turning to the explicit formulation of the equilibrium, the operator's activity level is embodied in her FOC, subject to the additional constraint that

$q \geqslant 0$. The Lagrangian for the bystander is:

$$\mathcal{L} = \rho(s)(1-m)Hq + s - \lambda[\rho(s)(v-mH) - c'(q)]. \tag{3.55}$$

The bystander has the FOCs:

$$\frac{\partial \mathcal{L}}{\partial q} = \rho(s)(1-m)H + \lambda c''(q) = 0 \tag{3.56}$$

$$\frac{\partial \mathcal{L}}{\partial s} = \rho'(s)(1-m)Hq + 1 - \lambda\rho'(s)(v-mH) = 0 \tag{3.57}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = \rho(s)(v-mH) - c'(q) = 0 \tag{3.58}$$

I show in Appendix 3.C.1 that, given the above FOCs, the equililbrium occurs at:

$$[\rho'(s)(1-m)H]\,\alpha q + (\alpha - 1) = 0.$$

The equilibrium occurs at a point on the operator's best response curve, hence:

$$\begin{aligned} &[\rho'(s)(1-m)H]\,\alpha q^*(s;m,H) + (\alpha-1) = 0 \\ &\qquad\qquad \Rightarrow \rho'(s)q^*(s;m,H) = -\frac{(\alpha-1)}{(1-m)H\alpha}. \end{aligned}$$

Utilising equation (3.4) for the operator's best response and the assumed functional form for $\rho(s)$, I show in Appendix 3.C.2 that the equilibrium value of s becomes:

$$s = \max\left\{0, \left[\frac{n(1-m)H\alpha}{(\alpha-1)}\right]^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]}\left(\frac{v-mH}{\eta}\right)^{\left[\frac{1}{(n+1)(\alpha-1)+n}\right]} - 1\right\}. \tag{3.59}$$

The boundary of the region for which $s = 0$ is therefore given by:

$$\left[\frac{n(1-m)H\alpha}{(\alpha-1)}\right]^{(\alpha-1)}\left(\frac{v-mH}{\eta}\right) = 1. \tag{3.60}$$

Lemma 16. *When the bystander is leader, the equilibrium is independent of the value of κ.*

Proof. The term κ does not appear in equation (3.59). □

Lemma 17. *When the bystander is leader, an increase in harm, H, has an* *ambiguous effect on the bystander's effort towards self-defence,* s*. If* $H < \frac{(\alpha-1)}{\alpha m}v$ *then the bystander's effort towards self-defence will increase, but if* $H > \frac{(\alpha-1)}{\alpha m}v$ *then the bystander's effort towards self-defence will decrease.*

Proof. See Appendix 3.C.3. □

Lemma 18. *When the bystander is leader, an increase in* m *unambiguously decreases the level of self defence.*

Proof. See Appendix 3.C.4. □

3.4 Numeric Example

The analysis in the previous section established that, while some characteristics of the equilibrium could be analytically determined, other characteristics require numeric analysis. Of particular importance, the question of whether self-defence should be allowed or prohibited could not be determined. In this section I present a numeric example to gain further insight into the impact of self defence on welfare and ascertain the optimal policy.

Section 3.4.1 suggests parameter estimates for analysing the games for both unmanned aircraft and for small manned aircraft, allowing us to test whether predictions for manned aircraft align with existing aviation regulation, and whether there is a difference in optimal regulation for manned and unmanned aircraft.

In section 3.4.2 I present the analysis for the Cournot-like model with simultaneous interaction between the drone operator and the bystander. I first show the best response curves and equilibria for selected parameter values. I then illustrate the construction of the policy regime boundary, being the boundary between the region where self-defence is welfare-enhancing and the region where self-defence reduces welfare relative to the status quo with self-defence prohibited.

Section 3.4.3 presents the policy regime boundary for the Stackelberg-like game with the drone operator as leader, and section 3.4.4 presents the policy regime boundary for the Stackelberg-like game with the bystander as leader. The best response curves and construction of the policy regime boundary for these games is provided in Appendix 3.D.

3.4.1 Parameter Values

In section 3.3.1 the costs associated with destroying the drone were defined as $\kappa \in \mathbb{R}_+$. To aid clarity in the consideration of manned and unmanned aircraft, I now define $\kappa = \kappa_1 + \kappa_2$ where:[6]

- $\kappa_1 \in \mathbb{R}_+$ denotes the direct cost to the operator of the drone being shot down, representing the value of the drone including future earnings.
- $\kappa_2 \in \mathbb{R}_+$ denotes the cost of harm to any person that is on-board the aircraft (recalling that a drone is currently classified as an aircraft by regulatory authorities), including the cost of fatality. This cost will be zero for a drone that does not carry any person, but positive for a manned aircraft. The inclusion of κ_2 facilitates the predictions of this model being validated against existing regulation for manned aircraft.

Analysis of optimal regulation for manned and unmanned aviation requires parameter values that are representative of the differences between the two forms of aviation.

Parameters for analysis of Drones

In July 2017, a New Zealand online retailer advertised drones for sale at the prices in Table 3.1, with prices in the range \$130-\$1,300 for consumer drones, \$800-\$3,500 for "prosumer" drones, and \$3,100-\$8,800 for professional drones. All 12 professional drones and 9 of the 10 prosumer drones were the popular DJI brand. [7]

Based on the figures in Table 3.1, κ_1 could be anywhere in the range \$134-\$8,800. There are also specialist drones available at much higher prices, as well as small drones available for less than \$100. For the purpose of this analysis, an estimate of $\kappa_1 = 3$ has been adopted, representing the drones costing approximately \$3,000 at the upper end of the prosumer range and bottom end of the professional range.

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[6] Numeric subscripts are used for the parameters κ_1 and κ_2 to avoid confusion with partial derivatives of a function w.r.t. a parameter.

[7] As at 9 June 2015, 48% of drones authorised for commercial use in the United States were manufactured by Shenzhen-based drone manufacturer DJI (Mortimer, 2015). Also in 2015, US market research firm Frost & Sullivan reportedly estimated that DJI had a 70% share of the consumer drone market (Mac, 2015).

Table 3.1

Summary of advertised drone prices

Category	Number	Minimum	Average	Maximum
Consumer	11	\$134.00	\$452.96	\$1,298.99
Prosumer	10	\$803.85	\$2,052.37	\$3,498.99
Professional	12	\$3,099.00	\$5,580.81	\$8,799.00

Parameters for analysis of Manned Aircraft

On 22 July 2017, a selection of aircraft were advertised for sale on the TradeMe website at the prices shown in Table 3.3 in Appendix 3.E. As might be expected from the nature of the website, all aircraft listed are light aircraft. No aircraft that might generally be used for regular passenger transport services are for sale on this site, although the list does include some aircraft that might be used for scenic flights or irregular charter services, such as the Cessna 172 and the Piper PA31. The aircraft therefore represent the lower cost forms of manned aviation, and include the aircraft that might be used by less skilled pilots engaging in activities that could result in the kinds of harm considered in this analysis.

Table 3.2 summarises average aircraft prices per category, and shows the corresponding value assumed for κ_1. In all cases κ_1 represents the cost of the aircraft in thousands of dollars, rounded to two significant figures.

Table 3.2 also shows the maximum number of people carried by each category of aircraft, and the corresponding assumed value of κ_2. The New Zealand Ministry of Transport estimates the statistical value of life to be approximately \$4.1 million (MOT, 2016). On the basis of this estimate, the value of a pilot's life is assumed to be $\kappa_2 = 4100$. However, a number of the categories of aircraft listed in Table 3.2 can carry more than one person. In the absence of data on how many people are actually carried, I assume that the pilot's seat is always occupied and on average half of the passenger seats are occupied. The parameter κ_2 is then proportional to the expected number of people on board the aircraft (including the pilot). A four-seat aircraft is therefore assumed to have an average of 1.5 passengers on board and a total of 2.5 people including the pilot, for a cost of $\kappa_2 = 10,250$ if the aircraft is destroyed.

Table 3.2

Summary data by aircraft category

Aircraft Category	Number in Sample	Average Price	κ_1	Average People On Board	κ_2
Aeroplane	34	\$98,729	99	3.4	9,020
Amateur Built Aeroplane and Microlight Class 2	32	\$58,671	59	2.0	6,150
Microlight Class 1	5	\$14,500	15	1.0	4,100

It is apparent from consideration of these parameters that the value of human life, κ_2, is significantly higher than any other parameter, even for the smallest category of manned aircraft. This suggests that the welfare-optimal solution for unmanned aircraft (with $\kappa_2 = 0$) may be significantly different to the welfare-optimal solution for manned aircraft.

3.4.2 Simultaneous Interaction

Equilibria

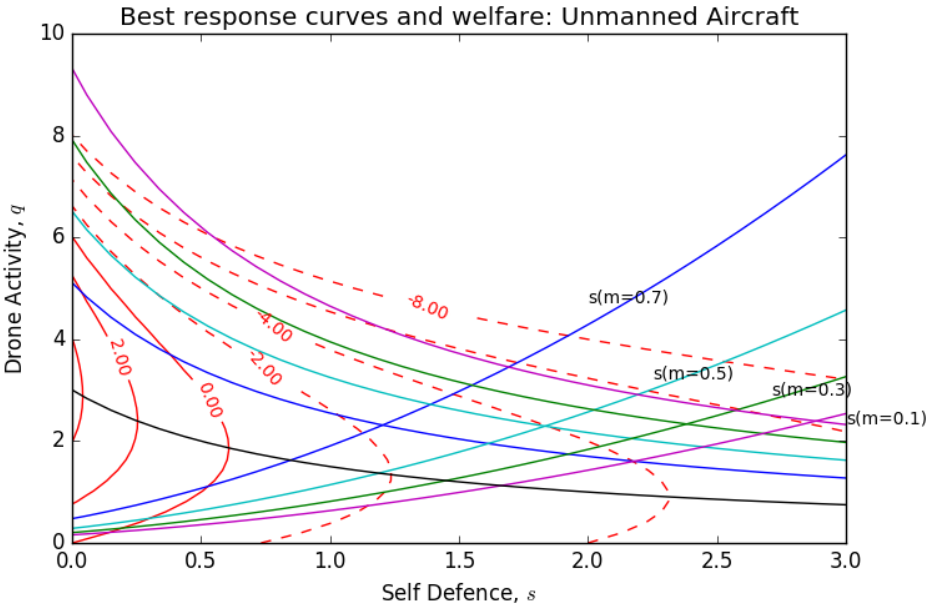
The equilibrium outcomes can be illustrated with a numeric example.

Let $v = 10, \alpha = 2, \eta = 1$, $H = 7$, and $m \in \{0.1, 0.3, 0.5, 0.7\}$. We will consider two illustrative scenarios: an unmanned aircraft and a manned aircraft. Note that $v > mH$ in all cases, so the necessary condition for the operator to fly the drone is satisfied.

Unmanned Aircraft

In this scenario the aircraft is unmanned so that $\kappa_2 = 0$. Assume further that the cost to the operator if the aircraft is destroyed is $\kappa_1 = 3$. The result is illustrated in Figure 3.1. The red curves are iso-welfare curves, with positive welfare shown by a solid line and negative welfare shown by dashed lines. The magenta curves show the best response functions when $m = 0.1$, the green curves when $m = 0.3$, the cyan curves when $m = 0.5$, and the blue curves when $m = 0.7$.

When $m = 0.3$ the green best response functions intersect at $(q, s) \approxeq (2.34, 2.38)$ with welfare $W \approxeq -5.15$. The $s = 0$ intercept for the operator's best response function occurs at a lower level of welfare $W \approxeq -7.505$. Similarly, the magenta best response functions for $m = 0.1$ intersect at



Iso-welfare curves (red) and best response curves for the bystander (upward sloping) and the drone operator (downward sloping). The colour of the best response curves denotes the proportion of liability, m, borne by the injurer: magenta, $m = 0.1$; green, $m = 0.3$; cyan, $m = 0.5$; and blue, $m = 0.7$. Parameters are: $v = 10$, $H = 7$, $\alpha = 2$, $\eta = 1$, $\kappa_1 = 3$, and $\kappa_2 = 0$.

Figure 3.1. Best Response Curves and Welfare, Unmanned Aircraft

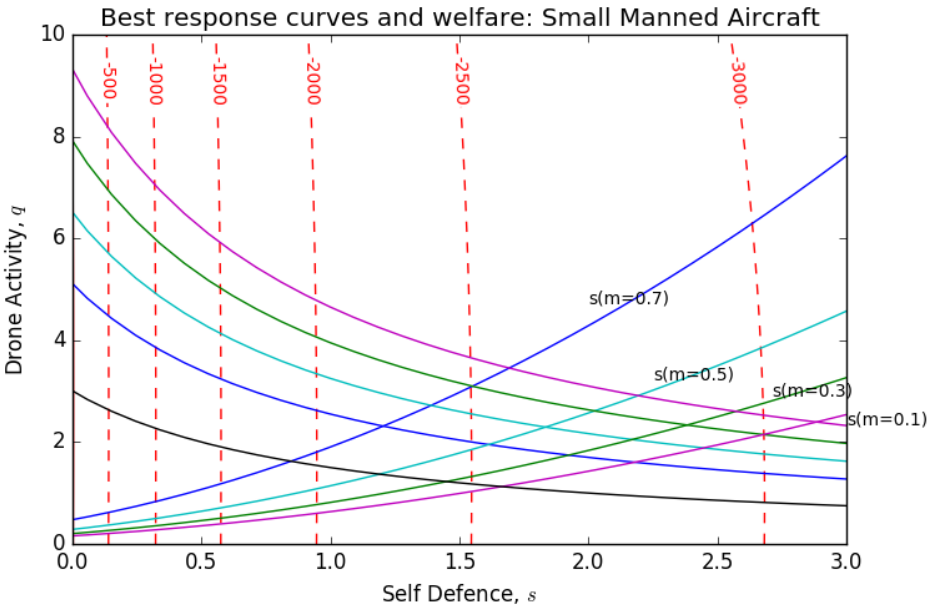
a higher level of welfare ($W \approxeq -6.13$) than the $s = 0$ intercept for the operator's best response function ($W = -15.345$). In both of these cases welfare is improved by allowing the destruction of drones.

When $m = 0.5$ the cyan best response functions intersect at $(q, s) \approxeq (2.29, 1.83)$ with welfare level $W \approxeq -3.98$. The $s = 0$ intercept for the operator's best response function occurs at the higher level of welfare $W \approxeq -1.625$. Similarly, the blue best response functions for $m = 0.7$ intersect at a lower level of welfare ($W \approxeq -2.37$) than the $s = 0$ intercept for the operator's best response function ($W = 2.295$). In both of these cases welfare is improved by prohibiting the destruction of drones.

Manned Aircraft

In this scenario the aircraft is manned, which means that $\kappa_2 > 0$. Assume the smallest category of aircraft from Table 3.2 so that $\kappa_1 = 15$ and $\kappa_2 = 4,100$. The resulting best-response functions are shown in Figure 3.2. The operator's best-response curves, being independent of κ_1 and κ_2, are the same as in Figure 3.1. The bystander's best-response curves are also as shown in Figure 3.1.

The red iso-welfare curves have changed significantly from those in Figure 3.1, being almost vertical and with a relatively large negative magnitude for all $s > 0$, becoming increasingly negative as s increases. In all cases welfare is lower at the intersection of the best-response curves than it is at $s = 0$. When the bystander bears no liability for harm caused to those on board the aircraft, the socially optimal policy is to prohibit the destruction of aircraft. This optimal policy is reflected in the Montreal Convention (United Nations, 1975).



Iso-welfare curves (red) and best response curves for the bystander (upward sloping) and the aircraft operator (downward sloping). The colour of the best response curves denotes the proportion of liability, m, borne by the injurer: magenta, $m=0.1$; green, $m=0.3$; cyan, $m=0.5$; and blue, $m=0.7$. Parameters are: $v=10$, $H=7$, $\alpha=2$, $\eta=1$, $\kappa_1=15$, and $\kappa_2=4100$.

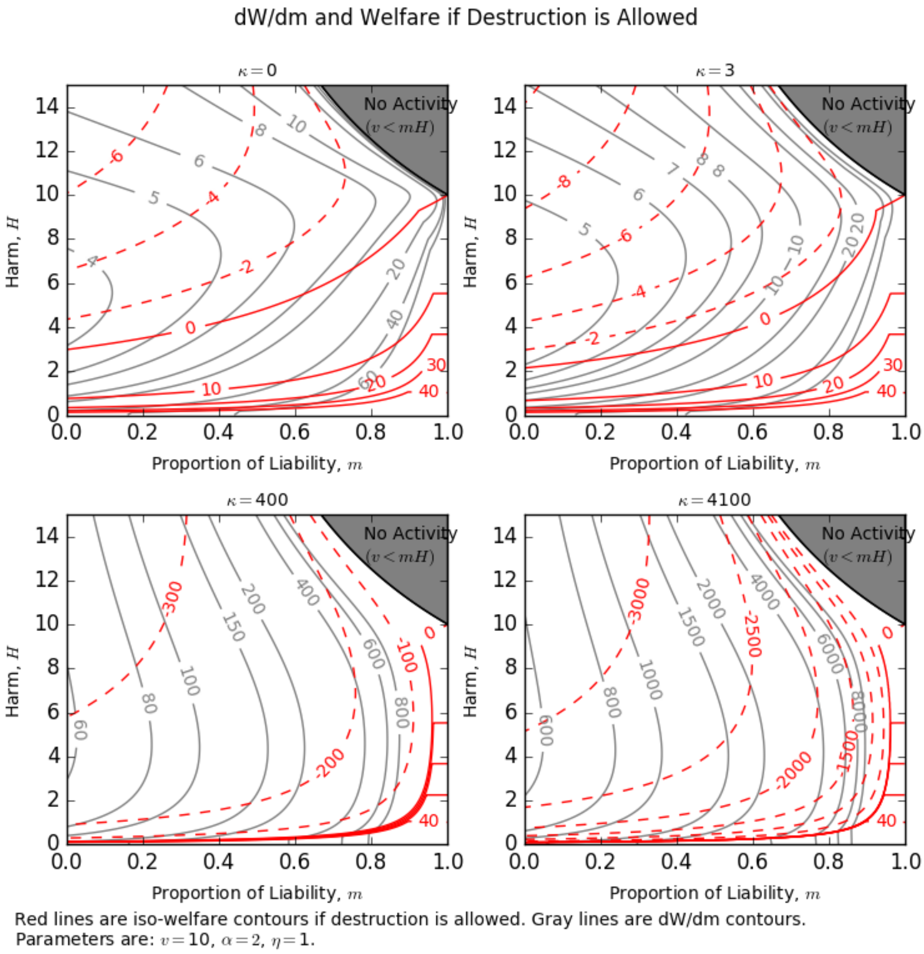
Figure 3.2. Best Response Curves and Welfare, Small Manned Aircraft

Visual inspection of Figures 3.1 and 3.2 confirms Lemma 2 that κ has no effect on the equilibrium level of activity or self defence. Accordingly, equilibrium activity and self defence are independent of the case being analysed.

Optimal Liability

An unanswered question from section 3.3.2 was whether the welfare-optimal level of liability for the operator is less than unity. Figure 3.3 shows the dW/dm curves for $\kappa \in \{0, 3, 40, 4100\}$. The red curves are the iso-welfare contours, and the gray curves are the dW/dm contours. The two charts on the right-hand side of the figure ($\kappa = 3$ and $\kappa = 4100$) represent the unmanned aircraft and small manned aircraft scenarios.

It is evident from figure 3.3 that the lowest value of dW/dm occurs with $\kappa = 0$ and that dW/dm is increasing in κ. The minimum value of dW/dm is > 0, so there is no point at which the welfare-optimal level of liability for the operator is less than one. This means that policies that increase the expected liability of the operator, such as policies that increase the ability to identify the operator, will increase welfare.



dW/dm and Welfare if Destruction is Allowed

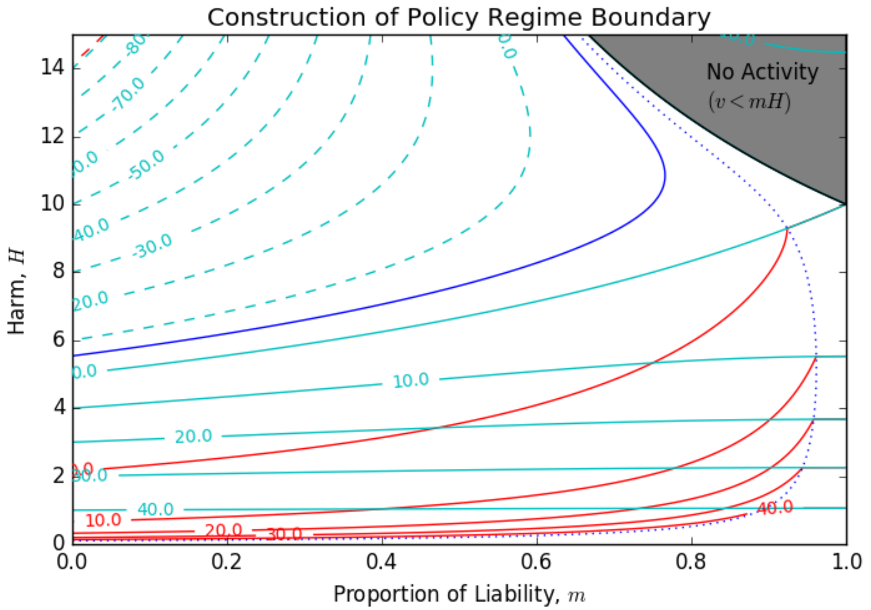
Red lines are iso-welfare contours if destruction is allowed. Gray lines are dW/dm contours.
Parameters are: $v=10$, $\alpha=2$, $\eta=1$.

Figure 3.3. Simultaneous Interaction: dW/dm (black curves) welfare curves (red curves)

Optimal Policy

The comparison of the FOCs demonstrated that the bystander will not adopt the socially efficient level of self-help, but the analysis in the numerical example demonstrated that in some instances the welfare achieved if the bystander undertakes self-defence is greater than the welfare achieved if the bystander does not exert any effort in self-defence. In all cases examined, both outcomes (equilibrium self-defence and no self-defence) yielded an inferior level of welfare to the social optimum. The question of interest is, therefore, whether the privately-optimal level of self-help yields a second-best outcome, or whether it would be second-best to prohibit the destruction of drones.

In section 3.3.2 it was established that the optimal policy could not be determined analytically but rather required numerical solution. Let $W^A = W^P$ denote the policy regime boundary, being the locus of points at which we are indifferent between allowing and prohibiting the destruction of drones. Figure 3.4 shows the construction of the policy regime boundary from the iso-welfare curves when destruction is allowed (red curves) and when destruction is prohibited (cyan curves). The solid blue curve is the policy regime boundary, tracing the points of intersection between the iso-welfare curves for the two scenarios. The dotted blue curve is the boundary of the region for which $\hat{s} = 0$ when destruction is allowed. The shaded area in the top right is the area in which the drone operator will choose not to fly because $v < mH$.



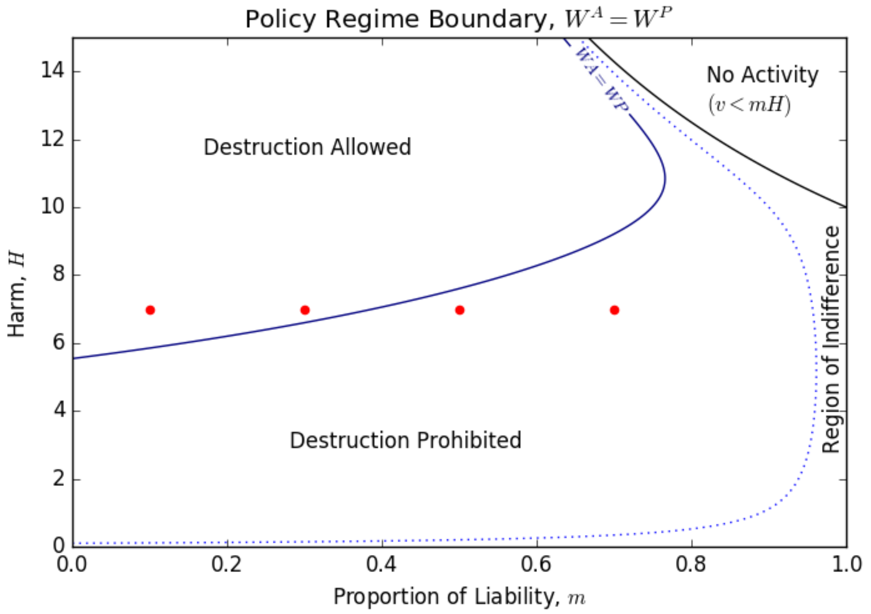
Construction of the policy regime boundary for sequential self-defence model. Red lines are the iso-welfare curves if destruction is allowed. Cyan lines are the iso-welfare curves if self-defence is prohibited. Blue lines are the welfare indifference curves.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$, $\kappa = 3$.

Figure 3.4. Construction of Policy Regime Boundary $W^A = W^P$

It is readily apparent from Figure 3.4 that at any given point throughout the area between the two blue curves, welfare when destruction is allowed is less than welfare when destruction is prohibited. The optimal policy in this region is, therefore, to allow the destruction of drones.

In the upper-left quadrant of Figure 3.4, at any given point welfare when destruction is allowed is greater than welfare when destruction is prohibited. The optimal policy in this region is, therefore, to allow the destruction of drones.

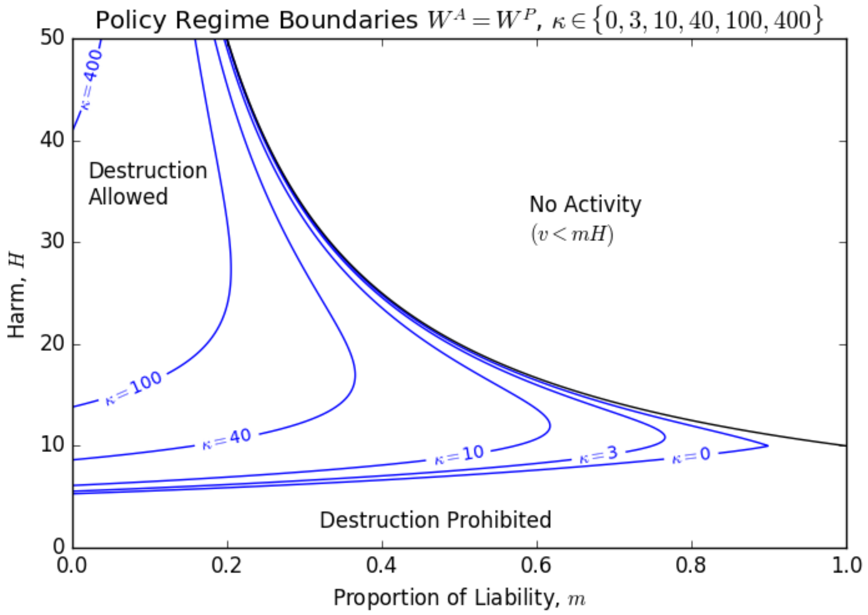
Figure 3.5 plots the policy regime boundary together with the four equilibria for unmanned aircraft analysed in section 3.4.2. Each of the red dots represents one of the equilibria. It was shown to be welfare-enhancing to allow the destruction of drones for $m = 0.1$ and $m = 0.3$, and these points lie in the region where destruction is allowed; it was also shown to be optimal to prohibit the destruction of drones for $m = 0.5$ and $m = 0.7$, and these points lie within the region where destruction is prohibited.



Line represents the welfare indifference curve at which the welfare from allowing destruction, W^A, equals the welfare from prohibiting destruction, W^P. Coloured dots are the equilibria from the modelled scenarios.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$, $\kappa = 3$.

Figure 3.5. Policy Regime Boundary $W^A = W^P$ and Modelled Equilibria

The influence of κ_1 and κ_2 on whether it is efficient to allow destruction of drones is illustrated in Figure 3.6, which shows the policy regime boundary for $\kappa = \kappa_1 + \kappa_2 \in \{0, 3, 10, 40, 100, 400\}$. The curve $\kappa = 3$ is the policy regime boundary in Figure 3.5. Increasing κ reduces the area in



Policy regime boundaries for which the welfare from allowing destruction, W^A, equals the welfare from prohibiting destruction, W^P. Each curve represents a different level of cost, κ, suffered by the inujurer if the technology is destroyed.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$.

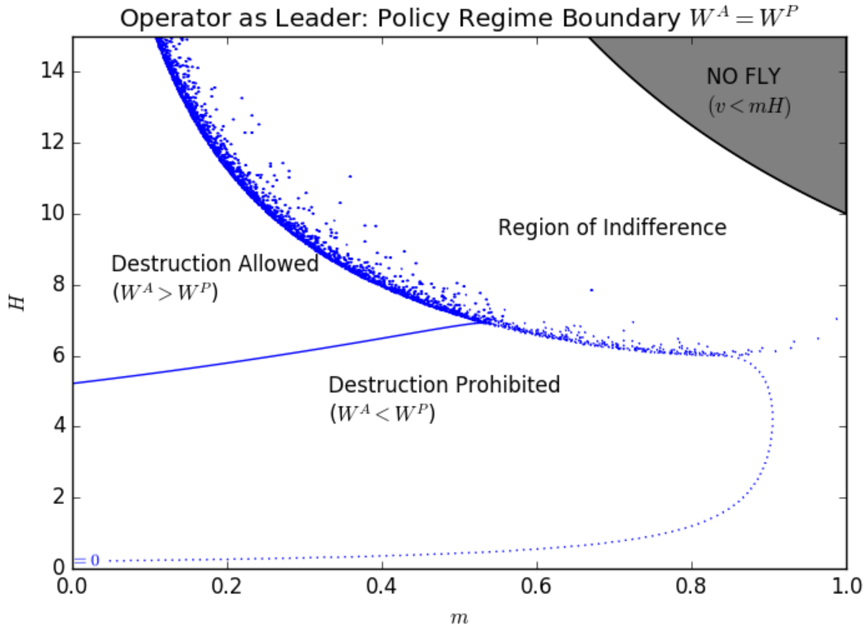
Figure 3.6. Policy Regime Boundaries for Different Values of κ

which it is efficient to allow destruction of drones because the social cost from destruction is higher. This has three important policy implications. First, the value of a statistical (human) life is relatively high, and therefore in all but the most extreme circumstances it is not welfare-enhancing to permit destruction of manned aircraft, but it may be efficient to allow the destruction of drones. Second, it is more likely to be efficient to destroy a small, cheap drone than it is to destroy a larger and more expensive drone. And third, it may be efficient to allow destruction of drones when the ability to attribute liability for harm caused is low.

In figures 3.5 and 3.6 that initially the policy regime boundary is upward sloping. This means that as the proportion of liability m increases, the level of harm required before it is efficient to destroy a drone also increases. At some point (dependent on $\kappa_1 + \kappa_2$) the policy regime boundary becomes backward sloping. Initially this seems paradoxical, as it suggests that an increase in harm may require a decrease in liability for it to remain efficient to allow destruction of drones. The reason for this apparently paradoxical result is evident from Figure 3.6: as harm increases, the “no fly” area expands to the left and the policy regime boundaries become compressed against the “no fly” boundary. An increase in harm is therefore associated with an increased likelihood that the operator will not fly, so the area in which it is efficient to destroy the drone decreases.

3.4.3 Drone Operator as Leader

Figure 3.7 shows the policy regime boundary for the game with the drone operator as the leader.[8] Parameters are the same as for the simultaneous game.



Blue curve is the policy regime boundary for the Stackelberg-like game with the Operator as leader. Dotted blue line shows the boundary of the area where $\hat{s} = 0$.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$, $\kappa = 3$.

Figure 3.7. Policy Regime Boundary for Self-Defence when the Operator is Leader

The policy regime boundary in figure 3.7 is significantly different to the boundary in figure 3.5 with simultaneous interaction. In particular, when the operator is leader there is a large region where we are indifferent to whether or not drones are allowed to be destroyed, the region where destruction of drones is allowed is reduced in size, and the region where destruction of drones is prohibited has is also reduced in size. When the probability of identifying the drone operator is low (< 0.2) then both games

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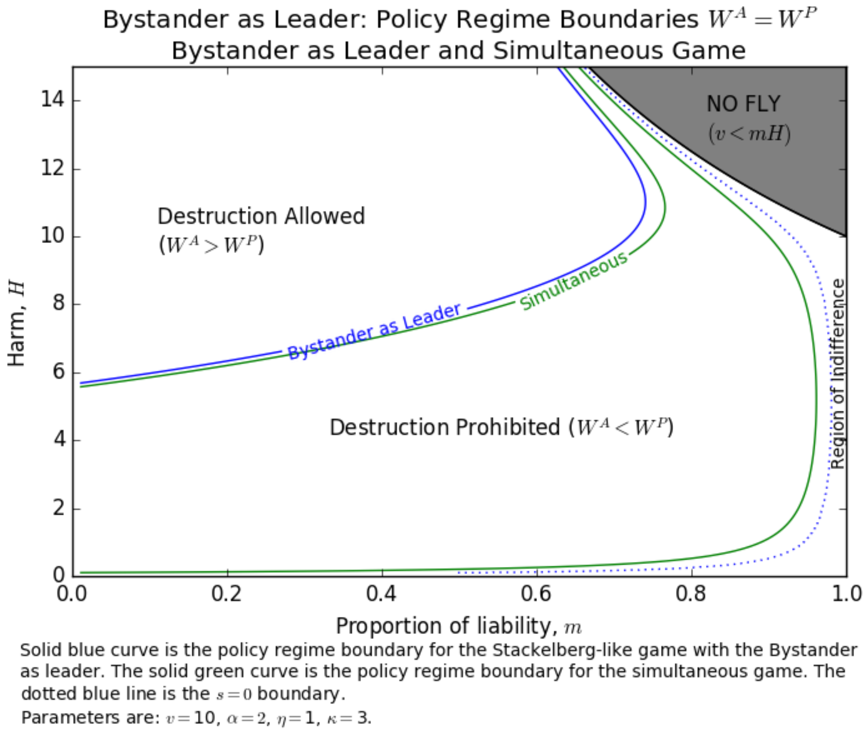
[8] Appendix 3.D.1 presents the best response curves for this game, for both unmanned aircraft and manned aircraft. This appendix also shows the construction of the policy regime boundary from the iso-welfare curves when destruction is allowed and the iso-welfare curves when destruction is prohibited.

allow for destruction of drones at moderate-to-high levels of harm, and prohibit destruction of drones at low levels of harm. When the probability of identifying the operator is high ($p > 0.8$), the simultaneous game prohibits the destruction of drones, but in the game with the operator as leader destruction is only prohibited at low-to-moderate levels of harm.

3.4.4 Bystander as Leader


Bystander as Leader: Policy Regime Boundaries $W^A = W^P$
Bystander as Leader and Simultaneous Game

Solid blue curve is the policy regime boundary for the Stackelberg-like game with the Bystander as leader. The solid green curve is the policy regime boundary for the simultaneous game. The dotted blue line is the $s = 0$ boundary.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$, $\kappa = 3$.

Figure 3.8. Bystander as Leader: Policy Regime Boundary $W^A = W^P$

Figure 3.8 shows the policy regime boundaries for the Stackelberg-like game with the bystander as the leader (blue curve) and for the simultaneous game.[9] Parameters are the same as for the simultaneous game in figure 3.5. It is evident that the policy regime boundary for the Stackelberg-like game is substantially the same as the upper policy regime boundary for the simultaneous game. In the simultaneous game there is a lower / left-hand side boundary to the region where destruction is prohibited; this boundary

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[9] Appendix 3.D.2 presents the best response curves with the bystander as leader in the same manner as was presented for the simultaneous case, for both unmanned aircraft and manned aircraft. This appendix also shows the construction of the policy regime boundary from the iso-welfare curves when destruction is allowed and the iso-welfare curves when destruction is prohibited.

is absent from the Stackelberg-like game. The level of similarity suggests that the analysis of the simultaneous game is, therefore, also applicable to the game with the bystander as the leader.

3.5 Discussion

Harm from drones can encompass a wide spectrum from physical harm to individuals, privacy violations, surveillance, damage to physical infrastructure, and compromising national security. The various characteristics of drones suggest that this harmful activity could be more frequent with drones than with manned aircraft, and also that the operators of drones may bear a low proportion of liability for any harm caused. This in turn means that the level of harm caused by drones may be higher than the socially efficient level.

3.5.1 Theoretical Analysis

This chapter has presented a model of the strategic game between a drone operator and a bystander that is able to engage in self defence against the drone. Three variants of the model were examined: a Cournot-like model where the players move simultaneously; a Stackelberg-like model with the operator as leader; and a Stackelberg-like model with the bystander as leader.

The standard literature on Stackelberg games assumes that the best response functions of the two players have the same slope, whether both positive or both negative (see, for example, Gal-Or (1985) and Dowrick (1986)). In contrast, a feature of the game presented here is that the best response curves for the operator and the bystander have opposite slopes. The conclusions of the standard literature therefore do not apply. One consequence of the opposite slopes is that in the simultaneous version of the game a change in liability, m, and harm caused, H, has a definite effect on one party but an ambiguous effect on the other party, and hence the welfare effect of such a change is also ambiguous. An increase in liability for the drone operator causes a reduction in the equilibrium level of self-defence under both the simultaneous variant of the game and the Stackelberg-like variant with the bystander as the leader; the effect could not be determined analytically for the Stackelberg-like games with the operator as leader.

A second consequence of the best response curves having opposite slopes is that the operator has lower activity in both sequential versions of the game than in the simultaneous version of the game, whereas the bystander has a lower effort towards self defence in the game with the operator as leader but a higher effort towards self defence in the game where the bystander is leader. If both Stackelberg-like variants of the game resulted in the same level of activity, we could logically conclude that welfare would be higher under the version of the game with the operator as the leader; however, we are unable to obtain an analytic solution for the equilibrium when the operator is the leader, so we are unable to determine whether equilibrium activity is the same or which variant of the game has the higher level of welfare.

In the simultaneous version of the game, a change in liability for harm caused and a change in the magnitude of harm were both shown to have an ambiguous effect on welfare. An explicit condition was derived for when an increase in the magnitude of harm would increase welfare; an explicit result could not be derived for liability. This ambiguity suggests that there may be conditions under which the welfare effects are counter-intuitive: we would normally expect that an increase in liability for harm caused would increase welfare because that would better align the harmer's incentives with the social welfare function.

3.5.2 Numeric Analysis

Numeric analysis was conducted using parameters suggested by data on the cost of drones and small manned aircraft. The numeric analysis allowed the construction of policy regime boundaries, which show the locus of points where we are indifferent between the policy of allowing destruction of drones and the policy of prohibiting destruction of drones. The policy regime boundaries for the simultaneous game (Figures 3.5 and 3.6), Stackelberg-like game with the operator as leader (Figure 3.7), and the Stackelberg-like game with the bystander as leader (Figure 3.8) are all similar in shape and location. The welfare maximising policies depend in part on whether harm H is greater or less than the value v from the drone operation.

Consider first when harm is less than the value from the drone operation ($H < v$) so that the drone operation increases aggregate welfare. For all variants of the game there is a small region of indifference at very high levels of liability and at very low levels of harm: in this region we are indifferent between the two policies because the level of harm suffered by the bystander, after expected compensation, is insufficient to cause the bystander to exert any effort in self-defence. If the cost when the drone is destroyed is sufficiently low then there is also a region where harm is at a “moderate” level and liability is relatively low, where it is welfare-enhancing to allow the destruction of drones: in this region the threat of potential destruction constrains the drone operator’s behaviour to a more efficient level than occurs with relying on liability alone. The policy regime boundary in this region is upward-sloping, indicating that as liability increases the threshold level of harm at which destruction should be allowed also increases. Between the region where destruction is allowed and the region of indifference is a large region where destruction is prohibited: with the drone operation increasing welfare it is preferable to allow on imperfect liability than to allow the destruction of the drone. It is apparent from Figure 3.6 that if the cost when the drone is destroyed becomes sufficiently high that there is no part of the region ($H < v$) where it is welfare enhancing to allow the destruction of drones.

Consider now when harm is greater than the value from the drone operation ($H > v$) so that the drone operation reduces aggregate welfare. There are now potentially four regions. To the left, where liability is low, it is welfare-enhancing to allow the destruction of drones. To the right, where liability is relatively high, the drone operator does not fly because their liability for harm caused is greater than the value that they receive from the flight ($mH > v$). The boundary of the region where the operator does not fly is $v - mH = 0$. Between the region where destruction is allowed and the region where the operator does not fly are one or two additional regions depending on the specific variant of the game.

For the Stackelberg-like game with the operator as leader and $H > v$, there is a single region between the region where destruction is allowed and the region where the operator does not fly. In this region we are indifferent between allowing and prohibiting destruction (see Figure 3.7): this suggests that if conduct can be best modelled as a game with the operator as leader, then the simple policy of allowing destruction of drones can be adopted whenever harm is higher than the value of the drone operation ($H > v$).

For the sequential game and the Stackelberg-like game with the bystander as leader, there are two regions between the region where destruction is allowed and the region where the operator does not fly. To the immediate left of the region where the operator does not fly, at relatively high levels of liability but outside the border of $v - mH = 0$, is a very narrow region of indifference between the two policies. To the left of that region is a narrow region where the optimal policy is to prohibit destruction: in this region the expected legal liability for harm is a more efficient constraint on the activity of the drone operator than is the threat of potential destruction of the drone. This suggests that if conduct can be best modelled as either a sequential game or as a game with the bystander as leader, then the destruction of drones should be allowed if it is difficult to attribute liability to a drone operator.

3.5.3 Registration

As discussed in the literature review, manned aircraft are easily identifiable and registered to a specific owner, so the expected proportion of liability m is high. At moderately high levels of harm (e.g. greater than 10), the high level of liability means that the manned aircraft operator may choose not to fly. More generally, if the operator faces liability for a high proportion of harm then her privately-optimal action is more likely to be socially-optimal and thus destruction of drones is less likely to be welfare enhancing.[10] A corollary of this proposition is that if the destruction of drones is prohibited then it is important to raise m as high as possible. One option would be to require all drones to carry an electronic identification beacon, with those not carrying a beacon to be used for tightly prescribed recreational purposes only. The radio beacon will enable identification of the drone, at least by those with appropriate equipment, thus increasing the proportion of liability borne. A requirement to have a radio beacon would be subject to adverse selection problems: this could, in part, be solved by allowing the destruction of drones without radio beacons in any circumstance, but prescribing a more restricted range of circumstances in which drones with radio beacons can be destroyed.

3.5.4 Policy Implications

The numeric analysis suggests that it is never efficient to allow the destruction of manned aircraft, but there are circumstances in which it is efficient to allow self-defence against - and the potential destruction of - drones. These results suggest that existing legal rules prohibiting the destruction of all kinds of aircraft are efficient for manned aircraft, but may

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[10] Recall that we saw earlier that when $m = 1$ the operator's FOC coincides with one of the FOCs for welfare maximisation.

be inefficient for drones.

The behaviours predicted by the models analysed are reflected in what we observe with manned aviation. Due to the presence of people on board the aircraft, the cost arising from the destruction of the aircraft is very high relative to potential harm caused, so destruction of aircraft is prohibited (United Nations, 1975). Nevertheless, countries or belligerents may deploy air-defence systems, and when this occurs civilian aviation plans flights subject to the constraint of those systems, almost always avoiding having any aircraft shot down.

We observe that the destruction of drones is only efficient if the harm caused is a relatively high proportion of the value obtained by the drone operator. In most situations it will not be possible for the bystander to know the value obtained by the operator, and it may also be difficult for them to objectively judge the value of harm. However, from a policy perspective it is possible to make judgements on the situations in which the relative magnitude of harm is likely to be high. For example, the relative magnitude of harm H is likely to be high when flying over crowds (Shelley, 2016a), flying contraband into prisons, and flying at airports or near manned aircraft. One policy option, therefore, would be to specify a range of circumstances in which the destruction of drones is permitted.

Consistent with the results of this analysis, the United States has recently enacted legislation to enable defensive actions to be taken against drones that potentially threaten the safety or security of of a broad range of assets or facilities. The National Defense Authorization Act for Fiscal Year 2018 (2017) allows action to be taken against drones that potentially threaten assets or facilities related to national security. The Preventing Emerging Threats Act (2018) enables the Department of Homeland Security, the Department of Justice, and the United States Coast Guard to also take action against drones in a wide range of circumstances. The actions allowed by both pieces of legislation include warning the operator, seizing control of the drone, destroying the drone, and the like.

3.6 Conclusion

The absence of a person on board the drone means that the social cost of a drone being destroyed is relatively low. Coupled with the difficulty of identifying the operator and attributing liability, my analysis demonstrates that it can be efficient to destroy a drone engaged in an activity that causes some form of harm to a bystander.

I analysed three strategic games: a simultaneous game where the drone operator and bystander simultaneously choose their actions; a Stackelberg-like game where the drone operator chooses her activity level and the drone operator responds; and a Stackelberg-like game where the operator commits to a level of self-defence and then the drone operator chooses her level of activity. The numeric analysis shows that the simultaneous game and the game with the bystander as leader have a visually identical policy regime boundary, even though the underlying equilibria may differ. This means that the predictions of the simultaneous model, at least in terms of optimal policy, are also relevant to the case where C-UAS equipment is installed at a particular facility to defend against errant drones even though that scenario is more accurately reflected in the third game with the bystander is leader. The game with the drone operator as leader had a significantly different policy regime boundary, but the practical effect of the change is that when the drone operator is leader there is a much larger area where we are indifferent to whether the destruction of drones is allowed.

The numeric analysis indicates that it can be efficient to destroy a drone if the harm caused is a relatively large fraction of the value derived from the drone activity. For the cases analysed, by inspection that fraction was always above 50 percent. As the cost associated with destruction of the drone increases, the fraction increases and the minimum level of harm at which destruction is allowed may exceed 100 percent of the value derived from the drone activity. For typical consumer drones the analysis supports a policy of allowing the destruction of drones whenever the operation of the drone reduces welfare, assuming that the expected liability of the drone operator is low.

There are a range of situations in which the relative magnitude of harm is likely to be high - such as flying over crowds, flying contraband into prisons, flying at airports or near manned aircraft, flying at critical infrastructure installations, and flying at sites relevant to national security. In all of these contexts the analysis presented in this chapter suggests that it is likely to be efficient to destroy drones in these situations.

My analysis assumes that harm is fixed and exogenously specified, which in turn implies that precaution by the operator is fixed. However, the operator could undertake a variety of forms of precaution such as pilot training, pilot licensing to ensure a minimum level of competence, adopting standard operating procedures to never fly over groups of people, adopting good maintenance practices, and the like. Each of these actions would reduce expected harm and may, in some instances, have a lower social cost than the destruction of a drone. Further research could analyse the effect of allowing the operator to vary her precaution and thereby including harm as an endogenous variable within the framework modelled.

My analysis also suggests that mechanisms for increasing the liability of the drone operator, such as registration, may be appropriate. Registration is analysed in the next chapter.

Appendix 3.A Mathematical Appendix: Simultaneous Model

3.A.1 Derivation of $\hat{s}$

Substituting equation (3.21) into equation (3.22) provides

$$\begin{aligned}
s^*(m,H) &= \left[(1+s^*)^{-n}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)}}[n(1-m)H]^{\frac{1}{n+1}} - 1 \\
\Rightarrow 1+s^* &= (1+s^*)^{\frac{-n}{(n+1)(\alpha-1)}}\left[n(1-m)H\left(\frac{\upsilon - mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}} \\
\Rightarrow (1+s^*)(1+s^*)^{\frac{n}{(n+1)(\alpha-1)}} &= \left[n(1-m)H\left(\frac{\upsilon - mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}} \\
\Rightarrow (1+\hat{s})^{\frac{(n+1)(\alpha-1)+n}{(n+1)(\alpha-1)}} &= \left[n(1-m)H\left(\frac{\upsilon - mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}} \\
\Rightarrow \hat{s} &= \left[(n(1-m)H)^{(\alpha-1)}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)+n}} - 1.
\end{aligned} \tag{3.61}$$

3.A.2 Derivation of $\hat{q}$

If $\hat{s} > 0$ then from equation (3.22) $1+\hat{s} = [n(1-m)Hq]^{\frac{1}{n+1}} \Rightarrow \rho(\hat{s}) = (1+\hat{s})^{-n} = \left[\frac{1}{n(1-m)Hq}\right]^{\frac{n}{n+1}}$. Substituting this expression for $\rho(\hat{s})$ into equation (3.21) and solving for $\hat{q}$ then provides:

$$\begin{aligned}
q^* &= \left[\left(\frac{1}{n(1-m)Hq^*}\right)^{\frac{n}{n+1}}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}} \\
&= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}}\left(\frac{1}{q^*}\right)^{\frac{n}{(n+1)(\alpha-1)}} \\
\Rightarrow \hat{q}^{\frac{(n+1)(\alpha-1)+n}{(n+1)(\alpha-1)}} &= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}} \\
\Rightarrow \hat{q} &= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{\upsilon - mH}{\eta}\right)\right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}}.
\end{aligned} \tag{3.62}$$

3.A.3 $\hat{q}_m$ and $\hat{s}_H$

To establish whether $\hat{q}_m$ and $\hat{s}_H$ have a definite or ambiguous sign, let H_{0q} and H_{0s} denote the value of H for which $\hat{q}_m = 0$ and $\hat{s}_H = 0$ respectively. H_{0i} is *feasible* if it is a value of H for which the operator would choose to fly, which simply requires that $\hat{q}(m, H_{0i}) > 0$. If H_{0i} is feasible then $H < H_{0i}$ and $H > H_{0i}$ are both possible, implying that $\hat{q}_m \lesseqgtr 0$ or $\hat{s}_H \lesseqgtr 0$ as appropriate. If H_{0i} is *not* feasible then $H < H_{0i}$ and $\hat{q}_m$ or $\hat{s}_H$ as appropriate must have a definite sign.

Recall that H_{0q} is the value of H for which $\hat{q}_m = 0$. Therefore:

$$\begin{aligned}
\hat{q}_m = 0 &\Rightarrow {q^*}_s {s^*}_m + {q^*}_m = 0 \\
&\Rightarrow \frac{n}{n+1}(v - mH_{0q}) - (1-m)H_{0q} = 0 \\
&\Rightarrow nmH_{0q} + (n+1)(1-m)H_{0q} = nv \\
&\Rightarrow H_{0q} = \frac{n}{n+1-m}v. \qquad (3.63)
\end{aligned}$$

The parameter η is absent from the expression for H_{0q}, which means that whether H_{0q} is associated with a corner-point solution or an interior solution depends on the specific parameter values.

Assume an interior solution. Then:

$$\begin{aligned}
\frac{v - mH_{0q}}{\eta} &= \left(\frac{1}{\eta}\right) v \left(1 - m\frac{n}{n+1-m}\right) \\
&= \left(\frac{1}{\eta}\right) \frac{(n+1)(1-m)}{n+1-m} v, \qquad (3.64) \\
n(1-m)H_{0q} &= \frac{n^2(1-m)}{n+1-m} v, \text{and} \qquad (3.65) \\
\hat{q}(m, H_{0q}) &= \left[\left(\frac{n+1-m}{n^2(1-m)v}\right)^{\frac{n}{n+1}} \left(\frac{(n+1)(1-m)v}{\eta\,(n+1-m)}\right)\right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}}. \qquad (3.66)
\end{aligned}$$

Feasibility requires that $\hat{q}(m, H_{0q}) > 0$. Signs are: $n + 1 - m \geqslant n > 0$, $n^2(1-m)v \geqslant 0$, and $(n+1)(1-m)v \geqslant 0$, hence $m < 1 \Rightarrow \hat{q}(m, H_{0q}) > 0$ and $m = 1 \Rightarrow \hat{q}(m, H_{0q}) = 0$. Therefore $\hat{q}(m, H_{0q})$ is feasible for $m < 1$ and hence $\hat{q}_m \lesseqgtr 0$.

3.A.4 Lemma 6

From equation (3.18) the sign of $\hat{q}_m$ depends on, and is the same sign as, ${q^*}_s {s^*}_m + {q^*}_m$. From equations (3.6), (3.13), and (3.7) we have:

$$\begin{aligned} {q^*}_s {s^*}_m + {q^*}_m &= \frac{\rho'(s)(v - mH)}{c''(q^*)} . \frac{\rho'(s^*)}{\rho''(s^*)(1-m)} - \frac{\rho(s)H}{c''(q^*)} \\ &= \frac{1}{(1-m)c''(q^*)} \left[\frac{\rho'(s^*)^2 (v - mH)}{\rho''(s^*)} - \rho(s)(1-m)H \right]. \end{aligned} \tag{3.67}$$

Given the assumed functional form for $\rho(s)$:

$$\frac{\rho'(s)^2}{\rho''(s)} = \frac{n^2(1+s)^{-2(n+1)}}{n(n+1)(1+s)^{-(n+2)}} = \frac{n}{n+1}(1+s)^{-n} = \frac{n}{n+1}\rho(s),$$

and hence:

$${q^*}_s {s^*}_m + {q^*}_m = \frac{\rho(s)}{(1-m)c''(q^*)} \left[\frac{n}{n+1}(v - mH) - (1-m)H \right]. \tag{3.68}$$

The term outside the square brackets in the above equation is non-negative. The term inside the square brackets can potentially have either sign.

Let $\alpha = 2, \eta = 1, n = 1, m = 0.5$, and $v = 10$. As I show in the calculations that follow, if $H = 6.67$ then the term in square brackets is zero, if $H < 6.67$ then the term in square brackets is $\geqslant 0$, and if $H > 6.67$ then the term in square brackets is $\leqslant 0$.

Recall that $\alpha = 2, \eta = 1, n = 1, m = 0.5$, and $v = 10$.

$H_{0q} = \frac{n}{n+1-m} v = \frac{10}{1.5} = 6.67$.

Equilibrium activity $\hat{q}$ is given by:

$$\begin{aligned} \hat{q} &= \left[\left(\frac{1}{n(1-m)H_{0q}} \right)^{\frac{n}{n+1}} \left(\frac{v - mH_{0q}}{\eta} \right) \right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}} \\ &= \left[\left(\frac{1}{0.5 \times 6.67} \right)^{\frac{1}{2}} \left(\frac{10 - 0.5 \times 6.67}{\eta} \right) \right]^{\frac{2}{3}} \\ &= \left[\frac{6.67}{\eta\sqrt{3.33}} \right]^{\frac{2}{3}} \end{aligned}$$

Let $\eta = 1$ then $\hat{q} = 2.37 > 0$, hence H_{0q} is feasible.

Let $H = 6$. Then:

$$(n(1-m)H)^{(\alpha-1)}(v - mH) = (0.5 \times 6)^1(10 - 0.5 \times 6) = 21 > \eta,$$

and hence from equation (3.24) we must have an interior solution.

Given an interior solution, equilibrium activity is:

$$\begin{aligned}\hat{q} &= \left[\left(\frac{1}{0.5 \times 6}\right)^{\frac{1}{2}}\left(\frac{10 - 0.5 \times 6}{1}\right)\right]^{\frac{2}{3}} \\ &= \left[\frac{7}{\sqrt{3}}\right]^{\frac{2}{3}} = 2.54.\end{aligned}$$

The sign of ${q^*}_s{s^*}_m + {q^*}_m$, and hence the sign of $\hat{q}_m$ is determined by the sign of the term in square brackets in equation (3.68):

$$\begin{aligned}\frac{n}{n+1}(v - mH) - (1-m)H = \frac{(10 - 0.5 \times 6)}{2} - 0.5 \times 6 = 0.5 > 0 \\ \Rightarrow {q^*}_s{s^*}_m + {q^*}_m \geqslant 0 \\ \Rightarrow \hat{q}_m \geqslant 0.\end{aligned}$$

Now let $H = 7$. Then:

$$\begin{aligned}(n(1-m)H)^{(\alpha-1)}(v - mH) &= (0.5 \times 7)^1(10 - 0.5 \times 7) \\ &= 22.75 > \eta,\end{aligned}$$

and hence from equation (3.24) we must have an interior solution.

Given an interior solution, equilibrium activity $\hat{q}$ is given by:

$$\begin{aligned}\hat{q} &= \left[\left(\frac{1}{0.5 \times 7}\right)^{\frac{1}{2}}\left(\frac{10 - 0.5 \times 7}{1}\right)\right]^{\frac{2}{3}} \\ &= \left[\frac{6.5}{\sqrt{3.5}}\right]^{\frac{2}{3}} = 2.29.\end{aligned}$$

The sign of ${q^*}_s{s^*}_m + {q^*}_m$, and hence the sign of $\hat{q}_m$ is determined by the sign of the term in square brackets in equation (3.68):

$$\begin{aligned}\frac{n}{n+1}(v - mH) - (1-m)H &= \frac{(10 - 0.5 \times 7)}{2} - 0.5 \times 7 = -0.25 < 0 \\ &\Rightarrow {q^*}_s{s^*}_m + {q^*}_m \leqslant 0 \\ &\Rightarrow \hat{q}_m \leqslant 0.\end{aligned}$$

With the term in square brackets having either sign we therefore have $\hat{q}_m \lesseqgtr 0$.

3.A.5 Lemma 7

From equation (3.20) the sign of $\hat{s}_H$ depends on, and has the same sign as, ${s^*}_q {q^*}_H + {s^*}_H$. From equations (3.12), (3.8), and (3.14) we have:

$$\begin{aligned} {s^*}_q {q^*}_H + {s^*}_H &= \frac{-\rho'(s^*)}{\rho''(s^*)q} . \frac{-\rho(s)m}{c''(q^*)} - \frac{\rho'(s^*)}{\rho''(s^*)H} \\ &= \left(\frac{\rho'(s^*)}{\rho''(s^*)}\right) \left[\frac{\rho(s)m}{qc''(q^*)} - \frac{1}{H}\right]. \end{aligned} \tag{3.69}$$

Given the assumed functional form of $c(q)$ it is possible to eliminate the term $qc''(q)$ from equation (3.69). Note that:

$$\begin{aligned} c'(q) = \eta q^{(\alpha-1)} &\text{ and } c''(q) = (\alpha-1)\eta q^{(\alpha-2)} \\ \Rightarrow c'(q) &= \frac{1}{(\alpha-1)} qc''(q). \end{aligned}$$

The operator's FOC therefore can be expressed as:

$$qc''(q) = (\alpha-1)\rho(s)(v - mH).$$

Substituting this expression into equation (3.69) then provides:

$${s^*}_q {q^*}_H + {s^*}_H = \left(\frac{\rho'(s^*)}{\rho''(s^*)}\right) \left[\frac{mH - (\alpha-1)(v-mH)}{(\alpha-1)(v-mH)H}\right]. \tag{3.70}$$

The term in parentheses (.) is negative, and the denominator of the term in square brackets [.] is positive. The sign of ${s^*}_q {q^*}_H + {s^*}_H$ therefore depends on, and is opposite to, the sign of $mH - (\alpha-1)(v-mH)$.

Let $\alpha = 2, n = 1, m = 0.5, v = 10$, and $\eta = 1$ as assumed in the lemma 6. I show in the calculations below that if $H = 10$ then the term in square brackets is zero, if $H < 10$ then the term in square brackets < 0, and if $H > 10$ then the term in square brackets is > 0. With the term in square brackets having either sign we therefore have $\hat{s}_H \lesseqgtr 0$.

Recall from section 3.A.3 that H_{0s} is the value of H for which $\hat{s}_H = 0$. Therefore:

$$\begin{aligned}\hat{s}_H = 0 &\Rightarrow {s^*}_q {q^*}_H + {s^*}_H = 0\\ &\Rightarrow mH_{0s} - (\alpha-1)(v - mH_{0s}) = 0\\ &\Rightarrow H_{0s} = \left(\frac{\alpha-1}{\alpha}\right)\frac{v}{m}. \qquad (3.71)\end{aligned}$$

The parameter η is absent from the expression for H_{0s}, which means that whether H_{0s} is associated with a corner-point solution or an interior solution depends on the specific parameter values.

Assume an interior solution. Then:

$$\frac{v - mH_{0s}}{\eta} = \left(\frac{1}{\eta}\right)\left(\frac{v}{\alpha}\right), \qquad (3.72)$$

$$n(1-m)H_{0s} = n\left(\frac{1-m}{m}\right)(\alpha-1)\left(\frac{v}{\alpha}\right), \text{and} \qquad (3.73)$$

$$\begin{aligned}\hat{q}(m, H_{0s}) &= \left[\left(n\left(\frac{1-m}{m}\right)(\alpha-1)\left(\frac{v}{\alpha}\right)\right)^{\frac{-n}{n+1}}\left(\frac{1}{\eta}\right)\left(\frac{v}{\alpha}\right)\right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}}\\ &= \left[\left(\left(\frac{1}{n}\right)\left(\frac{m}{1-m}\right)\left(\frac{1}{\alpha-1}\right)\right)^{n}\left(\frac{1}{\eta}\right)^{(n+1)}\left(\frac{v}{\alpha}\right)\right]^{\frac{1}{(n+1)(\alpha-1)+n}}. \qquad (3.74)\end{aligned}$$

Feasibility requires that $\hat{q}(m, H_{0s}) > 0$. By assumption, $0 \leqslant m \leqslant 1, n > 0, \alpha \geqslant 2, \text{and} v \geqslant 0$. Therefore $\hat{q}(m, H_{0s}) = 0$ if $m = 0$ or $v = 0$, but is > 0 if $m > 0$ and $v > 0$. Hence H_{0s} is feasible for $m > 0$ and $v > 0$, and $\hat{s}_H \lesseqgtr 0$ under the same conditions.

Recall that $\alpha = 2, n = 1, m = 0.5, v = 10$, and $\eta = 1$. Then $H_{0s} = \left(\frac{\alpha-1}{\alpha}\right)\left(\frac{v}{m}\right) = \left(\frac{1}{2}\right)\left(\frac{10}{0.5}\right) = 10$.

The test for an interior solution is:

$$(n(1-m)H_{0s})^{(\alpha-1)}(v - mH_{0s}) = (0.5\times 10)^1(10 - 0.5\times 10) = 25 > \eta,$$

and hence we have an interior solution.

Given an interior solution, equilibrium activity $\hat{q}$ is given by:

$$\begin{aligned}\hat{q}(m, H_{0s}) &= \left[\left(\frac{1}{0.5 \times 10}\right)^{\frac{1}{2}} \left(\frac{10 - 0.5 \times 10}{1}\right)\right]^{\frac{2}{3}} \\ &= \left[\sqrt{5}\right]^{\frac{2}{3}} = 1.71 > 0,\end{aligned}$$

hence H_{0s} is feasible.

By testing a value of H on each side of H_{0s} we can demonstrate that $\hat{s}_H$ can have either sign.

First, let $H = 8$. Then:

$$\begin{aligned}(n(1-m)H)^{(\alpha-1)}(v - mH) &= (0.5 \times 8)^1(10 - 0.5 \times 8) \\ &= 24 > \eta,\end{aligned}$$

and the equilibrium will be an interior solution.

Given an interior solution, equilibrium activity $\hat{q}$ is given by:

$$\begin{aligned}\hat{q} &= \left[\left(\frac{1}{0.5 \times 8}\right)^{\frac{1}{2}} \left(\frac{10 - 0.5 \times 8}{1}\right)\right]^{\frac{2}{3}} \\ &= \left[\frac{6}{\sqrt{4}}\right]^{\frac{2}{3}} = 2.08 > 0,\end{aligned}$$

and hence $H = 8$ is feasible.

The sign of ${s^*}_q {q^*}_H + {s^*}_H$, and hence the sign of $\hat{s}_H$ is:

$$\begin{aligned}mH - (\alpha - 1)(v - mH) = 0.5 \times 8 - (2-1)(10 - 0.5 \times 8) = -2 < 0 \\ \Rightarrow {s^*}_q {q^*}_H + {s^*}_H > 0 \\ \Rightarrow \hat{s}_H > 0.\end{aligned}$$

Now let $H = 12$. Then:

$$\begin{aligned}(n(1-m)H)^{(\alpha-1)}(v - mH) &= (0.5 \times 12)^1(10 - 0.5 \times 12) \\ &= 24 > \eta,\end{aligned}$$

and the equilibrium will be an interior solution.

Given an interior solution, equilibrium activity $\hat{q}$ is given by:

$$\begin{aligned}\hat{q} &= \left[\left(\frac{1}{0.5 \times 12}\right)^{\frac{1}{2}} \left(\frac{10 - 0.5 \times 12}{1}\right)\right]^{\frac{2}{3}} \\ &= \left[\frac{4}{\sqrt{6}}\right]^{\frac{2}{3}} = 1.39 > 0,\end{aligned}$$

and hence $H = 12$ is feasible.

The sign of ${s^*}_q {q^*}_H + {s^*}_H$, and hence the sign of $\hat{s}_H$ is:

$$\begin{aligned}mH - (\alpha - 1)(v - mH) = 0.5 \times 12 - (2 - 1)(10 - 0.5 \times 12) = 2 > 0 \\ \Rightarrow {s^*}_q {q^*}_H + {s^*}_H < 0 \\ \Rightarrow \hat{s}_H < 0.\end{aligned}$$

Appendix 3.B Mathematical Appendix: Drone Operator as Leader

3.B.1 Equilibrium

The expression for the equilibrium is derived as follows. Solving equation (3.47) for λ provides:

$$\lambda = \frac{\rho'(s)(v - mH)q + \rho'(s)\kappa}{\rho''(s)(1 - m)Hq} \leqslant 0. \tag{3.75}$$

Substituting λ into equation (3.46) yields the tangency condition:

$$\begin{aligned}\rho(s)(v - mH) - c'(q) - \frac{\rho'(s)(v - mH)q + \rho'(s)\kappa}{\rho''(s)(1 - m)Hq}\rho'(s)(1 - m)H = 0 \\ \Rightarrow \rho(s)(v - mH)q - c'(q)q - \frac{\rho'(s)^2}{\rho''(s)}\left[(v - mH)q + \kappa\right] = 0\end{aligned} \tag{3.76}$$

The equilibrium point is obtained by substituting the constraint in equation (3.48) into equation (3.76):

$$\rho(s)(v - mH)q^3 - c'(q)q^3 - \frac{(v - mH)q + \kappa}{\rho''(s)(1 - m)^2 H^2} = 0 \tag{3.77}$$

Without specific functional forms for $c(q)$ and $\rho(s)$ this is not amenable to further solution.

Utilising the functional forms assumed in section 3.3.2, we have:

$$\frac{\rho'(s)^2}{\rho''(s)} = \frac{n^2(1+s)^{-2(n+1)}}{n(n+1)(1+s)^{-(n+2)}} = \left(\frac{n}{n+1}\right)(1+s)^{-n} = \left(\frac{n}{n+1}\right)\rho(s)$$

and therefore the tangency condition becomes:

$$\begin{aligned} \rho(s)(v-mH)q - \eta q^{(\alpha-1)}q - \left(\frac{n}{n+1}\right)\rho(s)\left[(v-mH)q+\kappa\right] = 0 \\ \Rightarrow \rho(s)(v-mH)q\left(\frac{1}{n+1}\right) - \eta q^{\alpha} - \left(\frac{n}{n+1}\right)\rho(s)\kappa = 0 \end{aligned}$$

From the constraint in equation (3.48), for an interior solution we have:[11]

$$\rho(s) = (1+s)^{-n} = \left[n(1-m)Hq\right]^{\frac{-n}{n+1}}. \tag{3.78}$$

Substituting the constraint into the tangency condition then provides the equilibrium as:[12]

$$(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} q^{\left(\alpha+\frac{n}{n+1}\right)} - (v-mH)q + n\kappa = 0. \tag{3.79}$$

---

[11] From the constraint in equation (3.48), the closed form expression for $\rho(s)$ can be derived as:

$$\begin{aligned} \rho'(s)(1-m)Hq + 1 &= 0 \\ \Rightarrow -n(1+s)^{-(n+1)} &= \frac{-1}{(1-m)Hq} \\ \Rightarrow (1+s)^{(n+1)} &= [n(1-m)Hq] \\ \Rightarrow (1+s) &= [n(1-m)Hq]^{\frac{1}{n+1}} \\ \Rightarrow \rho(s) = (1+s)^{-n} &= [n(1-m)Hq]^{\frac{-n}{n+1}}. \end{aligned}$$

[12] The equilibrium is calculated as:

$$\begin{aligned} \rho(s)(v-mH)q\left(\frac{1}{n+1}\right) - \eta q^{\alpha} - \left(\frac{n}{n+1}\right)\rho(s)\kappa &= 0 \\ \Rightarrow \rho(s)\left[(v-mH)q - n\kappa\right] - (n+1)\eta q^{\alpha} &= 0 \\ \Rightarrow [n(1-m)Hq]^{\frac{-n}{n+1}}\left[(v-mH)q - n\kappa\right] - (n+1)\eta q^{\alpha} &= 0 \\ \Rightarrow (n+1)\left[n(1-m)Hq\right]^{\frac{n}{n+1}}\eta q^{\alpha} - (v-mH)q + n\kappa &= 0 \\ \Rightarrow (n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} q^{\left(\alpha+\frac{n}{n+1}\right)} - (v-mH)q + n\kappa &= 0. \end{aligned}$$

3.B.2 Proof of Lemma 12

Differentiating equation (3.49) wrt t and setting equal to zero for the turning point:

$$(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}\left(\alpha(n+1)+n\right)t^{(\alpha(n+1)+n-1)}-(n+1)(v-mH)t^{n}=0. \tag{3.80}$$

There are two solutions to this equation. Let t_{TP} denote the value of t at the turning point. The first solution is $t_{TP}=0 \Rightarrow \hat{q}=0$. Substituting $t=0$ into equation (3.49) requires that $n\kappa=0 \Rightarrow \kappa=0$.

The second solution to the turning point is:

$$t_{TP}{}^{(\alpha(n+1)-1)}=\frac{(v-mH)}{\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}\left(\alpha(n+1)+n\right)}>0. \tag{3.81}$$

The second differential of the equilibrium equation (3.80) wrt t is:[13]

$$(n+1)(v-mH)\left[\alpha(n+1)-1\right]t^{(n-1)}>0. \tag{3.82}$$

The second differential is >0, hence the turning point is a local minimum of the function in t. With the function of t at a local minimum, $n\kappa$ must be at a local maximum so that the equilibrium condition is met.

---

[13] Differentiating equation (3.80) wrt t to obtain the second differential:

$$\begin{aligned}&(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}\left(\alpha(n+1)+n\right)\left(\alpha(n+1)+n-1\right)t^{(\alpha(n+1)+n-1)-1}-n(n+1)(v-mH)t^{(n-1)}\\&\quad=(n+1)\left[\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}\left(\alpha(n+1)+n\right)\left(\alpha(n+1)+n-1\right)t^{(\alpha(n+1)-1)}-n(v-mH)\right]t^{(n-1)}.\end{aligned}$$

Making use of equation (3.81) for $t^{(\alpha(n+1)-1)}$ and simplifying, the second differential becomes:

$$(n+1)(v-mH)\left[\alpha(n+1)-1\right]t^{(n-1)}$$

The value of κ at the turning point is:[14]

$$\kappa = (v - mH)\left(\frac{1}{n}\right)\left[1 - \frac{(n+1)}{(\alpha(n+1)+n)}\right] t_{TP}{}^{(n+1)} > 0. \tag{3.83}$$

If κ exceeds this relevant value then there is no feasible solution to the equilibrium equation (3.80).

3.B.3 Proof of Lemma 13

Lemma 12 demonstrated that there is a maximum value of κ that occurs at a local minimum in the equilibrium function for t, with that minimum occurring at $t > 0$.

Setting $\kappa = 0$ in the equilibrium equation (3.49)

$$\begin{aligned} (n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} t^{(\alpha(n+1)+n)} - (v - mH)t^{(n+1)} &= 0 \\ \Rightarrow \left[(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} t^{(\alpha(n+1)-1)} - (v - mH)\right] t^{(n+1)} &= 0. \end{aligned} \tag{3.84}$$

Let t_{MAX} denote the maximum value of t, which occurs when $\kappa = 0$. One solution to equation (3.84) is $t_{MAX} = 0$. A second solution is provided by:

$$\begin{aligned} (n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} t_{MAX}{}^{(\alpha(n+1)-1)} - (v - mH) = 0 \\ \Rightarrow t_{MAX}{}^{(\alpha(n+1)-1)} = \frac{(v - mH)}{(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}}. \end{aligned} \tag{3.85}$$

This solution is similar to, but not the same as, the expression for the turning point in equation (3.81).

---

[14] Equation (3.49) for the equilibrium can be rewritten as:

$$\left[(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} t^{(\alpha(n+1)-1)} - (v - mH)\right] t^{(n+1)} + n\kappa = 0.$$

Substituting equation (3.81) into the equilibrium then provides:

$$\begin{aligned} \left[(n+1)\eta\left[n(1-m)H\right]^{\frac{n}{n+1}} \frac{(v - mH)}{\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}(\alpha(n+1)+n)} - (v - mH)\right] t^{(n+1)} + n\kappa = 0 \\ \Rightarrow (v - mH)\left[\frac{(n+1)}{(\alpha(n+1)+n)} - 1\right] t^{(n+1)} + n\kappa = 0. \end{aligned}$$

Hence κ at the turning point is:

$$\kappa = (v - mH)\left(\frac{1}{n}\right)\left[1 - \frac{(n+1)}{(\alpha(n+1)+n)}\right] t_{TP}{}^{(n+1)}$$

as shown.

Let:

$$X = \frac{(v - mH)}{\eta\left[n(1-m)H\right]^{\frac{n}{n+1}}}.$$

Then the non-zero values of t_{TP} and t_{MAX} can be expressed as:

$$t_{TP} = \left[\frac{X}{(\alpha(n+1)+n)}\right]^{\frac{1}{\alpha(n+1)-1}} \qquad \text{and} \qquad t_{MAX} = \left[\frac{X}{(n+1)}\right]^{\frac{1}{\alpha(n+1)-1}},$$

hence $t_{TP} < t_{MAX}$ since $(\alpha(n+1)+n) > (n+1)$.

Given the existence of the turning point associated with the maximum value of κ, and the two values of t associated with $\kappa = 0$, every value of κ from zero to the maximum is potentially associated with two values of t: one less than the turning point and one greater than the turning point. At $t < t_{TP}$ an increase in κ would be associated with an increase in the operator's level of activity, but at $t > t_{TP}$ an increase in κ would be associated with a decrease in the operator's level of activity. Assume that the operator first adopts the level of activity at $t < t_{TP}$. At this point the operator can further increase activity, resulting in a direct increase in utility offset by a reduction in probability that the drone will not be destroyed. The operator will continue to increase activity until reaching the higher level of activity at $t > t_{TP}$. The operator therefore chooses an activity level $t > t_{TP}$.

The slope of the curve relating t to κ is downward sloped in the region $t > t_{TP}$, terminating at t_{MAX} when $\kappa = 0$. On this downward-sloped portion of the t curve, an increase in κ increases the cost to the operator if the drone is destroyed. The operator therefore reduces her activity level, which indirectly reduces the bystander's level of self-defence and therefore increases the probability that the drone is not destroyed.

Appendix 3.C Mathematical Appendix: Bystander as Leader

3.C.1 General Form of the Equilibrium

Solving equation (3.56) for λ provides:

$$\lambda = -\frac{\rho(s)(1-m)H}{c''(q)} \leqslant 0. \qquad (3.86)$$

Substituting λ into (3.57) then yields the tangency condition:

$$[\rho'(s)(1-m)H]\,qc''(q)+c''(q)+[\rho'(s)(1-m)H]\,[\rho(s)(v-mH)]=0. \tag{3.87}$$

The equilibrium point is obtained by substituting the constraint from equation (3.58) into equation (3.87):

$$[\rho'(s)(1-m)H]\,[qc''(q)+c'(q)]+c''(q)=0 \tag{3.88}$$

Given the assumed functional form for $c(q)$ the equilibrium can be expressed as:[15]

$$\left([\rho'(s)(1-m)H]\,\alpha q+(\alpha-1)\right)\eta q^{(\alpha-2)}=0. \tag{3.89}$$

One solution is $q=0$. A second solution is provided by:

$$[\rho'(s)(1-m)H]\,\alpha q+(\alpha-1)=0. \tag{3.90}$$

3.C.2 Equilibrium s

Utilising the expression in equation (3.4) for the operator's best response, and the assumed functional form for $\rho(s)$, the equilibrium value of s for an interior solution is:

$$\begin{aligned}
\rho'(s)\left[\rho(s)\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}} &= -\frac{(\alpha-1)}{(1-m)H\alpha}\\
\Rightarrow -n(1+s)^{-(n+1)}\left[(1+s)^{-n}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}} &= -\frac{(\alpha-1)}{(1-m)H\alpha}\\
\Rightarrow (1+s)^{-\left[\frac{(n+1)(\alpha-1)+n}{(\alpha-1)}\right]} &= \left[\frac{(\alpha-1)}{n(1-m)H\alpha}\right]\left(\frac{\eta}{v-mH}\right)^{\frac{1}{\alpha-1}}
\end{aligned}$$

---

[15] Note that $c'(q)=\eta q^{(\alpha-1)}$ and $c''(q)=(\alpha-1)\eta q^{\alpha-2)}$. Then $qc''(q)=(\alpha-1)c'(q)$ and:

$$\begin{aligned}
[\rho'(s)(1-m)H]\,[qc''(q)+c'(q)]+c''(q)&=0\\
\Rightarrow [\rho'(s)(1-m)H]\,[(\alpha-1)c'(q)+c'(q)]+c''(q)&=0\\
\Rightarrow [\rho'(s)(1-m)H]\,\alpha\eta q^{(\alpha-1)}+(\alpha-1)\eta q^{(\alpha-2)}&=0\\
\Rightarrow \left([\rho'(s)(1-m)H]\,\alpha q+(\alpha-1)\right)\eta q^{(\alpha-2)}&=0.
\end{aligned}$$

Hence the equilibrium value of s for an interior solution is:

$$\Rightarrow (1+s)^{-1} = \left[\frac{(\alpha-1)}{n(1-m)H\alpha}\right]^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]} \left(\frac{\eta}{v-mH}\right)^{\left[\frac{1}{(n+1)(\alpha-1)+n}\right]}$$

$$\Rightarrow s = \left[\frac{n(1-m)H\alpha}{(\alpha-1)}\right]^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]} \left(\frac{v-mH}{\eta}\right)^{\left[\frac{1}{(n+1)(\alpha-1)+n}\right]} - 1.$$

3.C.3 Proof of Lemma 17

Differentiating equation (3.59) wrt H provides:

$$\frac{ds}{dH} = \left[\frac{n(1-m)\alpha}{(\alpha-1)}\right]^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]} \cdot \left[\frac{1}{(n+1)(\alpha-1)+n}\right]$$
$$\cdot \left[H^{(\alpha-1)}\left(\frac{v-mH}{\eta}\right)\right]^{\left[\frac{1}{(n+1)(\alpha-1)+n}-1\right]}$$
$$\cdot \left[(\alpha-1)H^{(\alpha-2)}\left(\frac{v-mH}{\eta}\right) - H^{(\alpha-1)}\left(\frac{m}{\eta}\right)\right].$$

The differential ds/dH is the same sign as the last term in square brackets:

$$\left[(\alpha-1)H^{(\alpha-2)}\left(\frac{v-mH}{\eta}\right) - H^{(\alpha-1)}\left(\frac{m}{\eta}\right)\right]$$
$$= \frac{H^{(\alpha-2)}}{\eta}\left[(\alpha-1)(v-mH) - (mH)\right]$$
$$= \frac{H^{(\alpha-2)}}{\eta}\left[(\alpha-1)v - \alpha mH\right].$$

H and η are both positive, so the differential ds/dH has the same sign as $(\alpha-1)v - \alpha mH$. The differential is zero when:

$$(\alpha-1)v - \alpha mH = 0 \Rightarrow H = \frac{(\alpha-1)}{\alpha m}v.$$

If $H < \frac{(\alpha-1)}{\alpha m}v$ then $dH/ds > 0$, but if $H > \frac{(\alpha-1)}{\alpha m}v$ then $dH/ds < 0$.[16]

---

[16] Let $n = 1, \alpha = 2, m = 0.5$, and $v = 10$. Then $ds/dH = 0 \Rightarrow H = \frac{(\alpha-1)}{\alpha m}v = \frac{(2-1)}{2\times 0.5} \times 10 = 10$. By testing a value of H on each side of this value of H we can demonstrate that ds/dH can have either sign.

3.C.4 Proof of Lemma 18

Differentiating equation (3.59) wrt m provides:

$$
\begin{aligned}
\frac{ds}{dm} = {} & \left(\frac{nH\alpha}{\alpha-1}\right)^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]} . \frac{1}{(n+1)(\alpha-1)+n} \\
& . \left[(1-m)^{(\alpha-1)}\left(\frac{v-mH}{\eta}\right)\right]^{\left[\frac{1}{(n+1)(\alpha-1)+n}-1\right]} \\
& . \left[(\alpha-1)(1-m)^{(\alpha-2)}(-1)\left(\frac{v-mH}{\eta}\right)+(1-m)^{(\alpha-1)}\left(\frac{-H}{\eta}\right)\right].
\end{aligned}
$$

All variables are positive hence ds/dm is the same sign as the final term in square brackets:

$$
\begin{aligned}
& \left[(\alpha-1)(1-m)^{(\alpha-2)}(-1)\left(\frac{v-mH}{\eta}\right)+(1-m)^{(\alpha-1)}\left(\frac{-H}{\eta}\right)\right] \\
& \qquad = -\frac{(1-m)^{(\alpha-2)}}{\eta}\left[(\alpha-1)\left(v-mH\right)+(1-m)H\right]
\end{aligned}
$$

The operator's FOC and best response function is the same as in the simultaneous variant of the game, hence from Lemma 1 we have $v-mH>0$. With all variables and terms in the above non-negative, the overall expression is $\leqslant 0$ and $ds/dm \leqslant 0$.

From equation (3.59) the equilibrium value of s is:

$$
\begin{aligned}
s &= \left[\frac{n(1-m)H\alpha}{(\alpha-1)}\right]^{\left[\frac{(\alpha-1)}{(n+1)(\alpha-1)+n}\right]}\left(\frac{v-mH}{\eta}\right)^{\left[\frac{1}{(n+1)(\alpha-1)+n}\right]}-1 \\
&= \left[\frac{0.5\times H\times 2}{1}\right]^{\left[\frac{1}{3}\right]}\left(\frac{10-0.5H}{1}\right)^{\left[\frac{1}{3}\right]}-1 \\
&= \left[H\left(10-0.5H\right)\right]^{\frac{1}{3}}-1.
\end{aligned}
$$

First, let $H=8$. Then $s=\left[H\left(10-0.5H\right)\right]^{\frac{1}{3}}-1=\left[8\left(10-0.5\times 8\right)\right]^{\frac{1}{3}}-1=2.63$.
Now let $H=10$. Then $s=\left[H\left(10-0.5H\right)\right]^{\frac{1}{3}}-1=\left[10\left(10-0.5\times 10\right)\right]^{\frac{1}{3}}-1=2.68$.
Finally, let $H=12$. Then $s=\left[H\left(10-0.5H\right)\right]^{\frac{1}{3}}-1=\left[12\left(10-0.5\times 12\right)\right]^{\frac{1}{3}}-1=2.63$.
The maximum value of s occurs at the point at which $H=\frac{(\alpha-1)}{\alpha m}v=10$, confirming that $ds/dH=0$ at this point, and that s is increasing in H for H below the maximum point but decreasing in H for H below the maximum point.

Appendix 3.D Numerical Analysis for Leader-Follower Models

3.D.1 Drone Operator as Leader

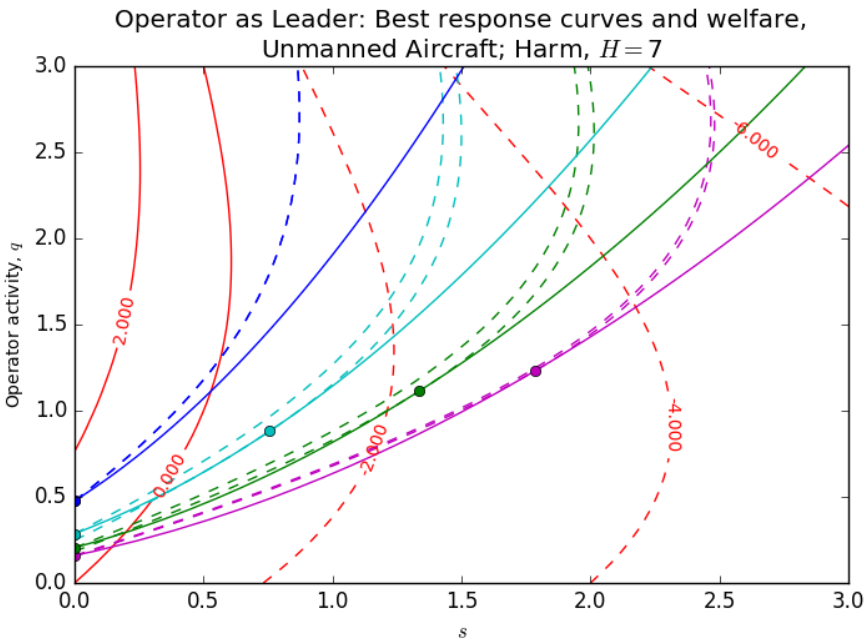
Best Response Curves

The charts in figures 3.9 and 3.10 show the best response curves and equilibria for unmanned aircraft and small manned aircraft respectively. In both cases harm is set at $H = 7$. The dots show the potential equilibria. The red curves are iso-welfare curves, with positive welfare shown by a solid line and negative welfare by a dashed line. The solid coloured (non-red) curves show the bystander's best response curve. The dashed (non-red) lines show the operator's iso-utility curve for the calculated equilibria. The operator's maximisation problem is one of achieving the highest utility possible subject to the bystander's best response. Where multiple utility curves are shown, the upper left utility curve has the higher utility because for a given level of operator activity q the upper left curve implies a lower level of self-defence s, and hence a lower level of losses from the drone being destroyed. For interior solutions the operator's maximum utility will occur at a point of tangency between the operator's utility function and the bystander's best response curve; for corner-point solutions the operator's maximum utility will occur at $s = 0$ on the bystander's best response curve.

Unmanned Aircraft

Figure 3.9 shows the best response curves and potential equilibria for the representative unmanned aircraft. The magenta curves represent $m = 0.1$. There are two potential equilibria on the bystander's best response curve: one at $(s, q) = (0, 0.16)$ and one at $(s, q) = (1.79, 1.23)$. The operator's iso-utility curve for the first potential equilibrium has the value of 1.46. The operator's iso-utility curve for the second potential equilibrium has the value of 1.43 and is tangent to the bystander's best response curve at the equilibrium point. The corner-point solution $(s, q) = (0, 0.16)$ has the higher utility and is therefore the equilibrium point. The operator's utility-maximising equilibrium is also welfare-maximising: welfare at the tangency point is -3.14, but welfare at the equilibrium point is 0.46.

The green ($m = 0.3$) and cyan ($m = 0.5$) curves show a similar pattern: there are two potential equilibria and in each case the corner-point solution at $s = 0$ which has the higher level of operator utility. The blue



Operator as Leader: Best response curves and welfare,
Unmanned Aircraft; Harm, $H = 7$

Iso-welfare curves (red), best-response curves for bystander (solid line), and iso-utility curves for operator (dashed lines). The colour of the curves denotes the proportion of liability, m, borne by the drone operator: magenta, $m = 0.1$; green, $m = 0.3$; cyan, $m = 0.5$; blue, $m = 0.7$. Parameter values are: $\kappa = 3$, $v = 10$.

Figure 3.9. Best response curves and potential equilibria when the Operator is Leader; Unmanned Aircraft, Harm $H = 7$

($m = 0.7$) curves have a single equilibrium point at $(s, q) = (0, 0.48)$ with utility of 2.32. The point $s = 0$ always represents maximum welfare on the bystander's best response curve, so the operator's utility maximising equilibrium is also the welfare maximum. Comparing these equilibria with the equilibria for the simultaneous game clearly illustrates Lemmas 10 and 11.

Manned Aircraft

Figure 3.10 shows the best response curves and potential equilibria for the small manned aircraft. The colour of the curves is as per figure 3.9, i.e. magenta represents $m = 0.1$, green represents $m = 0.3$, cyan represents $m = 0.5$, and blue represents $m = 0.7$. In each case there is a single corner-point solution at $s = 0$. Operator activity is just sufficient to avoid eliciting a self-defence response from the bystander. The low level of activity is welfare optimal given the social costs of harm to the person on board the aircraft if the aircraft was destroyed.

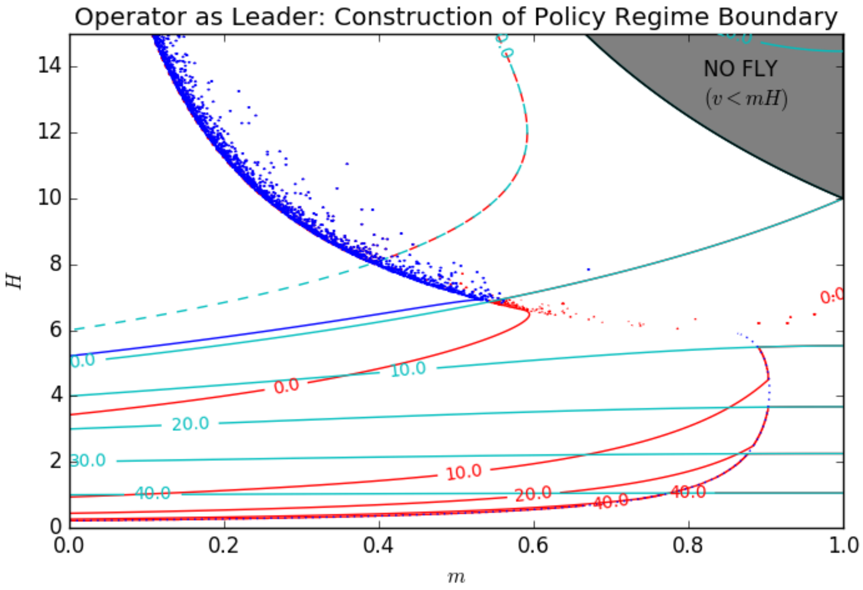
Iso-welfare curves (red), best-response curves for bystander (solid line), and iso-utility curves for operator (dashed lines). The colour of the curves denotes the proportion of liability, m, borne by the drone operator: magenta, $m = 0.1$; green, $m = 0.3$; cyan, $m = 0.5$; blue, $m = 0.7$. Parameter values are: $\kappa = 4115, v = 10$.

Figure 3.10. Best response curves and potential equilibria when the Operator is Leader; Small Manned Aircraft, Harm $H = 7$

Construction of Policy Regime Boundary

Figure 3.11 shows the construction of the policy regime boundary when the drone operator is the leader. The red curves are the welfare curves if destruction is allowed (W^A). The cyan curves are the welfare curves when self-defence is prohibited (W^P). The solid blue curve traces the points of intersection between the two sets of welfare curves and thus represents the policy regime boundary $W^A = W^P$. The dotted blue curve represents the $s = 0$ boundary. The vertical scale in figure 3.11 has been extended from the charts in the earlier figures to provide better visibility of the behaviour of the W^A and W^P curves in the upper left quadrant. The optimal policy in the various regions demarcated by the blue $W^A = W^P$ curves is as follows:

- The upper left portion of the chart bounded by the blue curve is characterised by $W^A > W^P$ so it is optimal to allow the destruction of drones in this region.
- In the middle of the chart, within the $s = 0$ boundary but below the blue curve, the red W^A curve is always below the cyan W^P curve. This indicates that $W^A < W^P$ in this region and it is optimal to prohibit



Construction of policy regime boundary for sequential self-defence model. Red lines are iso-welfare curves for the sequential model. Cyan lines are the iso-welfare curves if self-defence is prohibited. Solid blue lines is the welfare indifference curves. Dotted blue line is the the $s = 0$ boundary.
Parameters are: $v = 10$, $\alpha = 2$, $\eta = 1$, $\kappa = 3$.

Figure 3.11. Operator as Leader: Construction of Policy Regime Boundary from the Iso-Welfare Curves for the Sequential Self-Defence Model and Unconstrained Model

self-defence against drones.

- In the region where $s = 0$, $W^A = W^P$ and we are indifferent to whether destruction of drones is allowed.

3.D.2 Bystander as Leader

Best Response Curves

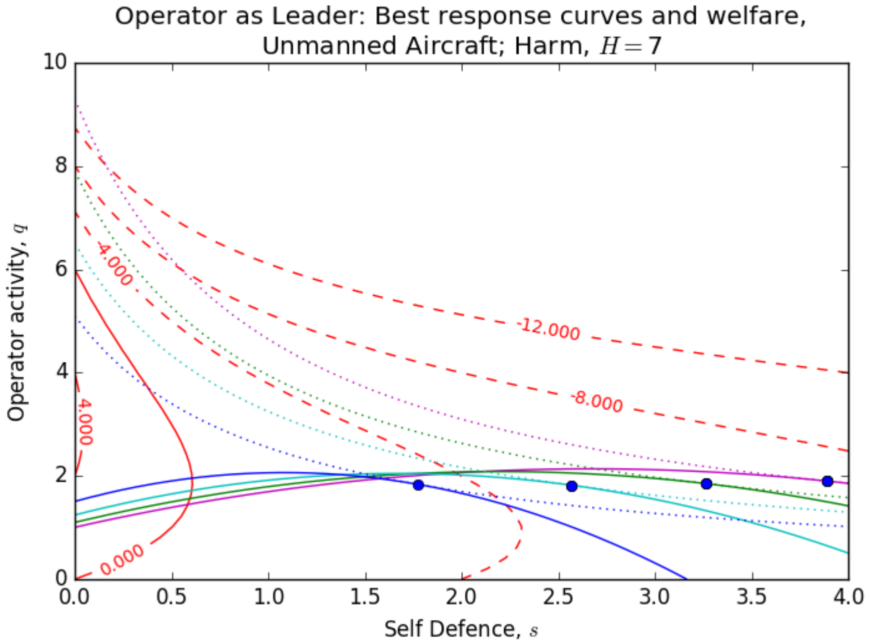
The charts in figures 3.12 and 3.13 show the best response curves and equilibria for unmanned aircraft and small manned aircraft respectively. In both cases harm is set at $H = 7$. The large dots show the equilibria. The dotted lines show the operator's downward-sloping best response curves, which are the same as in figures 3.1 and 3.2. The solid lines show the bystander's iso-cost curves for the calculated equilibria. Each equilibria occurs at the point of tangency between the bystander's iso-cost curve and the operator's best response curve.

The colour of the curves in figures 3.12 and 3.13 is as per figures 3.9

and 3.10, i.e. magenta represents $m = 0.1$, green represents $m = 0.3$, cyan represents $m = 0.5$, and blue represents $m = 0.7$.

Unmanned Aircraft

Figure 3.12 shows the best response curves and potential equilibria for the representative unmanned aircraft. The equilibria occur at $(s, q) = (3.89, 1.90)$ for $m = 0.1$, $(s, q) = (3.26, 1.85)$ for $m = 0.3$, $(s, q) = (2.57, 1.82)$ for $m = 0.5$, and $(s, q) = (1.78, 1.84)$ for $m = 0.7$. In all cases operator activity is restricted to $\hat{q} < 2$. Welfare is negative, but by a relatively small amount. Welfare increases (becomes less negative) as the proportion of liability borne by the operator, m, increases.

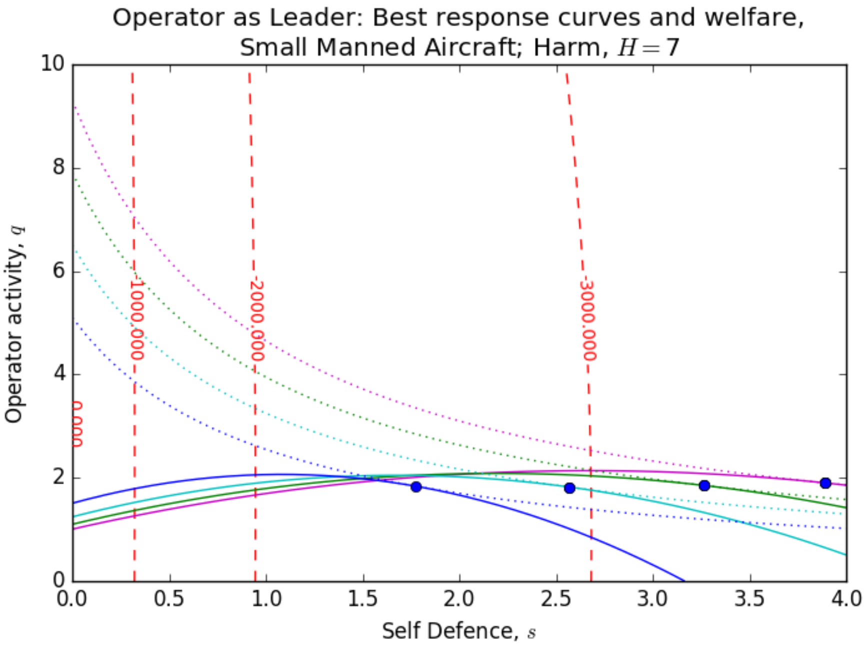

Operator as Leader: Best response curves and welfare, Unmanned Aircraft; Harm, $H = 7$

Iso-welfare curves (red), iso-cost curves for bystander (solid line), and best response curves for operator (dotted lines). The colour of the curves denotes the proportion of liability, m, borne by the drone operator: magenta, $m = 0.1$; green, $m = 0.3$; cyan, $m = 0.5$; blue, $m = 0.7$. Parameter values are: $\kappa = 3, v = 10$.

Figure 3.12. Best response curves and potential equilibria when the Bystander is Leader; Unmanned Aircraft, Harm $H = 7$

Manned Aircraft

Figure 3.13 shows the best response curves and potential equilibria for the small manned aircraft. The equilibria again occur at $(s, q) = (3.89, 1.90)$ for $m = 0.1$, $(s, q) = (3.26, 1.85)$ for $m = 0.3$, $(s, q) = (2.57, 1.82)$ for $m = 0.5$, and $(s, q) = (1.78, 1.84)$ for $m = 0.7$. These are exactly the same equilibria as occurred for the unmanned aircraft; this result arises because $\kappa = \kappa_1 + \kappa_2$ is absent from equation (3.59). Welfare is negative and of a relatively large magnitude. As with the unmanned aircraft case, welfare but increases (becomes less negative) as operator liability for harm, m, increases.



Iso-welfare curves (red), iso-cost curves for bystander (solid line), and best response curves for operator (dotted lines). The colour of the curves denotes the proportion of liability, m, borne by the drone operator: magenta, $m=0.1$; green, $m=0.3$; cyan, $m=0.5$; blue, $m=0.7$. Parameter values are: $\kappa=4115, v=10$.

Figure 3.13. Best response curves and potential equilibria when the Bystander is Leader; Small Manned Aircraft, Harm $H = 7$

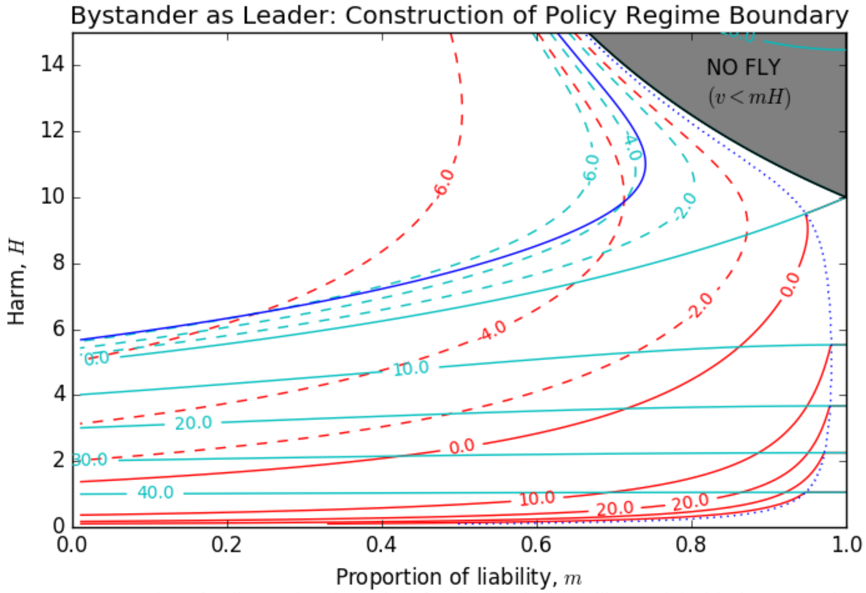
Construction of Policy Regime Boundary

Figure 3.14 shows the construction of the policy regime boundary. The red curves are the iso-welfare curves if destruction is allowed (W^A). The cyan curves are the iso-welfare curves when self-defence is prohibited (W^P). The solid blue curve traces the points of intersection between the two sets of welfare curves and thus represents the policy regime boundary $W^A = W^P$. The dotted blue curve represents the $s = 0$ boundary.

The vertical scale in figure 3.14 has been extended from the charts in the earlier figures to provide better visibility of the behaviour of the W^A and W^P curves in the upper left quadrant. The optimal policy in the various regions demarcated by the blue $W^A = W^P$ curves is as follows:

- The upper left portion of the chart bounded by the solid blue curve is characterised by $W^A > W^P$ so it is optimal to allow the destruction of drones in this region.

- In the middle of the chart, within the $s = 0$ boundary but below the blue curve, the red W^A curve is always below the black W^P curve. This indicates that $W^A < W^P$ in this region and it is optimal to prohibit self-defence against drones.
- In the region where $s = 0$, $W^A = W^P$ and we are indifferent to whether destruction of drones is allowed.



Construction of policy regime boundary for the Stackelberg-like model with the Bystander as leader. Red lines are iso-welfare curves if self defence is allowed. Cyan lines are the iso-welfare curves if self-defence is prohibited. The solid blue line is the policy regime boundary. The dotted blue line is the $s=0$ boundary.
Parameters are: $v=10$, $\alpha=2$, $\eta=1$, $\kappa=3$.

Figure 3.14. Bystander as Leader: Construction of Policy Regime Boundary from the Iso-Welfare Curves for the Sequential Self-Defence Model and Unconstrained Model

Appendix 3.E Data

This appendix provides tabular data referred to elsewhere in this chapter.

Table 3.3

Aircraft listed for sale on TradeMe website, 22 July 2017

Aircraft	Category	Price
R44 Raven 2	Helicopter	$280,000
R44 Raven 2. (Or Engine)	Helicopter	$130,000
AS350B3+ 2009	Helicopter	$1,950,000
RagWing RW-1 Ultrapiet	Microlight Class 1	$6,000
Avid Heavy Hauler Mark IV	Microlight Class 2	$36,000
Nesmith Cougar	Microlight Class 2	$45,000
Rans S6	Microlight Class 2	$35,000
Jabiru SP500 Aircraft	Microlight Class 2	$32,500
Cessna 172S	Aeroplane	$150,000
Robinson R44 Raven II	Helicopter	$265,000
1995 Bell 206 L4	Helicopter	$1,300,000
1975 PIPER PA31-350 CHIEFTAIN	Aeroplane	$295,000
Partenavia P68 C 1985	Aeroplane	$95,000
2006 Cirrus SR22 GTS	Aeroplane	$400,000
Rutan Vari Eze	Amateur Built Aeroplane	$28,000
1978 Piper Arrow 3	Aeroplane	$110,000
BULLDOG MK-1	Aeroplane	$79,900
Glider LS3	Glider	$42,000
Jabiru SK80 Microlite DAM	Microlight Class 2	$30,000
Dynamic WT9	Microlight Class 2	$150,000
RV-4 ZK-JRX	Amateur Built Aeroplane	$45,000
Tecnam P2002 RG	Aeroplane	$120,000
Piper Seneca 2	Aeroplane	$110,000
BELL 47G 3B1	Helicopter	$260,000
1975 Pacific Aerospace CT4-A	Aeroplane	$125,000
2012 Robinson R44 Raven II. ZK-ICP	Helicopter	$549,000
Piper PA32-R 'Lance'	Aeroplane	$155,500
Piper Navajo	Aeroplane	$150,000
1962 Cessna 172 C	Aeroplane	$65,000
1974 Hughes 500C	Helicopter	$420,000

Table 3.3

Aircraft listed for sale on TradeMe website, 22 July 2017

Aircraft	Category	Price
Magni Gyro M22	Gyroplane	$89,800
A150M cessna 150 hp	Aeroplane	$46,000
Bantam B22	Microlight Class 2	$8,000
R22 Beta II	Helicopter	$145,000
Alpi Pioneer 200	Microlight Class 2	$88,000
Foxcon Terrier	Microlight Class 2	$42,500
Cessna 172N	Aeroplane	$59,000
Searey Amphibian	Aeroplane	$79,000
Thorp S-18T ZK-MBY	Amateur Built Aeroplane	$57,500
Robinson Raven II ZK IKH	Helicopter	$455,000
Zlin Shock Cub New.	Microlight Class 2	$175,000
Robinson R44 Raven II	Helicopter	$285,000
SAFARI S22 HELICOPTER	Helicopter	$130,000
Robinson R44 Raven II - 2004	Helicopter	$525,000
Robinson R44 Raven II	Helicopter	$190,000
CYGNET CLASS 2 DUAL CONTROL MICROLIGHT	Microlight Class 2	$40,000
Karrotoo J6C Microlight	Microlight Class 2	$73,000
FANTASY AIR ALLEGRO 2000	Microlight Class 2	$72,000
ONE Aircraft (LSA Two Seat or GA Four Seat) New.	Microlight Class 2	$195,000
Trike (Pegasus XLQ)	Microlight Class 1	$8,500
H125 (B)	Helicopter	$750,000
EC130B4	Helicopter	$2,300,000
Percival Piston Provost T Mark 1 (1954)	Aeroplane	$80,000
Piper Cub	Aeroplane	$50,000
1971 Piper PA -28-180	Aeroplane	$69,500
Airborne Edge X 582 injected	Microlight Class 2	$23,000
Socata TB9 Tampico	Aeroplane	$52,000
Thatcher CX4 ZK-JDY	Microlight Class 1	$35,000
Cessna 150H	Aeroplane	$37,500
SOCATA TAMPICO TB 9	Aeroplane	$39,000
- STORCH - FlySynthesis	Microlight Class 2	$69,990

Table 3.3

Aircraft listed for sale on TradeMe website, 22 July 2017

Aircraft	Category	Price
Z Max Microlight	Microlight Class 1	$8,000
Bantam B22	Microlight Class 2	$9,995
CFM Shadow	Microlight Class 2	$9,995
Rihn DR-107	Amateur Built Aeroplane	$140,000
RANS S-6ES Taildragger ZK-VIN	Microlight Class 2	$32,000
Auster J1B	Aeroplane	$53,000
Robinson R44 Raven 2, ZK-ITH	Helicopter	$350,000
Pegasus Quantum 912	Microlight Class 2	$45,000
Magni Gyro M24 Orion New.	Gyroplane	$156,570
Nieuport 17 Microlight	Microlight Class 1	$15,000
Pitts Special S1 Aerobatics Airplane	Aeroplane	$50,000
Piper Tri Pacer PA22 with 180 Hp engine.	Aeroplane	$4,050
Quad City Challenger 2	Microlight Class 2	$13,000
Auto Gyro MTO Sport Microlight New.	Gyroplane	$99,000
Mooney Ranger 1978	Aeroplane	$100,000
Guimbal Cabri G2 Helicopter	Helicopter	$454,000
VPM Gyrocopter/Gyroplane	Gyroplane	$49,000
Quad City Challenger II	Microlight Class 2	$29,995
Ultravia Pelican Club VS	Microlight Class 2	$39,000
Cessna 172RG Cutlass	Aeroplane	$75,000
Cessna 172RG Cutlass	Aeroplane	$102,350
R22 Beta Helicopter HRD	Helicopter	$165,000
Falco F8L	Amateur Built Aeroplane	$110,000
C182 300HP	Aeroplane	$195,000
Airtourer 115	Aeroplane	$50,000
Hughes 269A - 1965	Helicopter	$150,000
SILENT IN Self Launching Sailplane	Glider	$46,000
Piper Pawnee 260	Aeroplane	$105,000
Sirocco MJ5	Amateur Built Aeroplane	$35,000

Table 3.3

Aircraft listed for sale on TradeMe website, 22 July 2017

Aircraft	Category	Price
Foxcon Terrier 200	Microlight Class 2	\$38,000
Gyrocopter	Gyroplane	\$13,000
Cessna 172RG Cutlass	Aeroplane	\$70,000
Rand KR2 Microlight	Amateur Built Aeroplane	\$15,000
Pitts S2A	Aeroplane	\$65,000
TRI-PACER PA-22/150	Aeroplane	\$5,000
Rans S20	Microlight Class 2	\$115,000
Fleet 16B Finch	Aeroplane	\$115,000
Phoebus C 17mtr	Glider	\$8,500

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Chapter 4

Registration of Drones[1]

Synopsis

This essay considers whether registration alone can be an adequate means of controlling the potential harms associated with drones, and if so the circumstances in which that will be true.

4.1 Introduction

On 19-21 December 2018 one or more drones flew over Gatwick Airport and its runways, causing the airport to be closed for almost 33 hours at one of the busiest times of the year for air travel, resulting in the cancellation of approximately 800 flights, and disrupting travel for approximately 120,000 people (Baylis, Stickings & Fielding, 2018; Topham, Weaver & Siddique, 2018). The drone flights reportedly ceased at around 10pm on the 20 December 2018 (Baylis et al., 2018), with two people being arrested shortly after 10pm (Sussex Police, 2018a). The airport was reopened at 6am on 21 December with no drones having been detected during the night. Operations were further halted for just over an hour at 5:10pm on 21 December after a report of another drone (Topham & Perraudin, 2018). The two people arrested were released without charge on 23 December, no longer suspects in the inquiry (Sussex Police, 2018b).

Following the Gatwick incident the British Airline Pilots' Association called for an existing 1km exclusion zone around airports to be extended to 5km, and for "registration and licensing of operators so that the police can track and trace drones" (Topham et al., 2018).

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[1] Parts of this chapter were first published as Shelley (2019) 'Registration will not prevent another Gatwick', *Working Paper*, Victoria University of Wellington. The relevant parts are: portions of section 4.1, all of section 4.2.2, and section 4.3.

In New Zealand, there were at least nine incidents in 2018 where small drones have either closed airports or required manned aircraft to adopt precautionary procedures.[2] In the first hour of 2019 a drone came within 10m of the Police 'Eagle' helicopter "at just under 1400 feet" over central Auckland. The helicopter pilot took evasive action and the Eagle helicopter operations were suspended for the rest of the night (New Zealand Police, 2019). Another helicopter pilot has reported encountering three drones over central Auckland while filming the New Year's fireworks display (Smith, 2019).

Following the incidents in early 2018 there were calls from Airways New Zealand (Fonseka, 2018) and the New Zealand Airline Pilots Association (Hatton, 2018; Strang, 2018) for drones to be registered, and from New Zealand's major airline for stronger penalties (Fonseka, 2018). Airways New Zealand and the New Zealand Airline Pilots Association repeated their calls after the Gatwick incident, with Airways New Zealand specifically calling for "mandatory registration of all drones, ... certification and training for pilots, and ... the ability to track drones either through software or hardware on the drone itself" (RNZ, 2018b).

This essay analyses the effectiveness of drone registration for reducing the harmful effects of drones to third parties. I specifically consider the question of whether registration would avoid incidents such as the Gatwick incident.

Registration and licensing are used to protect property rights, such as

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[2] On 6 March 2018 a drone was observed in airspace near the approach path for aircraft landing at Auckland International Airport. Approximately 20 aircraft entered a holding pattern while air traffic control halted operations for 30 minutes, and a Boeing 777 aircraft arriving from Japan diverted 500km to Ohakea airbase to refuel (NZ Herald, 2018a). Less than three weeks later, on 25 March 2018, a drone approached to within approximately 5 metres of another Boeing 777 aircraft landing at Auckland International Airport (Lawrence, 2018). On 6 April 2018 a drone was seen at 1200ft above ground three nautical miles from Auckland International Airport, resulting in 7 flights being delayed (Boyle, 2018). Three days later, on 9 April 2018, operations at Whenuapai air force base were suspended when a drone came within 60m of a helicopter flying at 3,000ft above ground (NZ Herald, 2018c). On 23 April 2018 a passenger flight was delayed at Tauranga because of a drone seen 1.6km from the end of the runway (Motion, 2018). On 9 August 2018 five flights at Auckland International Airport were delayed when a drone was observed by the pilot of a Dash-8 aircraft (NZ Herald, 2018b). On 11 November 2018, controlled airspace at Wellington Airport was closed for 30 minutes when a drone was seen operating at 600ft above ground 3km from the end of the runway (Radio New Zealand [RNZ], 2018a). On 6 December 2018 Queenstown airspace was closed for 15 minutes when a drone passed in front of an airliner at about 3000ft above ground less than 4km from Queenstown Airport (Hudson, 2018). Three days later, on 9 December 2018, Queenstown airspace was again closed for 15 minutes when a drone was reported flying at 1000ft less than 4km from Queenstown Airport (Hudson, 2018).

through land ownership registration, and to control a wide range of potential negative externalities. Negative externalities may arise from undertaking an activity with insufficient care or skill, and thus one form of licensing and registration is limiting the right to undertake an activity that could harm third parties: this may be applied to individuals (for example, motorists, medical practitioners, and pilots) or organisations (for example, childcare centres and passenger transportation by almost any mode of transportation). Negative externalities may also arise from the use of physical objects, such as firearms. Registration of objects may also enable the detection and attribution of harmful behaviour by individuals. For example, the registration of motor vehicles increases the ability to attribute potentially harmful driving to the driver. Consider, for example, a speed camera. In the first instance, excessive speed is attributed to the owner of the motor vehicle. If it was not the owner driving, and assuming that the motor vehicle is used with the permission of the registered owner, the owner should then know who was the driver at the time of excessive speed.

At this point it is helpful to clarify nomenclature. The term "personnel licensing" denotes that a person has passed a test or examination and has at least a minimum required level of knowledge or competence. Personnel licensing includes licensing for both activities and occupations. The term "registration" may be used in relation to an object, such as an aircraft or a motor vehicle, and may be coupled with minimum standards, such as a warrant of fitness for a motor vehicle. Registration may also be used for occupations (for example, Registered Medical Practitioners and Registered Master Builders), in which case registration is the same as personnel licensing.

The term "certification" can have different meanings in different bodies of literature. In the economics literature, the term certification is typically used to refer to a system where consumers are provided with information on the training or competence level of the individual (Shapiro, 1986), and thus is equivalent to licensing. In the aviation literature, certification is used to describe the licensing of organisations. In this chapter I adopt the aviation definition of certification. Finally, "licensing" can be viewed as an umbrella term covering personnel licensing, registration, and certification.

From an economic perspective, safety can be regarded as being analogous to a product attribute such as quality, although the consequences of inadequate safety may be more significant than other aspects of quality

(Savage, 2013), particularly in aviation where the consequence of inadequate safety may be multiple fatalities. When quality is important to consumers but is unobservable to them, licensing can raise total surplus (Shapiro, 1986). Thus licensing is used across a wide range of situations where there is a safety risk to consumers and third parties.

In section 4.2, I discuss relevant aspects of existing aviation regulation. Section 4.2.1 describes the application of licensing and registration within the civil aviation regulatory system. Section 4.2.2 describes the existing approach to regulating drones in both New Zealand and the United States.

Proponents of drone registration suggest that it will significantly aid the identification of drone operators that are involved in unsafe activities such as flying a drone in close proximity to airliners (see, for example, Hatton, 2018; RNZ, 2018b; Topham et al., 2018). For this proposition to be true requires that (a) the drone is detected, (b) an identifier carried by the drone is "read", and (c) the identifier is on a register of drones that link the drone back to an operator. In Section 4.2.2, I discuss the application of drone registration in the United States of America, which has a register of drones, but lacks the remotely readable identifier that would make the registration regime effective.

In section 4.3, I describe existing identification technologies which provide a means of remote identification, including "secondary surveillance systems" and ADS-B, and DJI's 'Aeroscope' system. In section 4.4, I present a formal model of drone registration to analyse the conditions under which the registration of drones is more efficient than the status quo. The solution to the formal analytical model is sufficiently complex that numeric analysis, presented in section 4.5, is required. A key assumption in the analysis is the form of the function representing the probability of identifying the drone absent registration. I assume a logistic function that has the characteristics of the probability of identification increasing with both activity and drone weight. The analysis then identifies when registration is more efficient than the status quo, for differing assumptions about the length of time spent within range of a technology that able to 'read' or a remotely readable identifier carried by a drone that is registered. Section 4.6 discusses the results of the analysis, and section 4.7 provides conclusions.

4.2 Aviation Regulation

I first review the use of licensing and regulation within the civil aviation regulatory system, and then consider in more detail the regulation of drones. Civil aviation is governed by the 'Convention on International Civil Aviation' (1944) and associated annexes, so civil aviation regulation is consequently very similar across countries. I describe civil aviation regulation in New Zealand, but the framework is very similar to that employed in other countries, to the extent that the majority of rule "Parts" even have the same number between countries. For example, Civil Aviation Rule Part 61 in New Zealand covers the same subject matter as 14 CFR Part 61 in the United States (both cover pilot licensing). The regulation of drones is not as mature as the regulation of other aspects of civil aviation, with significant country-specific differences. These differences are illustrated by a comparison of drone regulation in New Zealand and the United States.

4.2.1 Licensing and Registration within the Civil Aviation Regulatory System

Within the aviation industry generally, latent safety levels are unobservable to consumers, and even to many people within the aviation system. How does one know, for example, whether maintenance on an aircraft has been conducted to an appropriate standard? Much of the body of civil aviation regulation can therefore be understood as welfare-enhancing licensing.

Licensing as broadly defined is effectively employed in each of the following three main areas:

- personnel, governing the entry of personnel into specific occupations within the aviation sector;
- aircraft, governing whether an aircraft is considered "airworthy" and able to fly; and
- organisations, governing the entry of organisations into the aviation sector.

Personnel Training and Licensing

All personnel involved in the civil aviation system must be trained, and most must be licensed or otherwise authorised to conduct their duties.

The most obvious role requiring training and licensing is that of the pilot. Pilot licensing is governed by Civil Aviation Rules Part 61 *Pilot Licences and Ratings* [CAR Part 61 (2018)]. Pilots flying for their own private purposes must hold a “Private Pilot License” (PPL), which requires a minimum of 50 hours flight time both under the supervision of an instructor and solo, classroom training, passing a number of specified exams, and passing a flight test administered by a Flight Examiner.

Air operations for the carriage of people or goods for hire or reward require a minimum of a Commercial Pilot Licence (CPL), which has a greater experience requirement than a PPL (a minimum 200 hours flight time), stricter flight test standards, and more advanced knowledge requirements. Pilots of agricultural aircraft have an experience requirement equivalent to that of a CPL, but with a specialised programme of training and instruction. Pilot licenses are endorsed with a “Type Rating” indicating that, following an appropriate course of instruction, the pilot has demonstrated competence in flying a particular make and model (“Type”) of aircraft. Flight instructors must have a minimum of a CPL, undergo an additional programme of classroom and practical training, and obtain a flight instructor rating. Pilot licenses and ratings, and Flight Instructor ratings, can only be obtained after assessment but an appropriately qualified and rated Flight Examiner.

The second major functional area requiring licenses or authorisation is that of the maintenance engineers. Traditionally maintenance was always conducted by, or under the supervision of, a Licensed Aircraft Maintenance Engineer (LAME). A LAME has received training, been assessed as competent, and passed detailed examinations as occurs with other engineering trades. The engineer is then issued with a license under Civil Aviation Rules Part 66 *Aircraft Maintenance Personnel Licensing* [CAR Part 66 (2018)]. Some maintenance activities can only be conducted by an organisation certified under Civil Aviation Rules Part 145 *Aircraft Maintenance Organisations – Certification* [CAR Part 145 (2018)]. Not all engineering personnel employed by an Aircraft Maintenance Organisation (“AMO”) are required to be LAMEs; instead, the AMO has the delegated authority to approve personnel to perform particular maintenance activities, with final approval by a LAME. The Part 145 AMO must also have an approved quality assurance system to ensure that personnel only conduct maintenance activities within the scope of their authorisation and in accordance with documented procedures.

Similar to the above, Flight Engineers are issued licenses and ratings under Civil Aviation Rules Part 63 *Flight Engineer Licences and Ratings* [CAR Part 63 (2006)], and Air Traffic Controllers are licensed under Civil Aviation Rules Part 65 *Air Traffic Service Personnel Licences and Ratings* [CAR Part 65 (2015)]. Civil Aviation Rules Part 67 *Medical Standards and Certification* [CAR Part 67 (2007)] specifies the detail of the medical requirements for licenses issued under Parts 61, 63, and 65. Notwithstanding the licenses issued under the listed rule parts, certified operators are required to establish programmes for recurrent training of personnel and ensuring their ongoing competence. Certified operators are also authorised to train and assess the competence of persons performing other functions such as Cabin Crew, flight despatch, ground handling, etc.

Aircraft Airworthiness

An aircraft is deemed to be airworthy if it is capable of safe flight. The process of ensuring airworthiness starts with type certification for the aircraft design, issuance of a certificate of airworthiness for a specific aircraft to ensure that it conforms to the design specified in the type certificate, a programme of inspection and maintenance to ensure that aircraft components remain airworthy, and a periodic "Review of Airworthiness" to ensure that the aircraft remains compliant with the type design.

The type certification process starts with approval of the engineering design of an aircraft, followed by a series of inspections to ensure that the aircraft as built conforms to the engineering design. The aircraft is then issued an experimental certificate to allow it to undergo a programme of test flying. When the experimental aircraft has successfully demonstrated safe flight under normal and abnormal conditions, and over a sufficiently long test flying programme, the design is issued with a Type Certificate. Rules concerning Type Certificates, including experimental certificates, are specified in Civil Aviation Rules Part 21 *Certification of Products and Parts* [CAR Part 21 (2017)].

Civil aviation regulators may issue "Technical Standard Orders" (TSO) specifying the minimum standards that particular aircraft components must comply with. A component that is certified as compliant with a TSO is then an airworthy component. The process of type certification is made less onerous if aircraft manufacturers utilise components that have been certified as compliant with a TSO. As at 24 December 2018, the Civil

Aviation Authority of New Zealand has two current TSOs (Civil Aviation Authority of New Zealand [NZCAA], n.d.), whereas the Federal Aviation Administration in the United States has 174 current TSOs (Federal Aviation Administration [FAA], n.d.).

Components may fail while an aircraft is in service, in which case the affected part must be replaced. In the worst case, however, failure of a safety-critical component while the aircraft is in flight could result in a crash. To avoid the situation where a safety-critical component fails in flight, the type design may have redundant (duplicate) systems, and there will always be a specified programme of inspections, preventive maintenance, and replacement of components at specified intervals. Inspections are aimed at identifying problems with components or structures (e.g. the airframe) before a failure occurs; maintenance and scheduled replacement of components is also aimed at ensuring components are repaired, maintained, or replaced before a failure occurs. Manufacturer's inspection and maintenance schedules are required as part of the documentation that accompanies type certification, and detailed rules concerning the process of conducting maintenance are specified in Civil Aviation Rules Part 43 *General Maintenance Rules* [CAR Part 43 (2018)].

An aircraft that is maintained according to an approved inspection and maintenance programme should remain in an airworthy state. However, for a variety of reasons the aircraft may have defects which have not been rectified, or unauthorised modifications may have been made. To reduce the chance of this affecting the airworthiness of the aircraft a Review of Airworthiness is conducted by an independent engineer. The Review of Airworthiness checks that the aircraft continues to comply with the specifications in the Type Certificate as well as the general condition of the aircraft (CAR Part 43, rule 43.153). A Review of Airworthiness is conducted every 24 months for privately operated aircraft, but every 12 months for aircraft used on operations for hire or reward (CAR Part 91, rule 91.615).

Organisational Licensing

In most instances it is not sufficient for an organisation to employ personnel who hold the appropriate licence for their occupation; the organisation itself must hold a licence to legally conduct the relevant activities on a commercial basis. Some of the more significant parts of the aviation industry to which organisation licensing requirements apply are: passenger transport (CAR Part 119); “Adventure Aviation” (CAR Part 115); agricultural aircraft operations (CAR Part 137); air traffic control (CAR Part 172); certain specified training and competency assessments (CAR Part 141 and CAR Part 147); some maintenance activities (CAR Part 145); aircraft and component design (CAR Part 146) and manufacturing (CAR Part 148). In each case the relevant Part of the Civil Aviation Rules specifies a set of requirements that the organisation must meet, including: required senior positions within the organisation, personnel training and competency assessment, requirements for records to be kept, quality assurance requirements, and requirements for management of fatigue. The organisation is required to prepare an “exposition” that specifies how it will meet the requirements prescribed in the relevant CARs. The operator is then audited against their compliance with the exposition.

One notable exception to organisational licensing occurs with maintenance. All maintenance must be conducted in accordance with the provisions of CAR Part 43. Some of that maintenance can be conducted by a LAME in an unlicensed organisation; but some more advanced maintenance tasks may only be conducted under the authority of a license issued to a Part 145 Aircraft Maintenance Organisation.

4.2.2 Regulation of Drones

Drones have historically been afforded very limited regulation on the basis that the aircraft were small and relatively unlikely to cause harm to people other than those operating them, or otherwise were flown at designated model aircraft flying sites. Those rules are now being expanded to accommodate a wider range of circumstances. In this section I review key provisions of the regulations that apply in New Zealand and in the United States, with a focus on both rules that act to minimise harm and rules that impose licensing or registration requirements.

In New Zealand the operation of drones is governed by Civil Aviation Rules Part 101 *Gyrogliders and Parasails, Unmanned Aircraft (including Balloons), Kites, and Rockets - Operating Rules* [CAR Part 101 (2015)], as well as by workplace safety regulation if work is being conducted.

In the United States there is a clear demarcation between recreational and commercial operation of a drone. Recreational operation is governed by 14 CFR Part 101 *Moored Balloons, Kites, Amateur Rockets, Unmanned Free Balloons, and Certain Model Aircraft* [14 CFR Part 101 (2012)], whereas commercial operation is governed by 14 CFR Part 107 *Small Unmanned Aircraft Systems* [14 CFR Part 107 (2016)].

The Legal Standard of Care in New Zealand

A person operating a drone is required to "take all practicable steps to minimise hazards to persons, property and other aircraft" [CAR 101.13]. This requirement provides a direct link between the required standard of precaution and the requirements of the repealed Health and Safety in Employment Act 1992. In *Attorney General v Gilbert* at [83], the New Zealand Court of Appeal held that the obligation to take all practicable steps "requires reasonable steps which are proportionate to known and avoidable risks". This suggests a standard in which cost can be weighed equally against risk, and thus is equivalent to the Hand Rule of negligence.

Commercial drone operators, who are by definition conducting work, are also subject to the Health and Safety at Work Act 2015. This legislation imposes the obligation to take "reasonably practicable" to control risks, which requires that hazard controls are implemented unless cost is grossly disproportionate to the risk. Grossly disproportionate is clearly much greater than the proportionate factor in *Attorney General v Gilbert*, so the standard imposed by the Health and Safety at Work Act 2015 is more stringent than the "all practicable steps" standard of CAR 101.13.

Interaction with Manned Aircraft

In New Zealand, drones are required to give way to all manned aircraft, both on the ground and in flight [CAR 101.213]. In the United States a similar provision applies, with the requirement not to interfere with, and to give way to, any manned aircraft [14 CFR 101.41(d), 14 CFR 107.37].

In addition, under the New Zealand rules drones are generally restricted to a maximum height of 400 feet above ground level [CAR 101.207(a)(3)], which provides a buffer of 100 feet between the drone and the minimum height of 500 feet above ground level allowed for manned aircraft in "uncongested" (generally rural) areas and a buffer of 600 feet between the drone and the minimum height of 1,000 feet above ground level allowed for manned aircraft in "congested" areas [CAR 91.311(a)].

In the United States, 14 CFR 101 does not explicitly mention a 400 feet above ground level height limit. However, 14 CFR 101.43 states that "[n]o person may operate model aircraft so as to endanger the safety of the national airspace system.” the FAA has interpreted this requirement to include following best practices “including limiting operations to 400 feet above ground level” (FAA, 2016). Under Part 107 drones are limited to 400 feet above ground level, or 400 feet above the highest point of a structure if flying within a 400 foot radius of that structure [14 CFR 107.51].

Less obvious is the requirement that the pilot of a drone must maintain unaided visual line of site with the aircraft [CAR 101.209, 14 CFR 101.1(5)(ii), 14 CFR 107.31]. In New Zealand, visual line of sight must be “unaided”, which is intended to ensure that a person is able to visually scan the surrounding airspace for manned aircraft, without the restrictions on peripheral vision that are imposed by devices such as binoculars and telescopes. In New Zealand and under Part 107 in the United States the pilot is also able to operate the drone out of line of sight but with an observer who maintains direct visual line of site with the aircraft and is in direct communication with the pilot.

Operation near an Aerodrome

Regulators all prescribe restrictions on operations near an aerodrome, but the extent of those restrictions differs between countries. These rules recognise the heightened risk around aerodromes, where manned aircraft may be operating at relatively low level during take-off and landing, and where aircraft density will be considerably higher than in general airspace. The heightened risk suggests that it is likely to be efficient to have more restrictive safety regulation in these areas.

In the United States, 14 CFR 101.41(e) requires that “[w]hen flown within 5 miles of an airport, the operator of the [drone] provides the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport) with prior notice of the operation”. Under Part 107, the requirement is simply that the drone must not be operated “in a manner that interferes with operations and traffic patterns at any airport, heliport, or seaplane base” [14 CFR 107.43].

In New Zealand the “boundary” is 4km, but the relevant rules provide significantly more prescriptive requirements. Within that 4km boundary the person operating the drone must be the holder of, or under the supervision of a person who is the holder of, a pilot qualification, licence, or certificate. This regulation is intended to ensure that the operator has the knowledge to understand what manned aircraft are likely to be doing.

However, there is no requirement for a drone to be registered, nor a facility for voluntary drone registration. Furthermore, the requirement for the pilot to hold some form of pilot qualification is routinely ignored, including by the provider of air traffic control services at controlled aerodromes.[3]

The rules also recognise an important distinction between aerodromes with air traffic control and those without. Drones cannot be operated on or within 4km of a controlled aerodrome "unless it is operated in accordance with an authorisation from the relevant [air traffic control] unit" [CAR 101.205(a)(2)]. This provision ensures that the air traffic control unit is aware of the drone operation and can ensure the safety of all users of the airspace. No such facility exists at an uncontrolled aerodrome, so the relevant rules are more prescriptive:

- "the operation is undertaken in accordance with an agreement with the aerodrome operator" [CAR 101.205(a)(1)(i)];
- "each pilot has an observer in attendance while the [drone] is in flight" [CAR 101.205(a)(1)(iii)(A)]; and
- "the [drone] is not operated at a height of more than 400 feet above ground level unless the operator has been approved by the Director to operate the [drone] above 400 feet above ground level" [CAR 101.205(a)(1)(iii)(A)].

Finally, all of the rules for operating within 4km have two exceptions: the rules do not apply if flying indoors; and they do not apply if flying within 100m of, and below the top of, a structure or object that lies between the drone and the aerodrome and is capable of arresting the flight of the

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[3] Air traffic control in New Zealand is provided by Airways Corporation. Airways Corporation has implemented a website called 'Airshare' to streamline the processing of permission requests from drone operators. On 24 December 2018, the author posed the following question on Airshare's public Facebook page (Shelley, 2018):

> [G]iven that Airways Head of Strategy Trent Fulcher is "pushing quite hard" for "certification and training for [drone] pilots", will Airshare be enforcing 101.205(a)(3) that requires a pilot qualification for operation within 4km of an aerodrome? Or will you be continuing your existing policy of not asking?

Airways Corporation's response did not in any way contest the idea that they do not ask for the individual's pilot qualification (Airshare, 2018):

> [I]n essence, Airshare is currently considering a range of options as we review how to best engage with users, including the range of questions asked of an operator requesting a flight authorisation.

drone (a “shielded operation”). In both cases the risk of the drone flying into the path of a manned aircraft is zero (indoors) or extremely low (shielded operation), and would not justify the costs of complying with the “within 4km” rules.

Flight over People and Property

Unless operating in a designated “danger area”, the person operating a drone in New Zealand must avoid operating above “persons who have not given consent”, and must avoid operating over property “unless prior consent has been obtained from any persons occupying that property or the property owner” [CAR 101.207(a)(1)]. If persons are assumed to be informed then this rule is efficient, as consent would rationally only be granted where the person perceives the benefits from the operation to be greater than the costs including potential harm. However, there may be classes of people who are uniformed as to the risks and for whom the drone has significant novelty value; such people may grant consent when it is not rational to do so. In such a situation the over-riding consideration is clearly the legal standard of precaution discussed in section 4.2.2.

In the United States, 14 CFR 101 does not provide an equivalent restriction on flying over people or property without consent. However, 14 CFR 107.39 provides that a drone cannot be operated over a person unless that person is “directly participating” in the operation of the drone, or is “Located under a covered structure or inside a stationary vehicle that can provide reasonable protection from a falling [drone].”

Operator Certification

In New Zealand, Civil Aviation Rules Part 102 *Unmanned Aircraft Operator Certification* [CAR Part 102 (2015)] governs operations taking place outside the narrow scope of the Part 101 rules. The CAA will grant certification for operation outside of the Part 101 rules if it considers that the operator has sufficient mitigations in place to keep risk to an acceptable level.

As an example of one of the higher risk operations, operators intending to utilise drones for the aerial application of herbicides must either comply with all of the relevant rules for manned aircraft, or make an application for certification under CAR Part 102. The CAA requires personnel to hold a pilot qualification, be assessed for competency by one of the organisations approved for that purpose, and hold relevant qualifications for the application of agricultural chemicals.

As with certification for operators in other parts of the civil aviation system, the operator is required to prepare an exposition specifying how the operator will comply with relevant rules and mitigate any risks that arise from operating outside the constraints of Part 101 [CAR 102.11]. Certification is granted on the condition that the operator complies with the procedures in its exposition. This approach of allowing operators to propose how they will achieve an adequate level of safety aids efficient outcomes as it allows each operator to propose their least cost means of precaution.

In the United States, the equivalent of operator certification exists for commercial operators who wish to operate outside the confines of 14 CFR Part 107. Pursuant to 14 CFR 107.200, the FAA may grant a "certificate of waiver" from certain specified regulations if the "proposed small [drone] operation can safely be conducted under the terms of that certificate of waiver". Any application for a certificate of waiver "must contain a complete description of the proposed operation and justification that establishes that the operation can safely be conducted under the terms of a certificate of waiver", which is the equivalent of the exposition required by New Zealand's Part 102.

Personnel Licensing

Personnel licensing is utilised where there is a safety justification for doing so. As noted in section 4.2.2 above, CAR Part 101 explicitly requires a pilot qualification, licence, or certificate if the drone operation is conducted within 4km of an aerodrome. A high degree of flexibility is provided, with those holding a pilot qualification from another area of aviation not required to obtain a separate pilot qualification for drones.

Although not codified in any rule, the New Zealand CAA also requires that any person flying as a pilot for a Part 102 certificated organisation to hold a pilot qualification, licence, or certificate (CAA, 2015, pp. 16-17), and to have undertaken a flight competency assessment within the last 12 months (R. Kenny, personal communication, July 7, 2015).

As of 1 December 2018, the CAA had approved seven organisations for the issue of a pilot certificate specifically for drone operations. Two organisations were approved for the issue of pilot certificates that could only be used for Part 101 operations; while five organisations were approved for the issue of pilot certificates that could be used under Part 102 operations. Of the five organisations, only Model Flying New Zealand is “approved” without holding its own certification; the other four organisations are all certified Aviation Training Organisations under CAR Part 141.

In the United States there is no requirement for personnel licensing under 14 CFR Part 101. However, the only way to operate commercially is under 14 CFR Part 107, which requires that drone pilots hold a “Remote Pilot Certificate”. The holder of a Remote Pilot Certificate must “demonstrate aeronautical knowledge” by either (a) passing an aeronautical knowledge test, or (b) be the holder of a pilot licence issued under Part 61 and attend a Part 107 training course [14 CFR 107.61]. A recurrent aeronautical knowledge test must be passed every 24 months [14 CFR 107.65]. Unlike the requirements for a Part 102 pilot in New Zealand, there is no requirement in 14 CFR 107 for pilots in the United States to undertake a flight competency assessment.

Registration of Drones

In the United States, 14 CFR Part 48 *Registration and Marking Requirements for Small Unmanned Aircraft* [14 CFR Part 48 (2015)] requires that all unmanned aircraft weighing more than 250g (0.55lb) and 25kg (55lb) or less are registered prior to use [14 CFR 48.15]. If an unmanned aircraft is to be used as a model aircraft (i.e. a drone that is used purely for recreational purposes) then a registration number is issued to the operator, and that registration number must be displayed on all unmanned aircraft operated by that individual [14 CFR 48.115(a)]. If an operator intends to use unmanned aircraft for commercial purposes then each unmanned aircraft must be registered, and each unmanned aircraft has a unique registration number [14 CFR 48.110(a)]. In all cases the registration number is physically displayed on the aircraft; there is no provision for an identifier that can be remotely read.

In the United Kingdom, the Air Navigation (Amendment) Order 2018, made 23 May 2018, introduced a requirement for the operators of unmanned aircraft which weigh more than 250g to be registered from 30 November 2019 (s94C). A ten-digit registration number is issued to the operator, and that registration number must be physically displayed on the unmanned aircraft (s94D). Like the United States’ scheme, there is no provision for an identifier that can be remotely read.

The United States' system of registration, coupled with geofencing, has been insufficient to prevent drones flying in restricted airspace. On 16 November 2018 a man crashed his drone into Barclay's Bank in Midtown New York (Lampen, 2018), near the middle of restricted airspace around Trump Tower (McEvoy, 2018). The pilot was arrested and charged not because of registration information on the drone but because he tried to claim the drone. From 6-14 October 2018, a total of 40 drones conducting 46 separate flights were detected violating the restricted airspace declared for the Albuquerque Balloon Fiesta (Armor, 2018). There have also been multiple incidents of drones flying at large fires, causing fire-fighting aircraft to be grounded, even though there have been airspace restrictions in place (for a selection of incidents see Blowers, 2018; Craber, 2018; Dodson & England, 2018; Kivi TV, 2018; Urness, 2018). There is no indication that the pilot was identified in any of these incidents.

The requirement for drones to be registered has also been insufficient to stop a man in Pennsylvania from using a drone to drop improvised explosive devices on his ex-girlfriend's home (Hall, 2019). The alleged pilot was charged with a number of offences relating to firearms, possession of improvised explosives, and operating an unregistered drone.

Another incident that illustrates the limitations of a registration number displayed physically occurred on 21 September 2017 in New York, when a DJI Phantom 4 drone collided with a Sikorsky UH-60M Black Hawk helicopter operated by the US Army (National Transportation Safety Board [NTSB], 2017). Once again the drone flight occurred in restricted airspace, this time closed because of the United Nations General Assembly. The NTSB reports that the primary damage to the UH-60M helicopter was a 1.5 inch dent on the leading edge of one of the main rotor blades, surrounded by various scratches and material transfer. Some cracks were observed in the composite fairing and window frame material. The Phantom 4 was destroyed. However:

> One motor and a portion of an arm of the [drone] was recovered from the helicopter. Debris was found in the engine oil cooler fan by Army maintenance personnel. The components were transferred ... to the NTSB. Manufacturing serial number information inscribed on the motor enabled sales records provided by the manufacturer to aid in identifying the pilot, as the [drone] was purchased directly from the manufacturer. The remainder of the [drone] was not

recovered.

This incident highlights that while physical identifier numbers or serial numbers can be used to identify an errant drone, this method of identification is only useful in a situation where (a) the drone actually crashes, (b) components with serial numbers are recovered, and (c) the serial number can be traced to a purchaser. In situations where a drone disrupts air traffic, or causes privacy-related harm, but does not crash, then physical identification will not be possible. Similarly, if the motor had not been recovered in the this incident, or if the drone operator had purchased from a third-party retailer rather than directly from DJI, then it would not have been possible to trace the serial number back to the operator. Finally, as only one arm of the drone was recovered, the likelihood that a physical registration label or data plate on the exterior of the drone could have been recovered is very low.

4.3 Remote Identification Technologies

Identification and surveillance technologies are used within the international aviation system to facilitate air traffic control and thereby allow more efficient utilisation of airspace (International Civil Aviation Organisation Asia Pacific [ICAO-AP], 2007, p. 3). These technologies can be categorised into primary surveillance radar, secondary surveillance radar, and ADS-B.

4.3.1 Primary Surveillance Radar

Primary surveillance radar utilises a radio signal broadcast from the radar transmitter, which bounces off the target aircraft and returns to the radar receiver (ICAO-AP, 2007, p.6). Various information can be extracted from the primary radar surveillance signal, such as the target's location, speed, and direction (Skolnik, 1981, p.1), but it is not possible to identify the particular aircraft. The "standard" primary surveillance radar installed at airports is generally unable to detect drones, but specialised radar with shorter range is available that can detect drones. For example, following the spate of drone-related incidents in Auckland at the start of 2018, Airways Corporation of New Zealand - the provider of air traffic control services in New Zealand - decided to trial a drone-detection radar at Auckland International Airport (Akoorie, 2018). From the author's visual observation, the system being trialled is the Aveillant Gamekeeper (Aveillant, n.d.). This system is capable of providing a precise track for drones, allowing air traffic control to determine whether a drone poses a risk to manned aircraft. However, like primary surveillance radar generally, such systems are unable to identify the particular drone.

4.3.2 Secondary Surveillance and ADS-B

Secondary surveillance radar utilises a “transponder” on board the aircraft, which broadcasts information when it is interrogated by the radar signal (ICAO-AP, 2007, p. 7). Mode A/C transponders report the identification of the aircraft (Mode A) and altitude to the nearest 100 feet above mean sea level (Mode C) (ICAO-AP, 2007, p.7). Mode S transponders contain all of the functions of Mode A/C, but also allows over 16 million unique aircraft addresses, altitude reporting to within 25 feet, and a two-way data link between the aircraft and the ground station (ICAO-AP, 2007, p.8).

Much of the world is moving to “Automatic Dependent Surveillance-Broadcast” (ADS-B) which requires aircraft to carry a Mode S transponder, and broadcast their GPS-based position once every second (US Department of Transportation, Office of Inspector General, 2014). In contrast, ground-based radar systems only update position once every 5 to 12 seconds, and accuracy reduces as the distance between the aircraft and the radar increases (US Department of Transportation, Office of Inspector General, 2014). Thus if the GPS system is working and the aircraft is carrying an ADS-B transponder then ADS-B can be more accurate than position information provided by way of radar returns.

The maximum range of any detection system is the distance beyond which the target cannot be detected, and occurs when the received signal power just equals the minimum detectable signal (Skolnik, 1981, p.4). The power of a radio signal is inversely proportional to the square of the distance from the transmitter (Skolnik, 1981, p.3), and for a radar system the power of the received signal is inversely proportional to the fourth power of distance to the target (Skolnik, 1981, p.4). ADS-B utilises a network of ground-based ADS-B receivers, which means that the transponder will be relatively close to a receiver and the transmissions from the ADS-B transponder can be a much lower power than is required for a primary or secondary radar surveillance system. This in turn means that an ADS-B transmitter is much lower cost than a traditional radar.

While the absolute cost of an ADS-B transponder may be low relative to a primary surveillance radar, TSO-compliant ADS-B systems are relatively expensive for general aviation aircraft (Aircraft Owners and Pilots Association [AOPA], 2015; ICAO-AP, 2007). These aircraft will obtain little or no benefit from the ADS-B system, but are required to incur the cost of the ADS-B transponders. The primary benefit of ADS-B is avoiding of the cost of replacing existing radar systems, which are approaching the end of their useful life, but it appears that the net benefit of ADS-B may be negative (Ernst and Young Ltd, 2017; US Department of Transportation, Office of Inspector General, 2014).

ADS-B and GPS systems also have a number of vulnerabilities. At the simplest level, the GPS signal can be blocked by tall buildings, tall hills, and the like - limitations that are particularly likely to affect ADS-B transponders that are fitted to low-flying drones. GPS-based systems are also vulnerable to “spoofing”, discussed in Section 3.2.5 in the Introduction

Furthermore, ADS-B can be turned off or simply not fitted, and any transponder-based system is vulnerable to failure of, or interference with, the transponder. During the terrorist attacks in the United States on September 11, 2001, the terrorists turned off the transponders in three of the four aircraft (National Commission on Terrorist Attacks upon the United States, 2004, p.16). The disappearance of Malaysia Airlines flight MH370 in 2014 was associated with loss of communication from the aircraft’s transponders (Ministry of Transport Malaysia, 2018). Although the reason for the loss of communications with MH370’s transponders is not known (Ministry of Transport Malaysia, 2018), some commentators speculate that it was the pilot who turned the transponders off (see, for example, Wootson, 2018).

It seems unlikely that even if drones were currently required to carry ADS-B transponders that this would necessarily have prevented the Gatwick incident or made it easy to locate the operator of the drone(s): the person(s) responsible could simply turn off the transponder, disconnect it, or otherwise render the transponder inoperable.

4.3.3 DJI’s Aeroscope

One vendor-specific platform currently available that incorporates aspects of registration is Aeroscope from Chinese manufacturer Dà-Jiāng Innovations [DJI]. DJI is one of the largest drone manufacturers in the world, with one market research study giving it a share of 74 percent of all drones sold in the United States in 2018 (French, 2018). Firmware on DJI drones is set to broadcast certain information that can then be received by the Aeroscope system. This information includes the drone's "location, altitude, speed, direction, takeoff location, operator location, and an identifier" (DJI, 2017a). The Aeroscope system detects all DJI drones within a given range,[4] enabling the location of the operator and/or identity of the drone to be established for any drone that is engaged in malicious or otherwise harmful activity.

Research conducted at four international airports in the United Kingdom detected 285 drones over a period of 148 days, with only 43.9 percent of the drones manufactured by DJI (Dedrone, 2018). This means that less than half of all drone incursions might be detected by the Aeroscope system. It is perhaps not surprising, then, that the Aeroscope system is believed to have been unable to detect the intruding drone(s) at Gatwick (Baylis et al., 2018).

DJI suggests that their Drone ID system could be adopted by other manufacturers (DJI, 2017b). However, even if this system was mandated by regulatory authorities, a number of weaknesses exist in the Drone ID system. One researcher has shown that sending the home location can be disabled, the Drone ID can be hidden, and a fake serial number can be broadcast (Department 13, 2017, p.15). Another researcher has identified that information broadcast by the drone can easily be spoofed (Department 13, 2017, pp.17-18).

4.4 Model: Registration of Drones

I now consider a strategic game with a drone operator, who is required to register her drone, and a bystander who may be subject to harm, but is unable to take any action either in precaution or in self-defence. The intention of this game is to assess whether the requirement for registration is sufficient to adequately control the level of harm induced by the drone.

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[4] DJI claims that in an interference-free environment the reception range is up to 7km for the DJI Mavic, 5km for the DJI Phantom series, and 3km for the DJI Spark (DJI, 2018). A low gain directional antenna can double the range, and a high-gain directional antenna can quadruple the range.

4.4.1 General Setup

Following the basic setup of Chapter 3 there is a drone operator and a bystander. Let v denote the unit value received by the operator from flying her drone, and H denote the unit harm to the bystander. The values of v and H are exogenous.

Attribution of liability for any harm requires that the operator of the aircraft can be identified. Identification may be achieved either by way of the aircraft carrying an an identifier that can be "read" by the detection technology, or by visual observation coupled with investigation. The detection technology is capable of "reading" the identifier at a distance of up to $\bar{d}$. A register exists that enables the matching of an identifier to a legal person who is the registered operator of the drone. If an identifier is read then liability for any harm can be fully attributed to the registered operator. The cost of administering the drone registration scheme is $r \in \mathbb{R}_+$.

If the aircraft is *not* carrying a remotely-readable identifier then the probability of identifying the operator, p, is exogenous.

Let $t \in \{0, 1\}$ denote the drone operator's (discrete) choice of whether to carry an identifier; if $t = 1$ then an identifier is carried, but if $t = 0$ then an identifier is not carried. The drone operator also chooses an activity level, $q \in \mathbb{R}_+$.

Let $m \in (0, 1)$ denote the proportion of liability borne by the drone operator, and $\psi \in (0, 1)$ denote the proportion of time that the drone is expected to be within range of the detection technology. If the drone is within range of the detection technology then liability is unity if an identifier is carried, but p if an identifier is not carried. If the drone is not in range of the detection technology then liability is p. The proportion of liability m is therefore given by:

$$m(\psi, t) = \psi \left[(1 - t)p + t\right] + (1 - \psi)p \tag{4.1}$$

Let $c(q)$ denote the cost of operating the drone, which is strictly increasing and strictly convex. Let the opportunity cost of carrying an identifier be c_I. If an aircraft is required to have an identifier but does not carry one then the aircraft operator is liable for a fine of c_F. To attempt to identify the operator of an aircraft that is not carrying an identifier the enforcement agency incurs an enforcement cost of c_E.

Assuming risk-neutrality the expected utility of the drone operator is:

$$U(q;\psi,H,t) = \max\left\{0, (v - m(\psi,t)H)q - c(q) - tc_I - (1-t)pc_F\right\}. \quad (4.2)$$

The first term is the expected value received by the operator, net of any liability for harm caused. The second term is the cost of operation. The third term is the cost of carrying an identifier. The fourth term is the expected fine if an identifier is not carried.

Let U^* denote the unconstrained utility of the drone operator. Then:

$$U^*(q;\psi,H,t) = \begin{cases} (v - pH)q - c(q) - pc_F & : \ t = 0 \\ (v - [\psi + (1-\psi)p]\, H)q - c(q) - c_I & : \ t = 1 \end{cases}. \quad (4.3)$$

Note that if $q = 0$ then $U^* < 0$ for $pc_F > 0$ and $c_I > 0$. Utility in equation (4.2) can also be written as $U = \max\{0, U^*\}$.

4.4.2 Activity

The general form of the drone operator's FOC is:

$$U_q = v - m(\psi,t)H - c_q = 0. \quad (4.4)$$

The drone operator may choose to operate with an identifier or without an identifier.

Let q^* denote the unconstrained activity level. Then from equation (4.4) it must be that:

$$q^* = g(v - mH), \quad (4.5)$$

where $g(.)$ is the inverse of the marginal cost function.

Following the analysis in Chapter 3 assume that:

$$\begin{aligned} c(q) &:= \eta\frac{q^\alpha}{\alpha} \\ \Rightarrow c_q &= \eta q^{(\alpha-1)}, \end{aligned}$$

where $\alpha \geqslant 1$.

Then q^* has the closed-form solution:

$$q^* = \left[\frac{v - mH}{\eta}\right]^{1/(\alpha-1)}. \quad (4.6)$$

Lemma 19. *For an interior solution, if the drone is not carrying an identifier then the equilibrium level of activity is independent of the fine.*

Proof. The fine, c_F, does not appear in equation (4.6). ☐

Lemma 20. *For an interior solution, if the drone is carrying an identifier, then activity is independent of the opportunity cost of the identifier.*

Proof. The opportunity cost of the identifier, c_I, does not appear in equation (4.6). ☐

4.4.3 Conditions to Fly

Let $\hat{q}$ denote the constrained equilibrium level of activity, such that:

$$\hat{q} = \begin{cases} 0 & : \quad U^* < 0 \\ q^* & : \quad U^* \geqslant 0 \end{cases}. \tag{4.7}$$

Lemma 21. *A necessary but not sufficient condition for the drone operator to choose to fly is that $v > mH$.*

Proof. If the drone operator chooses to fly then it must be that both $q^* > 0$ and $\hat{q} > 0$. From equation 4.6, $q^* > 0$ implies that $v > mH$. However, this is not a sufficient condition for the operator to choose to fly since it is possible that both $q^* > 0$ and $U^* < 0$ are true, which from equation 4.12 implies that $\hat{q} = 0$. ☐

Corollary 21.1. *If the drone is not carrying an identifier then a necessary but not sufficient condition for the drone operator to choose to fly when not carrying an identifier is that $v > pH$.*

Proof. When the drone is not carrying an identifier ($t = 0$), equation (4.1) reduces to $m = p$. ☐

Corollary 21.2. *If the drone is carrying an identifier then a necessary but not sufficient condition for the drone operator to choose to fly when not carrying an identifier is that $v > [\psi + (1 - \psi)p]\, H$.*

Proof. When the drone is carrying an identifier ($t = 1$), equation (4.1) reduces to $m = \psi + (1 - \psi)p$. ☐

Lemma 22. *The necessary and sufficient condition for the drone operator to choose to fly is $v > mH + \eta^{1/\alpha} \left[(tc_I + (1 - t)pc_F)\left(\frac{\alpha}{\alpha-1}\right)\right]^{\frac{\alpha-1}{\alpha}}$.*

Proof. If the drone operator chooses to fly then $\hat{q} > 0$. From equation 4.7 this requires that $U^* \geqslant 0$, and hence:

$$\begin{aligned}
(v - mH)q_0^* - c(q_0^*) &\geqslant tc_I + (1-t)pc_F \\
\Rightarrow (v - mH)\left[\frac{v - mH}{\eta}\right]^{1/(\alpha-1)} - \left(\frac{\eta}{\alpha}\right)\left[\frac{v - mH}{\eta}\right]^{\alpha/(\alpha-1)} &\geqslant tc_I + (1-t)pc_F \\
\Rightarrow (v - mH)^{\alpha/(\alpha-1)}\left[\left(\frac{1}{\eta}\right)^{1/(\alpha-1)} - \left(\frac{1}{\alpha}\right)\eta^{(\alpha-1)/(\alpha-1)}\left(\frac{1}{\eta}\right)^{\alpha/(\alpha-1)}\right] &\geqslant tc_I + (1-t)pc_F \\
\Rightarrow (v - mH)^{\alpha/(\alpha-1)}\left(\frac{1}{\eta}\right)^{1/(\alpha-1)}\left(\frac{\alpha-1}{\alpha}\right) &\geqslant tc_I + (1-t)pc_F.
\end{aligned} \tag{4.8}$$

With some rearrangement the sufficient condition to fly when not carrying an identifier is:

$$\begin{aligned}
&(v - mH)^{\alpha/(\alpha-1)} \geqslant (tc_I + (1-t)pc_F)\left(\frac{\alpha}{\alpha-1}\right)\eta^{1/(\alpha-1)} \\
&\qquad \Rightarrow v \geqslant mH + \eta^{1/\alpha}\left[(tc_I + (1-t)pc_F)\left(\frac{\alpha}{\alpha-1}\right)\right]^{(\alpha-1)/\alpha}.
\end{aligned} \tag{4.9}$$

□

Corollary 22.1. *If the drone is not carrying an identifier then the necessary and sufficient condition for the drone operator to choose to fly is* $v > pH + \eta^{1/\alpha}\left[pc_F\left(\frac{\alpha}{\alpha-1}\right)\right]^{\frac{\alpha-1}{\alpha}}$.

Proof. If the drone is not carrying an identifier then $t = 0$, equation (4.1) reduces to $m = p$, and equation (4.9) becomes:

$$v \geqslant pH + \eta^{1/\alpha}\left[pc_F\left(\frac{\alpha}{\alpha-1}\right)\right]^{(\alpha-1)/\alpha}.$$

□

Corollary 22.2. *If the drone is carrying an identifier then the necessary and sufficient condition for the drone operator to choose to fly is* $v > [\psi + (1-\psi)p]\,H + \eta^{1/\alpha}\left[c_I\left(\frac{\alpha}{\alpha-1}\right)\right]^{\frac{\alpha-1}{\alpha}}$.

Proof. If the drone is carrying an identifier then $t = 1$, equation (4.1) reduces to $m = \psi + (1-\psi)p$, and equation (4.9) becomes:

$$v \geqslant [\psi + (1-\psi)p]\, H + \eta^{1/\alpha} \left[c_I \left(\frac{\alpha}{\alpha - 1} \right) \right]^{(\alpha-1)/\alpha}.$$

□

4.4.4 Activity and Utility with No Identifier

In this case, although regulations require the drone to carry an identifier the drone operator chooses not to carry an identifier. If the drone is detected and identified then the operator must pay a non-negative fine ($c_F \geqslant 0$).

Let q_0^* denote the unconstrained activity level when the drone is not carrying an identifier. Then from equation (4.6), q_0^* has the closed-form solution:

$$q_0^* = \left[\frac{v - pH}{\eta} \right]^{1/(\alpha-1)}. \tag{4.10}$$

Let U_0^* denote unconstrained utility when an identifier is not carried. Then from equation (4.3) we have:

$$U_0^* = (v - pH) q_0^* - c(q_0^*) - p c_F. \tag{4.11}$$

Let $U_0 = \max\{0, U_0^*\}$ and $\hat{q_0}$ denote the constrained equilibrium utility and constrained equilibrium level of activity, both when the drone is not carrying an identifier, respectively. Then:

$$\hat{q_0} = \begin{cases} 0 & : \; U_0^* < 0 \\ q_0^* & : \; U_0^* \geqslant 0 \end{cases}. \tag{4.12}$$

Lemma 23. *For any level of activity q_0^* there exists a threshold level of for the fine $\underline{c_F}$ at which unconstrained utility is zero ($U_0^* = 0$), and any fine greater than the threshold ($c_F > \underline{c_F}$) will result in negative unconstrained utility ($U_0^* < 0$) and the drone operator will choose not to fly the drone if not carrying an identifier ($\hat{q_0} = 0$).*

Proof. Assume values for v, p, and H such that $q_0^* > 0$. Then the threshold value of $\underline{c_F}$ at which $U_0^* = 0$ is given by:

$$U_0^* = 0 \Rightarrow \underline{c_F} = \frac{(v - pH) q_0^* - c(q_0^*)}{p}. \tag{4.13}$$

Increasing c_F above this threshold will result in no change to q_0^* (lemma 19), but will result in $U_0^* < 0$ by the amount of $p(c_F - \underline{c_F})$. From equation (4.12) we have $U_0^* < 0 \Rightarrow \hat{q}_0 = 0$, hence $c_F - \underline{c_F}$ implies that the drone operator will choose not to fly the drone. $\square$

Lemma 24. *Increasing the fine above the threshold in equation 4.13 will cause the unregistered drone operator to cease operation.*

Proof. If $c_F > \underline{c_F}$ then $U_0^* < 0$ and hence from equation 4.12 $\hat{q}_0 = 0$. $\square$

4.4.5 Activity and Utility with an Identifier

Let q_1^* denote the unconstrained activity level if the drone is carrying an identifier ($t = 1$). Then from equation (4.6), q_1^* has the closed-form solution:

$$q_1^* = \left[\frac{v - [\psi + (1-\psi)p]\, H}{\eta}\right]^{1/(\alpha-1)}. \tag{4.14}$$

Let U_1^* denote unconstrained utility when an identifier is carried. Then from equation (4.3) we have:

$$U_1^* = (v - [\psi + (1-\psi)p]\, H)q_1^* - c(q_1^*) - c_I. \tag{4.15}$$

Lemma 25. *For any level of activity q_1^* there exists a threshold cost for the identifier $\underline{c_I}$ at which unconstrained utility is zero ($U_1^* = 0$), and if the cost of the identifier is greater than this ($c_I > \underline{c_I}$) then unconstrained utility will be negative.*

Proof. Assume values for v, ψ, p, and H such that $q_0^* > 0$. Then from equation 4.15 the threshold value of $\underline{c_I}$ at which $U_1^* = 0$ is given by:

$$U_1^* = 0 \Rightarrow \underline{c_I} = (v - [\psi + (1-\psi)p]\, H)q_1^* - c(q_1^*). \tag{4.16}$$

Increasing c_I beyond the threshold will result in no change to q_1^* (lemma) but will result in $U_1^* < 0$ by the amount $c_I - \underline{c_I}$. $\square$

Let $U_1 = \max\{0, U_1^*\}$ and $\hat{q}_1$ denote the constrained equilibrium utility and constrained equilibrium activity, both when the drone is carrying an identifier, respectively. Then:

$$\hat{q}_1 = \begin{cases} 0 & : \ U_1^* < 0 \\ q_1^* & : \ U_1^* \geqslant 0 \end{cases}. \tag{4.17}$$

Lemma 26. *If the cost of the identifier exceeds the threshold in equation 4.16 then a drone operator will not register and operate.*

Proof. If $c_I > \underline{c_I}$ then $U_1^* < 0$ and hence from equation 4.17 $\hat{q}_1 = 0$. □

Lemma 27. *For an interior solution, if the drone is ever operated within range of the detection technology then activity with no identifier will be greater than activity with an identifier ($\hat{q}_0 > \hat{q}_1$), but if it is never operated within range of the detection technology then activity with no identifier will be the same as activity with an identifier ($\hat{q}_0 = \hat{q}_1$).*

Proof. Given the assumed characteristics of ψ and p, it must be that:

$$\begin{aligned} p &\leqslant \psi + (1-\psi)p \\ \Rightarrow v - pH &\geqslant v - [\psi + (1-\psi)p]\, H \end{aligned}$$

Marginal costs were assumed to be strictly increasing, so it therefore must be that:

$$\begin{aligned} g(v - pH) &\geqslant g(v - [\psi + (1-\psi)p]\, H) \\ \Rightarrow q_0^* &\geqslant q_1^*. \end{aligned} \tag{4.18}$$

Hence if the drone is ever operated within range of the detection technology then $\psi > 0 \Rightarrow q_0^* > q_1^* \; \forall \; p < 1$ but if the drone is never operated within range of the detection technology then $\psi = 0 \Rightarrow q_0^* = q_1^*$. For an interior solution this also implies that $\psi > 0 \Rightarrow \hat{q}_0 > \hat{q}_1 \; \forall \; p < 1$ and $\psi = 0 \Rightarrow \hat{q}_0 = \hat{q}_1$. □

4.4.6 Operator's Choice

The operator simultaneously chooses the activity level, q, and whether the drone carries an identifier.

The operator chooses whether the drone will carry an identifier on the basis of utility. Let U_{max} denote maximum utility. Then:

$$U_{max} = \max\left\{U_0, U_1\right\}. \tag{4.19}$$

Drone activity, $\hat{q}$, is given by:

$$\hat{q} = \begin{cases} \hat{q}_0 & : \quad U_{max} = U_0 \\ \hat{q}_1 & : \quad U_{max} = U_1 \end{cases}. \tag{4.20}$$

The drone operator will carry an identifier if utility when carrying an identifier is at least equal to utility when not carrying an identifier. For an internal solution, the drone operator chooses to carry an identifier if:

$$\begin{aligned} & U_1 \geqslant U_0 \\ \Rightarrow\ & pc_F - c_I \geqslant [(v - pH)\hat{q}_0 - c(\hat{q}_0)] - [(v - [\psi + (1-\psi)p]\,H)\hat{q}_1 - c(\hat{q}_1)] \\ \Rightarrow\ & pc_F - c_I \geqslant [(v - pH)\hat{q}_0 - c(\hat{q}_0)] - [(v - pH)\hat{q}_1 - c(\hat{q}_1)] + \psi\,(1-p)\,H\hat{q}_1. \end{aligned} \tag{4.21}$$

For any given value of q the marginal benefit of carrying an identifier is:

$$pc_F - c_I - \psi\,(1-p)\,Hq.$$

This implies a threshold quantity, q_T, such that:

$$q_T = \frac{pc_F - c_I}{\psi\,(1-p)\,H}. \tag{4.22}$$

When $q < q_T$ the marginal benefit of carrying an identifier is positive, but when $q > q_T$ the marginal benefit of carrying an identifier is negative.

Lemma 28. *A sufficient condition for the drone operator to choose not to carry an identifier is that the expected cost of the fine does not exceed the opportunity cost of carrying the identifier by an amount more than* $\psi(1-p)H\hat{q}_1$.

Proof. Consider the case where $\hat{q}_1 > q_T$. Substituting into equation (4.22), this case can also be represented as:

$$pc_F - c_I < \psi\,(1-p)\,H\hat{q}_1. \tag{4.23}$$

If $\hat{q}_1 > q_T$ then it must also be that $\hat{q}_0 > q_T$ since from lemma 27 $\hat{q}_0 \geqslant \hat{q}_1$. As both $\hat{q}_0$ and $\hat{q}_1$ exceed the threshold q_T, the marginal benefit of carrying an identifier must be negative at both quantities and the operator will choose not to carry an identifier.

□

Corollary 28.1. *The drone operator will choose not to carry an identifier if the expected cost of the fine is less than the opportunity cost of the identifier.*

Proof. If the expected cost of the fine is less than the opportunity cost of the identifier then:

$$pc_F < c_I \Rightarrow pc_F - c_I < 0 \leqslant \psi\,(1-p)\,H\hat{q}_1, \tag{4.24}$$

and hence the condition in lemma 28 is satisfied. □

Lemma 29. *A sufficient condition for the drone operator to choose to carry an identifier is that the expected cost of the fine exceeds the opportunity cost of carrying the identifier by an amount at least equal to* $\psi(1-p)H\hat{q}_0$.

Proof. Consider the case where $\hat{q}_0 < q_T$. Substituting into equation (4.22), this case can also be represented as:

$$pc_F - c_I > \psi\,(1-p)\,H\hat{q}_0. \tag{4.25}$$

If $\hat{q}_0 < q_T$ then it must also be that $\hat{q}_1$ is less than the threshold since from lemma 27 $\hat{q}_0 \geqslant \hat{q}_1$. As both $\hat{q}_0$ and $\hat{q}_1$ are less than the threshold, the marginal benefit of carrying an identifier must be positive at both quantities and the operator will choose to carry an identifier. □

Corollary 29.1. *If the drone is never within range of the detection technology then a sufficient condition for the drone operator to carry an identifier is that the expected cost of the fine is at least equal to the opportunity cost of carrying the identifier.*

Proof. If the drone is never in range of the detection technology then $\psi = 0$ and the RHS of equation (4.25) is zero and the sufficient condition becomes:

$$pc_F - c_I \geqslant 0.$$

□

Corollary 29.2. *If the drone can always be identified and liability attributed without the identifier then a sufficient condition for the drone operator to carry an identifier is that the expected cost of the fine is at least equal to the opportunity cost of carrying the identifier.*

Proof. If the drone can always be identified and liability attributed without the identifier then $p = 1$ and the RHS of equation (4.25) is zero and the sufficient condition becomes:

$$pc_F - c_I \geqslant 0.$$

□

From lemma 27 we know that $\hat{q}_0 \geqslant \hat{q}_1$. Therefore $\psi(1-p)H\hat{q}_0 \geqslant \psi(1-p)H\hat{q}_1$ and there is a range between $\psi(1-p)H\hat{q}_1$ and $\psi(1-p)H\hat{q}_0$ where neither lemma 28 nor lemma 29 is true. The precise threshold for when the operator will choose to carry an identifier is given by equation (4.21). Since $\hat{q}_0 \geqslant \hat{q}_1$ it must be that $[(v-pH)\hat{q}_0 - c(\hat{q}_0)] - [(v-pH)\hat{q}_1 - c(\hat{q}_1)] \geqslant 0$ because the cost of operating the drone, $c(q)$, is strictly increasing and a move away from the equilibrium $\hat{q}_0$ must necessarily reduce utility. The lower bound of the RHS of equation (4.21) is, therefore, $\psi\,(1-p)\,H\hat{q}_1$. Hence a sufficient condition for the operator to choose *not* to carry an identifier is that $pc_F - c_I$ is less than this lower bound, that is:

$$pc_F - c_I < \psi\,(1-p)\,H\hat{q}_1,$$

which is identical to equation (4.23) in lemma 28.

Lemma 30. *For a corner-point solution where the level of activity with an identifier is zero (*$\hat{q}_1 = 0$*), the drone operator will choose not to operate if the expected fine is greater than gross utility without an identifier.*

Proof. Assume a corner-point solution such that $\hat{q}_1 = 0 \Rightarrow U_1 = 0$. The drone operator will choose not to operate if $U_0 < 0$, which will occur if:

$$[(v-pH)\hat{q}_0 - c(\hat{q}_0)] < pc_F. \tag{4.26}$$

□

4.4.7 Welfare

Let c_E denote the cost of the effort of attempting to identify the drone if it was not detected by the detection system: the probability of such detection is p, and the total cost of effort to identify the drone is independent of the activity level.

Welfare is the sum of the operator's utility, harm suffered by the bystander, the cost of effort of identifying the drone, and the cost of administering the registration scheme. Let W_0 denote welfare if an identifier is not carried, and W_1 denote welfare if an identifier is carried. Then:

$$W_0 = \begin{cases} (v-H)\hat{q}_0 - c(\hat{q}_0) - c_E - r & : \hat{q}_0 > 0 \\ -r & : \hat{q}_0 = 0 \end{cases}. \tag{4.27}$$

$$W_1 = \begin{cases} (v-H)\hat{q}_1 - c(\hat{q}_1) - c_I - (1-\psi)c_E - r & : \hat{q}_1 > 0 \\ -r & : \hat{q}_1 = 0 \end{cases}. \tag{4.28}$$

The expected fine is a cost to the operator but is also a benefit to society: the two effects cancel out so the expected fine does not directly appear in the welfare function. If the drone is carrying an identifier then effort only needs to be exerted to identify the drone when it is operating beyond the range of the detection system, hence the cost of effort is $(1-\psi)c_E$. The cost of administering the registration scheme is incurred regardless of whether the drone operator chooses to register her drone and carry an identifier. The cost of administering the registration scheme is also incurred regardless of whether the drone operator chooses to fly or not.

Let W^R denote welfare with the registration scheme. Then:

$$W^R = \begin{cases} W_0 & : U_{max} = U_0 \\ W_1 & : U_{max} = U_1 \end{cases}. \tag{4.29}$$

Let W^{SQ} denote welfare under the status quo with no registration scheme. Then:

$$W^{SQ} = \begin{cases} (v-H)q_0^* - c(q_0^*) - c_E & : q_0^* > 0 \\ 0 & : q_0^* = 0 \end{cases}. \tag{4.30}$$

Lemma 31. *For both (i) an interior solution $\hat{q}_0 > 0$ and (ii) a $\hat{q}_0 = 0$ corner-point solution with welfare under the status quo greater than $-r$, if the drone operator chooses not to carry an identifier then the drone registration scheme reduces welfare.*

Proof. Consider first the interior solution with $\hat{q}_0 > 0 \Rightarrow q_0^* = \hat{q}_0$. If the drone operator chooses not to carry an identifier then $W^R = W_0$. The change in welfare from implementing the registration scheme therefore is:

$$W^R - W^{SQ} = -r < 0. \tag{4.31}$$

Consider now the corner-point solution with $\hat{q}_0 = 0$. If the drone operator chooses not to carry an identifier then $W^R = W_0 = -r$. If welfare under the status quo is greater than $-r$ ($W^{SQ} > -r$) then $W^R - W^{SQ} < 0$ and registration will unambiguously reduce welfare. □

Lemma 32. *Registration will always reduce welfare if the opportunity cost of the identifier is greater than or equal to the fine for not carrying an identifier.*

Proof. Suppose that $c_I \geqslant c_F \Rightarrow c_F - c_I \leqslant 0$. Then it must also be that $pc_F - c_I \leqslant 0$. From lemma 28 we know that a sufficient condition for an identifier *not* to be carried is $pc_F - c_I < \psi\,(1-p)\,H\hat{q}_1$. This condition is satisfied for $c_I \geqslant c_F$ therefore an identifier will *not* be carried. From lemma 31 we also know that registration is not efficient if the drone operator does not choose to carry an identifier, thus registration will reduce welfare if $c_I \geqslant c_F$. □

Lemma 33. *For an interior solution ($\hat{q}_0 > 0$ and $\hat{q}_1 > 0$), if the drone is never operated within range of the detection technology then a drone registration scheme reduces welfare.*

Proof. Assume, first, that the drone does not carry an identifier. Then from lemma 31 we know that the registration scheme will reduce welfare.

Now assume that the drone does carry an identifier but is always beyond the range of the detection technology ($\psi = 0$). Then welfare when an identifier is carried becomes:

$$W_{1,(\psi=0)} = (v-H)\hat{q}_1 - c(\hat{q}_1) - c_I - c_E - r.$$

The change in welfare from implementing the registration scheme is:

$$\begin{aligned} W^R - W^{SQ} &= W_{1,(\psi=0)} - W^{SQ} \\ &= \left[(v-H)\hat{q}_1 - c(\hat{q}_1) - c_I - c_E - r\right] - \left[(v-H)\hat{q}_0 - c(\hat{q}_0) - c_E\right]. \end{aligned}$$

Recall from lemma 27 that $\psi = 0 \Rightarrow \hat{q}_0 = \hat{q}_1$. Hence:

$$W^R - W^{SQ} = -c_I - r.$$

Therefore if the drone is never within range of the detection technology, a registration scheme reduces welfare regardless of whether the drone is carrying an identifier or not. □

4.5 Numeric Analysis

Whether registration will be welfare-enhancing in a specific situation will depend on the relevant parameter values. This section makes specific assumptions as to parameter values to identify the scenarios in which drone registration is likely to be welfare-enhancing and those scenarios in which it is likely to reduce welfare.

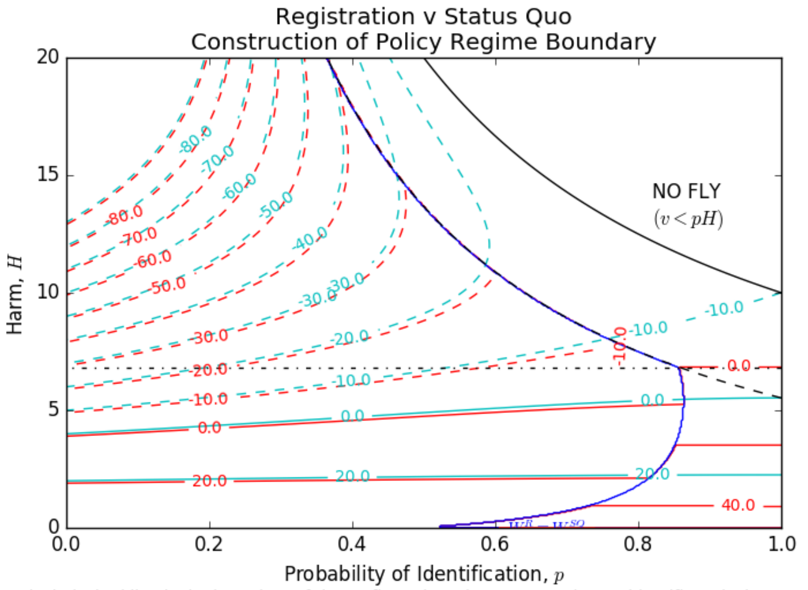
Section 4.5.1 analyses the conditions under which registration is welfare-enhancing. Reflecting the optimal policy analysis in Chapter 3, this analysis is presented graphically by probability of identification of the drone and the level of harm caused. Section 4.5.2 then illustrates the effect of the cost of enforcement on the size of the region in which registration is optimal.

4.5.1 Construction of Policy Regime Boundaries

The policy regime boundary is the locus of points for which welfare under registration equals registration under the status quo. Figure 4.1 shows the construction of the policy regime boundary when the fine for not carrying an identifier is $c_F = 10$, the cost of an identifier is $c_I = 5$, the cost of enforcement is $c_E = 10$, and the drone is always in range of the detection technology ($\psi = 1$). The cost of the registration scheme is set at a *de minimis* level of $r = 1$. Following Chapter 3, parameters for the cost function are $\alpha = 2$ and $\eta = 0.5$, and the unit value from the drone operation is $v = 10$.

The red curves are the iso-welfare curves with registration of drones. The cyan curves are the iso-welfare curves for the status quo. The blue curve is the policy regime boundary.

The downward-sloping dashed black line is the upper boundary of the region where the drone operator will choose to fly if a registration scheme exists but the drone is not carrying an identifier. Above and to the right of this line, if a registration scheme exists but the drone is not carrying an identifier then the drone operator will choose not to fly. The horizontal dash-dot black line is the upper boundary of the region where the drone operator will choose to fly if a registration scheme exists and the drone *is* carrying an identifier. Above this line, if a registration scheme exists and the drone is carrying an identifier then the drone operator will choose not to fly. In figure 4.1 the two no-fly boundaries intersect. The upper portion of the blue policy regime boundary is coincident with the dashed black line


Registration v Status Quo
Construction of Policy Regime Boundary

Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status--quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 1$; $c_I = 5$; $c_F = 10$; $C_E = 10$; $r = 1$.

Figure 4.1. Construction of policy regime boundary for Registration v Status Quo; always in range of detection technology. $\psi = 1$, $c_F = 10$, $c_I = 5$, $c_E = 10$.

above this point of intersection.

Above the dash-dot line and to the left of the blue policy regime boundary (which is also the dashed 'no fly' boundary), the drone operator will choose to fly without an identifier if a registration regime is in place. However, as shown in lemma 31 welfare is lower under registration than the status quo because of the cost of the registration scheme: this is evident by the red iso-welfare curves being parallel to but slightly below the cyan iso-welfare curves. Below the dash-dot line and to the left of the blue policy regime boundary, under registration the drone operator could choose to fly either with or without an identifier. The red iso-welfare curves continue to be parallel to but slightly below the cyan iso-welfare curves, which indicates that the drone operator chooses to fly without an identifier: again welfare is lower under registration than the status quo. Thus, to the left of the policy regime boundary the status quo has higher welfare than registration.

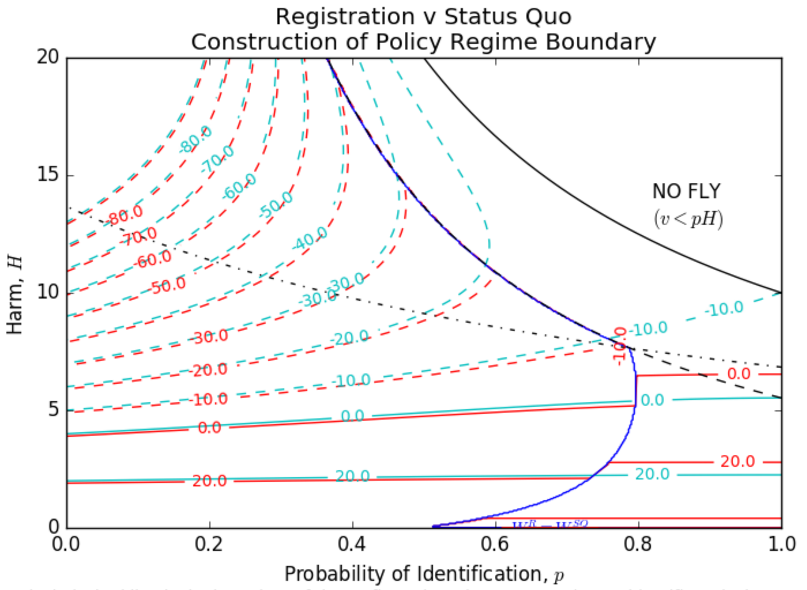
The blue policy regime boundary marks a change in the drone-operator's decision. Above the dash-dot line and to the right of the blue policy regime boundary (which is also the dashed 'no fly' boundary), the drone operator will choose not to fly if a registration scheme is in place. In this region the cyan iso-welfare curves are dashed indicating that welfare under the status quo is negative, but welfare is zero with registration (indicated by the absence of red iso-welfare curves). Thus, in this region of the chart registration has higher welfare than the status quo. Below the dash-dot line and to the right of the policy regime boundary, if a registration scheme is in place the drone operator chooses to fly with an identifier: the drone operator can therefore be identified with certainty and chooses the socially optimal level of activity. In this region of the chart the red iso-welfare curves have a higher value than the cyan iso-welfare curves indicating that registration has higher welfare than the status quo.

This example shows that registration does not improve welfare when there is a moderate to low probability of identifying the drone operator. However, in this example, registration improves welfare if there is already a relatively high probability of identifying the drone operator and attributing liability.

Figure 4.2 and figure 4.3 show the construction of the policy regime boundaries when the drone spends half of the time in range of the detection technology ($\psi = 0.5$), and when the drone spends 10 percent of the time within range of the detection technology ($\psi = 0.1$), respectively. Parameters are otherwise the same as in figure 4.1. The decrease in ψ means that the black dash-dot boundary line is no longer horizontal but is instead downward-sloping. This in turn shifts the point of intersection between the two ‘no fly’ boundaries upwards and to the left, reducing the area in which the status-quo has higher welfare and increasing the area in which registration has higher welfare. However, the essential conclusion remains that registration only improves welfare if there is a relatively high probability of identifying the drone operator without an identifier.

When the drone is never in range of the detection technology ($\psi = 0$, figure 4.4) there is a change in the blue policy regime boundary: in this case the policy regime boundary becomes the upper envelope of the two ‘no fly’ boundaries. Above the policy regime boundary registration is welfare-enhancing and the drone operator will not fly. Below the policy regime boundary the status-quo is the welfare enhancing policy. This is consistent with lemma 33, which shows that for an interior solution welfare under the status quo is always greater than welfare under registration when the drone is never in range of the detection technology.

A further example of when registration is never welfare-enhancing is when the opportunity cost of the identifier is greater than or equal to the

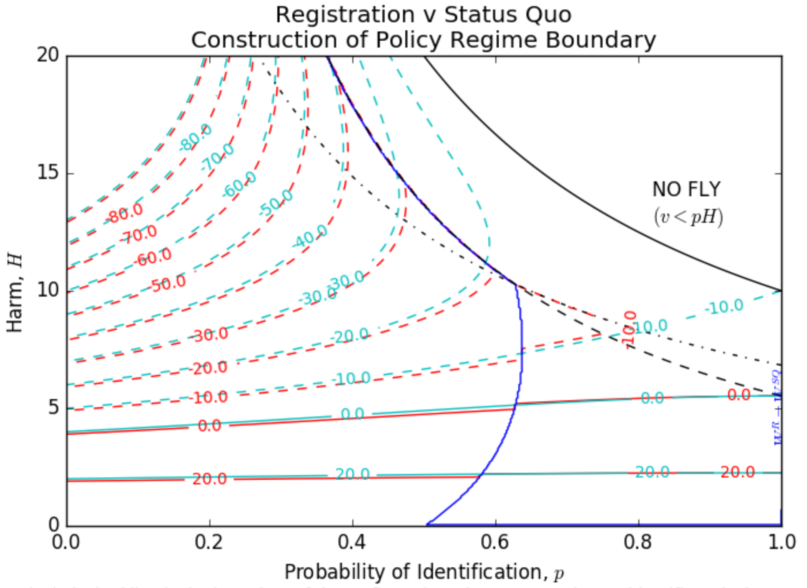


Registration v Status Quo
Construction of Policy Regime Boundary

Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status-quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0.5$; $c_I = 5$; $c_F = 10$; $C_E = 10$; $r = 1$.

Figure 4.2. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 50% of time. $\psi = 0.5$, $c_F = 10$, $c_I = 5$, $c_E = 10$.

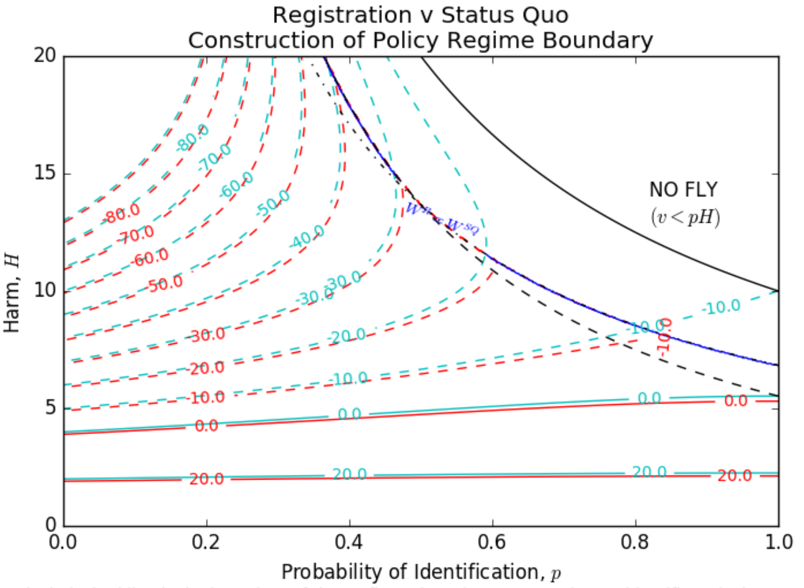
cost of the fine ($c_I \geqslant c_F$), as per lemma 32. This is illustrated by figure 4.5 which shows the welfare curves for the specific case of $\psi = 0.5, c_F = 10$, and $c_I = 20$. In this case the two 'no fly' boundaries no longer intersect, and the dashed boundary for flight with no identifier lies above the dash-dot boundary for flight with an identifier. To the left of the policy regime boundary welfare under the status quo is always greater than welfare under registration.



Registration v Status Quo
Construction of Policy Regime Boundary

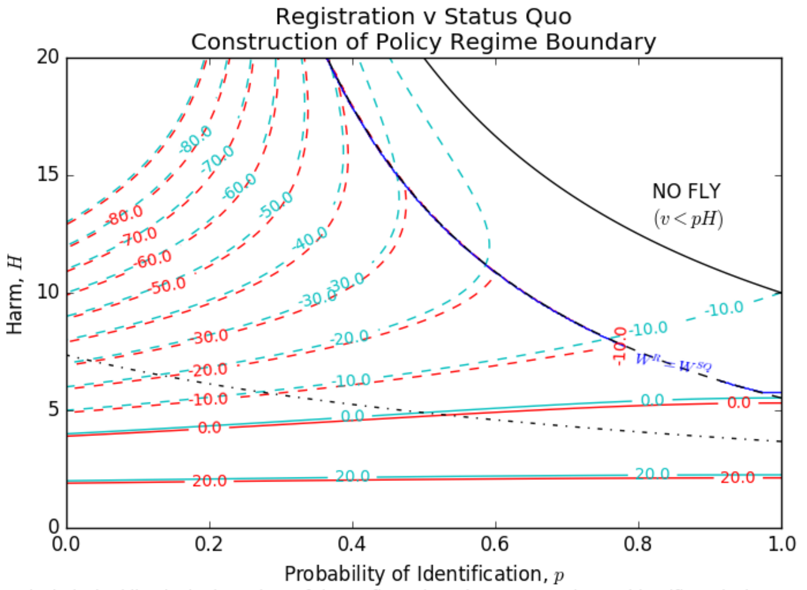
Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status-quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0.1$; $c_I = 5$; $c_F = 10$; $C_E = 10$; $r = 1$.

Figure 4.3. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 10% of time. $\psi = 0.1$, $c_F = 10$, $c_I = 5$, $c_E = 10$.


Registration v Status Quo
Construction of Policy Regime Boundary

Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status--quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0$; $c_I = 5$; $c_F = 10$; $C_F = 10$; $r = 1$.

Figure 4.4. Construction of policy regime boundary for Registration v Status Quo; never in range of detection technology. $\psi = 0$, $c_F = 10$, $c_I = 5$, $c_E = 10$.



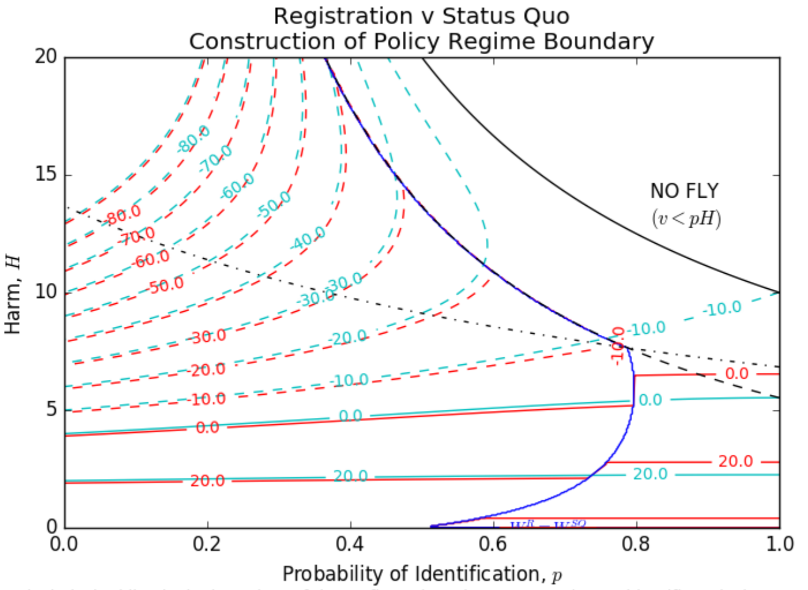
Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status-quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0.5$; $c_I = 20$; $c_F = 10$; $C_E = 10$.

Figure 4.5. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 50% of time. $\psi = 0.5$, $c_F = 10$, $c_I = 20$, $c_E = 10$.

4.5.2 Cost of Enforcement

The results presented above have all assumed that the cost of enforcement is $c_E = 10$, that is the cost of enforcement is the same as the gross value, v, that the drone operator receives per unit of drone operation. This model has not been designed to establish the optimal level of enforcement, but it can illustrate the effect that enforcement costs have on whether registration is welfare-enhancing.

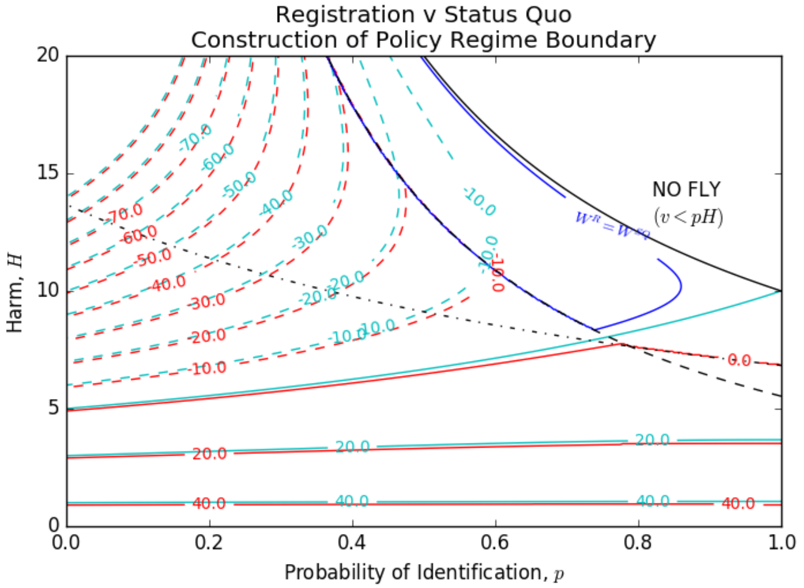
For ease of reference, figure 4.6 repeats figure 4.2, showing the construction of the policy regime boundary when the drone is in range of the detection technology half of the time ($\psi = 0.5$), the fine for not registering is $c_F = 10$, the opportunity cost of an identifier is $c_I = 5$, and the cost of enforcement is $c_E = 10$.



Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status-quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0.5$; $c_I = 5$; $c_F = 10$; $C_E = 10$; $r = 1$.

Figure 4.6. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 50% of time. $\psi = 0.5$, $c_F = 10$, $c_I = 5$, $c_E = 10$.

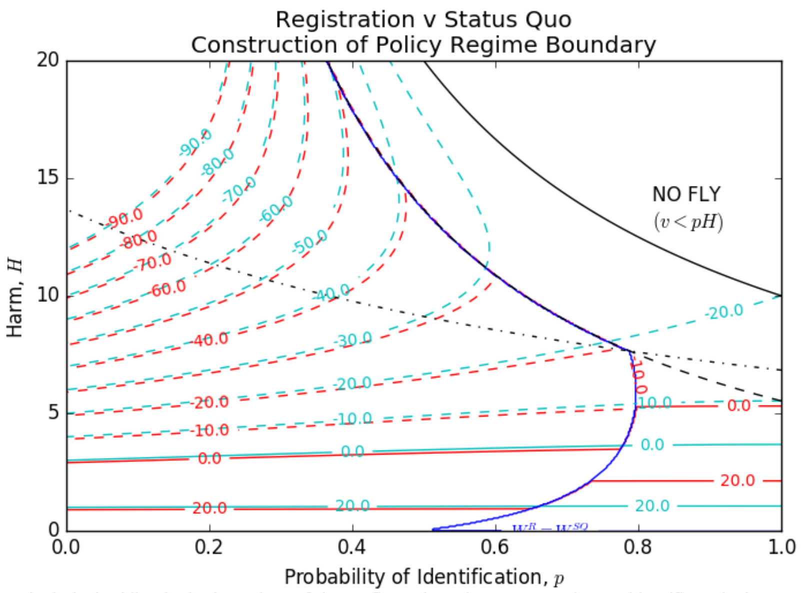
Figures 4.7 and 4.8 repeat the construction of the policy regime boundary for the same parameters as figure 4.6, with the exception that $c_E = 0$ and $c_E = 20$ respectively. Comparing figure 4.7 with figure 4.6, it is apparent that if the cost of enforcement decreases from $c_E = 10$ to $c_E = 0$, so that enforcement is costless but registration is costly, then the area in which registration is welfare-enhancing shrinks considerably, and only encompasses an area in which the probability of detection is moderately high and harm is moderately high. Comparing figure 4.8 with figure 4.6, it is apparent that if the cost of enforcement increases from $c_E = 10$ to $c_E = 20$ there is no discernable change in the area where registration is welfare-enhancing.



Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status--quo with no registration and self-defence prohibited. Blue line is the policy regime boundary.
Parameters are: $v=10$; $\psi=0.5$; $c_I=5$; $c_F=10$; $C_E=0$; $r=1$.

Figure 4.7. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 50% of time. $\psi = 0.5$, $c_F = 10$, $c_I = 5$, $c_E = 0$.

On comparing figures 4.7, 4.6, and 4.8 it seems reasonable to hypothesise that the area in which registration is welfare-enhancing reduces if the cost of enforcement is less than the unit gross value, v, obtained by the drone operator.



Black dashed line is the boundary of the no fly region when not carrying an identifier. Black dash-dot line is the boundary of the no fly region when carrying an identifier. Red lines are the iso-welfare curves with registration of drones. Cyan lines are the iso-welfare curves for the status--quo with no registration and self-defence prohibited. Blue line is the policy regime boundary. Parameters are: $v = 10$; $\psi = 0.5$; $c_I = 5$; $c_F = 10$; $C_E = 20$; $r = 1$.

Figure 4.8. Construction of policy regime boundary for Registration v Status Quo; in range of detection technology 50% of time. $\psi = 0.5$, $c_F = 10$, $c_I = 5$, $c_E = 20$.

4.6 Discussion

A body of aviation regulations exists to govern the operation of drones and thereby control at least some of the harm that might by induced by their use (Section 4.2.2 above). Other regulations exist to control the privacy-related harm that might be induced by drones (Chapter 2). These regulations will only be effective if drone operators choose to comply with them. As we saw with the Gatwick event, discussed in the introduction to this chapter, when individuals choose not to comply the effects can be significant. A registration scheme is premised on the presumption that registration will make it easy to identify the perpetrator of a harmful event, and thus allow attribution of liability to that individual. The self-interested operator will then elect to comply with the regulations. The purpose of this chapter has been to identify the circumstances in which registration will be more efficient than the status quo which has no registration and no ability to take defensive actions to destroy drones.

Given available technology and the characteristics of drones, it is apparent that registration can be bypassed and does not prevent harm from occurring. The registration system adopted in the United States requires drones to physically display an identification number, but does not have a provision for remote identification. This system has not stopped drones flying in areas of restricted airspace where there is significant potential for harm, and it has not improved the ability of authorities to identify the perpetrator. The only commercially available remote identification system for drones was available at Gatwick, but was unable to provide the information required to locate or identify the operator. It is unclear whether this was because of the make of drone, sources of radio interference, or for some other reason. However, the Gatwick incident was clearly malicious and intentional, and an individual that has such intent can readily circumvent any existing remote identification technology.

The analysis presented in this chapter suggests that in the absence of a remotely readable identifier, registration is only welfare-enhancing if harm is the probability of identifying an operator without an identifier is at least moderately high. Given current technology, for the registration schemes to enable identification of a drone or operator of a drone requires that (a) the operator of the drone displays the correct registration number on the drone, and (b) that the drone flies sufficiently close to a person, and in the correct orientation, so that the identification number could be viewed or photographed. It seems highly unlikely that a person intent on malicious activity would register the drone, and if they did register then it is unlikely that they would display their own registration number during the course of malicious activity.

The registration scheme adopted by the United Kingdom in November 2019 is the same as the United States' scheme in its essential characteristics. Given the experience of the United States and the results of the numeric analysis, it is apparent that, given available technology, this registration scheme would not have prevented the incident at Gatwick and will not prevent similar incidents in future.

The low likelihood of an identifier being within range of the detection technology is approximated by the scenario where $\psi = 0.1$. The analysis for this scenario indicates that there are some circumstances in which registration may be optimal, down to quite a low probability of identification. However, the exact region in which registration is welfare-enhancing depends on the opportunity cost of the identifier and the fine imposed. A very large fine, of at least 10 times the unit gross value, v, obtained by the drone operator, may be required to incentivise registration. Even then, if the probability of identification is very low then registration is likely to be bypassed and registration will reduce rather than increase welfare.

The analysis in this chapter can also be applied to other situations in which registration may be employed and certain activities may cause harm. Consider, for example, the use of hand-held mobile phones in cars. Drivers are licensed and cars are registered, and New Zealand (like many jurisdictions) has laws against the use of hand-held mobile phones in cars. While many or even most drivers will choose to comply with the law, some do not.

A survey conducted on the Auckland Southern Motorway in 2018 found that 671 of 18,651 drivers (3.6 percent) over a 7 hour period were touching, checking, or otherwise using their mobile phones (Earley, 2018). In the corresponding Auckland and Counties/Manakau regions, in 2017 the New Zealand Police recorded 6,545 offences of using a hand held device for calling or texting while driving (New Zealand Police, 2018). The nationwide total for 2017 was 23,412 offences. The observed rate at the Auckland Southern Motorway survey site for a period of less than a day, outside of peak traffic hours, was more than 37 times the daily average offences for the wider region in the year prior. In this instance, while the Police may issue an infringement notice for any offence that they detect, the statistics suggest that significantly less than 3 percent of mobile phone offences are detected.

The analysis presented here clearly suggests that if such a low percentage of offences are detected, then registration and licensing will be an ineffective means of preventing or deterring the offending.

Whether people comply with these regulations, and the reasons for compliance or non-compliance, can be considered from both instrumental and normative perspectives (Tyler, 1990). The instrumental perspective is that people will elect to comply or not comply on the basis of self-interest based on costs and benefits: this is the standard perspective of law and economics literature, and the perspective that underpins the model presented here. The normative perspective holds that people will comply with a law because they view the law as just and moral, and will comply despite personal cost, whereas they might not comply with a law that they consider lacks legitimacy. Thus, the instrumental perspective is that people comply with rules concerning mobile phone use in cars because they judge the expected cost of non-compliance less than the expected benefits from non-compliance. The 3.6 percent of drivers observed not complying may possess different information as to costs or may have higher benefits from mobile phone use than the rest of the driving population. The normative perspective, on the other hand, suggests that some fraction of the 96.4 percent that comply with the rules consider that those rules are legitimate and comply for that reason alone. With registration an ineffective tool for reducing hand-held mobile phone use in cars, regulatory authorities must turn to other means to change the underlying social norms, such as public education campaigns.

In a study conducted for the New Zealand Civil Aviation Authority, 35 percent of New Zealand drone operators did not consider that drones pose a risk to aviation safety (Colmar Brunton, 2017). One might reasonably hypothesise that individuals holding this view may consider that rules premised on the notion that drones pose a risk to aviation lack legitimacy. Thus while some drone operators may comply with the relevant regulations simply because they are regulations, others may not comply because of the perceived lack of legitimacy.

Given the lack of surveillance (detection) technology for drones, and the evidence of non-compliance with mobile phone laws when driving when detection rates are low, it seems likely that licencing or registration of drone operators would not solve the problem of lack of compliance with existing rules.

A further problem with registration given existing technology is that it does not change the fact that the casual bystander will not be able to determine whether a drone is registered and if so what the registration identifier is for that drone. There is, therefore, likely to be an ongoing problem of potentially hazardous use of drones, and this problem is likely to persist regardless of any registration regime that may be proposed.

Finally, those countries that have adopted a registration scheme have imposed a weight threshold below which registration does not apply. A weight threshold was not considered in the analysis presented in this chapter. However, if a monotonic relationship exists between the weight of the drone and harm, then the level of harm at the policy regime boundary implies a weight threshold for registration.

4.7 Conclusion

This analysis has shown that registration of drones may be welfare enhancing if certain conditions are met. A necessary condition for registration to be welfare-enhancing is that the cost of an identifier is less than the fine for not carrying an identifier. Furthermore, registration is generally welfare-enhancing when the probability of identifying the drone operator in the absence of an identifier is relatively high. Even a perfectly reliable remotely-readable identifier will be ineffective, and registration inefficient, if there is a low probability of identifying the operator of a drone that is not registered. Given the characteristics of drones, and the ease of operating them in a manner that keeps the operator anonymous, it seems likely that registration of drones will not be welfare-enhancing.

The space in which registration is welfare-enhancing relative to the status quo overlaps significantly with the space in which Chapter 3 finds that self defence against drones is efficient. Further research is required to establish the optimal combination of self defence and registration. It is this question that I consider in the final chapter of this thesis.

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Chapter 5

Optimal Policy

Synopsis

This chapter analyses the interaction between registration and the threat of destruction when bystanders are able to engage in self-defence against drones. I find that, for the likely probability of identifying the operator of a drone that is not carrying an identifier, it is optimal to allow self-defence against drones when harm is moderate-to-high, coupled with a voluntary registration scheme.

5.1 Introduction

Chapter 2, published as Shelley (2016), considers potential responses to mitigate privacy violations and surveillance by unmanned systems. A package of regulatory measures is proposed in that chapter, including a Code of Practice for Drone Operation issued under the Privacy Act 1993, drones to carry a remotely-readable encoded radio frequency identification beacon, and the right to take self-defence against drones that are not carrying such a beacon. Chapter 3 then considers a model in which a bystander can take action in self-defence against a drone operator. Self defence is found to be efficient when the probability of attributing liability is low and harm is relatively high. Chapter 4 analyses an alternative scenario in which the bystander is unable to take action in self-defence, but the drone operator may be registered and registration allows harm induced by a drone to be attributed to the drone operator.

In the present chapter I consider the question of the optimal regulatory policy. The various options are:

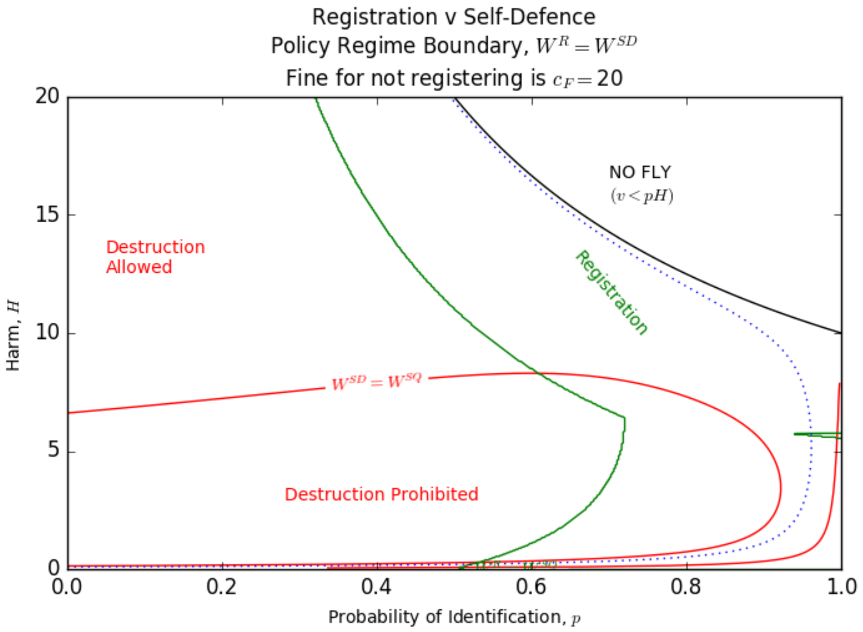
- the Status Quo, in which there is no registration and bystanders are not legally able to take action in self-defence;

- Self-Defence, in which bystanders are able to take action in self-defence in a specified set of circumstances;
- Registration, in which drones are required to be registered; and
- Registration and Self-Defence, in which drones are required to be registered, but bystanders are also able to take action in self-defence in a specified set of circumstances. Registration may be voluntary, or non-registration may be punishable by a fine.

As illustrated by figure 5.1, there may be considerable overlap between the 'space' in which registration is efficient and the space in which self-defence is efficient. The red curve in figure 5.1 is the policy regime boundary for self-defence: above and to the left of that policy regime boundary it is welfare-enhancing to allow self-defence against drones and destruction of drones. This is the policy regime boundary arising from the simultaneous move case in Chapter 3. The green curve in figure 5.1 is the policy regime boundary for registration: to the right of the green curve it is welfare-enhancing to require the registration of drones, but to the left of the green curve registration reduces welfare.

It is readily evident that in the lower-right quadrant of figure 5.1, both registration and self-defence may be individually welfare-enhancing. There is a clear overlap between the area that self-defence is welfare-enhancing and the area in which registration is optimal. However, the policy regime boundaries in figure 5.1 do not tell us anything about the optimal policy in area of overlap where both policies are individually welfare-enhancing. It may be that both together are optimal, or it may be that one policy dominates the other. There may also be interaction between self-defence and registration that either shrinks or expands the boundary of the region of overlap, or even alters the boundaries of a region where there is no overlap. To answer the question of the optimal policy or combination of policies in it is necessary to construct a model that combines both registration and self-defence. The welfare outcomes from the models in Chapter 3, Chapter 4, and this chapter can then be compared to determine the optimal policy.

Section 5.2 presents an analytical model where both registration and self-defence are utilised. This model is an amalgam of the models presented in Chapter 3 and Chapter 4, so the results can be directly compared with the analyses in those two chapters.



Red line is the policy regime boundary for self-defence vs the status quo. Green line is the policy regime boundary for registration vs the status quo. In all cases the status quo has no registration and self-defence is prohibited.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 10$; $c_F = 20$; $C_E = 10$; $r = 1$.

Figure 5.1. Policy Regime Boundaries for Self Defence (red) and Registration (green); drone in range of the detection technology half of the time.

Section 5.3 provides results from the numeric analysis. Results are presented to compare the combined registration and self-defence with (a) the status quo with no registration or self-defence, (b) registration only, and (c) self-defence with no registration.

Section 5.4 concludes with a discussion of the optimal policy.

5.2 Model: Drone Registration with Self Defence

5.2.1 General Setup

Following the analysis in Chapter 3, there is a drone operator and a bystander. Let v denote the unit value received by the operator from flying her drone, H denote the unit harm to the bystander, and $m \in (0, 1)$ denote the proportion of liability borne by the drone operator. Nature chooses v and H.

The drone operator chooses an activity level, $q \in \mathbb{R}_+$. The bystander chooses a level of effort toward self-defence, $s \in \mathbb{R}_+$. Although Chapter 3 allows these choices to be either be simultaneous or sequential, the present analysis assumes that all choices are made simultaneously.

The bystander's self-defence may destroy the drone. The probability that the drone will *not* be destroyed is denoted by $0 \leqslant \rho(s) \leqslant 1$, which is strictly decreasing and strictly convex. The costs associated with destroying the drone are κ.

Following the analysis in Chapter 4, attribution of liability for any harm requires that the operator of the aircraft can be identified. Identification may be achieved either by way of the aircraft carrying an an identifier that can be "read" by the detection technology, or by visual observation coupled with investigation. The detection technology is capable of "reading" the identifier at a distance of up to $\bar{d}$. A register exists that enables the matching of an identifier to a legal person who is the registered operator of the drone. If an identifier is read then liability for any harm can be fully attributed to the registered operator. The cost of administering the drone registration scheme is $r \in \mathbb{R}_+$.

If the aircraft is *not* carrying a remotely-readable identifier then the probability of identifying the operator, p, is exogenous.

Let $t \in \{0, 1\}$ denote the drone operator's (discrete) choice of whether to carry an identifier; if $t = 1$ then an identifier is carried, but if $t = 0$ then an identifier is not carried.

Let $m \in (0, 1)$ denote the proportion of liability borne by the drone operator, and $\psi \in (0, 1)$ denote the proportion of time that the drone is expected to be within range of the detection technology. If the drone is within range of the detection technology then the liability share is unity if an identifier is carried, but if an identifier is not carried then the liability share is equal to the probability of identifying the operator, p. If the drone is not in range of the detection technology then liability is p. The proportion of liability m is therefore given by:

$$m(\psi, t) = \psi \left[(1 - t)p + t\right] + (1 - \psi)p \tag{5.1}$$

Let $c(q)$ denote the cost of operating the drone, which is strictly increasing and strictly convex. Let the opportunity cost of carrying an identifier be c_I. If an aircraft is required to have an identifier but does not carry one then the aircraft operator is liable for a fine of c_F. To attempt to identify the operator of an aircraft that is not carrying an identifier the enforcement agency incurs an enforcement cost of c_E.

Following the specific assumptions of Chapter 3 and Chapter 4, assume that:

$$c(q) := \eta \frac{q^\alpha}{\alpha}, \qquad \rho(s) := (1+s)^{-n},$$

where $\alpha \geqslant 2$ and $n \geqslant 1$.

5.2.2 Operator's Best Response

Assuming risk-neutrality the expected utility of the drone operator is:

$$U(q; s, \psi, H, t) = \max\left\{0, \rho(s)(v - m(\psi, t)H)q - c(q) - tc_I - (1-t)pc_F - (1-\rho(s))\kappa\right\}. \tag{5.2}$$

The first term is the expected value received by the operator, net of any liability for harm caused. The second term is the cost of operation. The third term is the cost of carrying an identifier. The fourth term is the expected fine if an identifier is not carried. The fifth term is the expected cost from the drone being destroyed. The drone operator may choose to operate with an identifier ($t = 1$) or without an identifier ($t = 0$).

Let U^* denote the unconstrained utility of the drone operator. Then:

$$U^*(q; s, \psi, H) = \begin{cases} \rho(s)(v - m(\psi, t=0)H)q - c(q) - pc_F - (1-\rho(s))\kappa & : \quad t = 0 \\ \rho(s)(v - m(\psi, t=1)H)q - c(q) - c_I - (1-\rho(s))\kappa & : \quad t = 1 \end{cases}. \tag{5.3}$$

Note that if $q = 0$ then $U^* < 0$ for $pc_F + (1-\rho(s))\kappa > 0$ and $c_I + (1-\rho(s))\kappa > 0$.

The general form of the drone operator's FOC is:

$$U_q = \rho(s)\left(v - m(\psi, t)H\right) - c_q = 0. \tag{5.4}$$

Let q^* denote the operator's best response. The closed-form expression for her best response is:[1]

$$q^*(s;\psi,H,t) = \left[\rho(s)\left(\frac{v - m(\psi,t)H}{\eta}\right)\right]^{\frac{1}{\alpha-1}} \tag{5.5}$$

$$= \begin{cases} \left[\rho(s)\left(\frac{v-pH}{\eta}\right)\right]^{\frac{1}{\alpha-1}} & : \ t=0 \\ \left[\rho(s)\left(\frac{v-(\psi+(1-\psi)p)H}{\eta}\right)\right]^{\frac{1}{\alpha-1}} & : \ t=1 \end{cases}. \tag{5.6}$$

An increase in the net value received by the operator from the drone operation, $v - mH$, increases the value of q^*. An increase in the cost of operation via the parameter η reduces the value of q^*. An increase in the bystander's effort towards self-defence, s, reduces the value of q^*. These effects are consistent with the results from Chapter 3.

Note also that when the drone operator elects not to carry an identifier then the best response function is the same as the simultaneous case in Chapter 3.

5.2.3 Bystander's Best Response

The expected utility of the bystander is:

$$V(s;q,\psi,m,H,t) = -\rho(s)\,(1 - m(\psi,t))\,Hq - s. \tag{5.7}$$

The first term is the expected harm from the drone operation, net of any liability borne by the drone operator. The second term is the effort exerted in self-defence. The bystander only incurs cost so his utility is always negative.

The bystander's FOC is:

$$-V_s = \rho'(s)\,(1 - m(\psi,t))\,Hq + 1 = 0. \tag{5.8}$$

Let s^* denote the bystander's best response. The closed-form expression

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[1] $c(q) = \eta q^\alpha/\alpha \Rightarrow c'(q) = \eta q^{(\alpha-1)}$. From the operator's FOC we have $c'(q) = \rho(s)\,(v - m(\psi,t)H)$. Setting the two expressions for $c'(q)$ equal we have $q = \left[\rho(s)\frac{v-m(\psi,t)H}{\eta}\right]^{1/(\alpha-1)}$, which is positive for all $v > mH$.

for his best response is:[2]

$$s^*(q;\psi,H,t) = \max\left\{0, \left[n\left(1-m(\psi,t)\right)Hq\right]^{\frac{1}{n+1}} - 1\right\} \tag{5.9}$$

$$= \begin{cases} \max\left\{0, \left[n\left(1-p\right)Hq\right]^{\frac{1}{n+1}} - 1\right\} & : t = 0 \\ \max\left\{0, \left[n(1-\psi)(1-p)Hq\right]^{\frac{1}{n+1}} - 1\right\} & : t = 1 \end{cases}. \tag{5.10}$$

5.2.4 Equilibrium

Let $\hat{q}$ and $\hat{s}$ denote the equilibrium level of q and s respectively, prior to the implementation of the constraint $U = \max\{0, U^*\}$. For ease of exposition, I refer to this as the 'unconstrained' equilibrium, even though the bystander's best response function already includes a floor of zero on the value of s^* (and hence also on the value of $\hat{s}$).

Bystander

For an interior solution, $\hat{s}$ is given by:[3]

$$\hat{s}(\psi,H,t) = \max\left\{0, \left[\left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-1)}\left(\frac{v-m(\psi,t)H}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)+n}} - 1\right\}. \tag{5.11}$$

A corner point solution occurs when $\hat{s} = 0$. A corner point solution will arise when:

$$\hat{s} = 0 \Rightarrow \left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-1)}\left(v-m(\psi,t)H\right) \leqslant \eta, \tag{5.12}$$

and hence the boundary of the region for which $\hat{s} = 0$ is given by:

$$\left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-1)}\left(v-m(\psi,t)H\right) - \eta = 0.$$

The corner-point solution will arise for low levels of harm and/or high levels of liability (both $H \to 0$ and $m \to 1$ provide $\hat{s} = 0$).

Lemma 34. *If the drone operator chooses to carry an identifier and the drone is always within range of the detection technology then the bystander*

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[2] $\rho(s) = (1+s)^{-n} \Rightarrow \rho'(s) = -n(1+s)^{-(n+1)}$. From the bystander's FOC we have $\rho'(s)\left(1-m(\psi,t)\right)Hq + 1 = 0 \Rightarrow \rho'(s) = \frac{-1}{(1-m)Hq}$. Setting the two expressions for $\rho'(s)$ equal we have $\frac{1}{n}(1+s)^{(n+1)} = (1-m)Hq \Rightarrow s = \left[n\left(1-m(\psi,t)\right)Hq\right]^{\frac{1}{n+1}} - 1$ as shown.

[3] See equation (5.29) in Appendix 5.A.1.

will not exert any effort in self-defence.

Proof. If the drone operator chooses to carry an identifier then $t = 1$ and $m = \psi(1-p)+p$. If the drone is always within range of the detection technology then $\psi = 1$ and $m = 1$. Under these conditions, the term in square brackets in equation 5.11 reduces to zero and it must be that $\hat{s} = 0$. □

Lemma 35. *For an interior solution, if the drone is carrying an identifier then the effort exerted by the bystander in self-defence is inversely related to the proportion of time that the drone spends within range of the detection technology.*

Proof. Differentiating equation (5.11) wrt ψ for $\hat{s} > 0$ provides:

$$\hat{s}_\psi = \frac{d[.]}{d\psi} . \frac{1}{(n+1)(\alpha-1)+n} [.]^{\frac{1-(n+1)(\alpha-1)-n}{(n+1)(\alpha-1)+n}} .$$

where $[.] = \left[\left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-1)} \left(\frac{v-m(\psi,t)H}{\eta}\right) \right] > 0$. The differential of $[.]$ is:

$$\begin{aligned} \frac{d[.]}{d\psi} = & - n m_\psi H \left(\alpha-1\right)\left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-2)} \left(\frac{v-m(\psi,t)H}{\eta}\right) \\ & - m_\psi \left(\frac{H}{\eta}\right) \left(n\left(1-m(\psi,t)\right)H\right)^{(\alpha-1)} . \end{aligned} \tag{5.13}$$

By definition $0 \leqslant 1-m(\psi,t) \leqslant 1 \Rightarrow n(1-m(\psi,t))H \geqslant 0$. An interior solution also requires that $v - m(\psi,t)H > 0$. Hence:

$$\frac{d[.]}{d\psi} \propto -m_\psi = -\left[(1-t)p+t\right]+p. \tag{5.14}$$

If the drone is carrying an identifier then $t = 1 \Rightarrow m_\psi = 1-p$ and $-1 \leqslant -m_\psi \leqslant 0 \Rightarrow d[.]/d\psi \leqslant 0$. Therefore it must be that $s_\psi \leqslant 0$ and the effort exerted by the bystander in self-defence is inversely related to the proportion of time that the drone spends within range of the detection technology. □

Lemma 36. *If the drone is not carrying an identifier then the effort that the bystander exerts in self-defence is independent of the proportion of time that the drone spends within range of the detection technology.*

Proof. If the drone is not carrying an identifier then $t = 0 \Rightarrow m_\psi = p - p = 0$. Therefore from equation (5.14) it must be that $d[.]/d\psi = 0$ and hence $s_\psi = 0$. Thus the effort that the bystander exerts in self-defence is independent of the proportion of time that the drone spends within range of the detection technology. $\square$

Operator

There are two cases for $\hat{q}$: an interior solution with $\hat{s} > 0$, and a corner-point solution with $\hat{s} = 0$.

For an interior solution $\hat{q}$ is given by:[4]

$$\hat{q}(\psi, H, t) = \left[\left(\frac{1}{n(1 - m(\psi, t))H} \right)^n \left(\frac{v - m(\psi, t)H}{\eta} \right)^{(n+1)} \right]^{\frac{1}{(n+1)(\alpha-1)+n}}. \tag{5.15}$$

A corner-point solution will arise when $\hat{s} = 0$. For a corner-point solution the value of $\hat{q}$ is given by:

$$\hat{s} = 0 \Rightarrow \hat{q}(\psi, H, t) = \left(\frac{v - m(\psi, t)H}{\eta} \right)^{\frac{1}{\alpha-1}}. \tag{5.16}$$

Lemma 37. *For an interior solution, whether equilibrium activity with an identifier is higher or lower than equilibrium activity with no identifier depends on the proportion of time spent within range of the detection technology.*

Proof. Let $\hat{q}_0$ denote equilibrium activity when an identifier is not carried, and $\hat{q}_1$ denote equilibrium activity when an identifier is carried. If equilibrium activity with an identifier is higher than equilibrium activity with no identifier then:

$$\begin{aligned}
&\hat{q}_1 > \hat{q}_0 \\
&\Rightarrow \left[\left(\frac{1}{n(1-\psi)(1-p)H} \right)^n \left(\frac{v - [\psi + (1-\psi)p]\, H}{\eta} \right)^{(n+1)} \right] \\
&\quad > \left[\left(\frac{1}{n(1-p)H} \right)^n \left(\frac{v - pH}{\eta} \right)^{(n+1)} \right] \\
&\Rightarrow \left(\frac{1}{1-\psi} \right)^n (v - [\psi + (1-\psi)p]\, H)^{(n+1)} > (v - pH)^{(n+1)} \\
&\Rightarrow \psi > 1 - \left(\frac{v - [\psi + (1-\psi)p]\, H}{v - pH} \right)^{\frac{(n+1)}{n}}.
\end{aligned} \tag{5.17}$$

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[4] See equation (5.30) in Appendix 5.A.2.

Furthermore, $0 \leqslant \psi \leqslant 1 \Rightarrow \psi + (1-\psi)p \geqslant p$ and hence $v - [\psi + (1-\psi)p]\, H \leqslant v - pH$. Thus the RHS of equation (5.17) is $\leqslant 1$.

Equation (5.17) provides a threshold for ψ. If ψ is greater than the threshold then $\hat{q}_1 > \hat{q}_0$, but if ψ is less than the threshold then $\hat{q}_1 < \hat{q}_0$. Assume, for example, that $v = 10, p = 0.1, H = 8,$ and $n = 2$. Then the threshold occurs at $\psi = 0.6801$. Assume that $\psi = 0.67$ then the RHS of equation (5.17) is 0.6720 and hence the condition in equation (5.17) is not satisfied and it must be that $\hat{q}_1 < \hat{q}_0$. Assume now that $\psi = 0.69$ then the RHS of equation (5.17) is 0.6880 and hence the condition in equation (5.17) *is* satisfied and it must be that $\hat{q}_1 > \hat{q}_0$. ☐

Corollary 37.1. *For an interior solution, if the drone is never in range of the detection technology then equilibrium activity with an identifier is lower than equilibrium activity without an identifier.*

Proof. In the special case that the drone is never within range of the detection technology then $\psi = 0$ but the RHS of equation (5.17) is > 0. Therefore the condition in equation (5.17) is not met and it must be that $\hat{q}_1 < \hat{q}_0$. ☐

Corollary 37.2. *For an interior solution, if the drone is always in range of the detection technology then equilibrium activity with an identifier is higher than equilibrium activity without an identifier.*

Proof. If the drone is always in range of the detection technology then $\psi = 1$ and the RHS of equation (5.17) is $\geqslant 0$ and < 1. Whatever that value happens to be we know that ψ is greater than that threshold value so $\hat{q}_1 > \hat{q}_0$. ☐

Lemma 38. *For a corner-point solution, equilibrium activity with no identifier is at least equal to equilibrium activity with an identifier and may be greater.*

Proof. Assume a corner-point solution both when the drone is carrying an identifier and when the drone is not carrying an identifier. If equilibrium activity with no identifier is at least equal to equilibrium activity with an identifier then:

$$\begin{aligned} \hat{q}_{CP,0} &\geqslant \hat{q}_{CP,1} \\ \Rightarrow \left(\frac{v - pH}{\eta}\right)^{\frac{1}{\alpha-1}} &\geqslant \left(\frac{v - [\psi + (1-\psi)p]\, H}{\eta}\right)^{\frac{1}{\alpha-1}}, \end{aligned} \tag{5.18}$$

which is true for all $0 \leqslant \psi \leqslant 1$. ☐

5.2.5 Operator Choice and the Constrained Equilibrium

The operator chooses both whether or not the drone will operate and, if the decision is to operate, whether or not the drone will carry an identifier. These decisions are both made on the basis of utility. If utility would be negative at the equilibrium level of activity then the operator will choose not to fly and both operator and self-defence will be constrained to zero.

Let $\bar{q}_0$ denote the constrained level of activity when an identifier is *not* carried, and $\bar{q}_1$ denote the constrained level of activity when an identifier is carried. The drone operator will only choose to fly if utility is non-negative. Hence:

$$\bar{q}_0 = \begin{cases} 0 & : \quad U^*(\hat{q}_0) < 0 \\ \hat{q}_0 & : \quad U^*(\hat{q}_0) \geqslant 0 \end{cases} \tag{5.19}$$

$$\bar{q}_1 = \begin{cases} 0 & : \quad U^*(\hat{q}_1) < 0 \\ \hat{q}_1 & : \quad U^*(\hat{q}_1) \geqslant 0 \end{cases} \tag{5.20}$$

The operator's choice also potentially impacts the bystander's choice of effort towards self-defence: if the operator chooses not to fly then the bystander will also exert no effort towards self-defence. Let $\bar{s}_0$ denote the effort towards self-defence when an identifier is *not* carried, and $\bar{s}_1$ denote the effort towards self-defence when an identifier is carried. Then:

$$\bar{s}_0 = \begin{cases} 0 & : \quad U^*(\hat{q}_0) < 0 \\ \hat{s}(\psi, H, t = 0) & : \quad U^*(\hat{q}_0) \geqslant 0 \end{cases} \tag{5.21}$$

$$\bar{s}_1 = \begin{cases} 0 & : \quad U^*(\hat{q}_1) < 0 \\ \hat{s}(\psi, H, t = 1) & : \quad U^*(\hat{q}_1) \geqslant 0 \end{cases} \tag{5.22}$$

Let U_0 denote utility when an identifier is not carried, and U_1 denote utility when an identifier is carried. Then from equation (5.2) we have:

$$U_0 = \max\left\{0, \rho(\bar{s}_0)(v - pH)\bar{q}_0 - c(\bar{q}_0) - pc_F - (1 - \rho(\bar{s}_0))\kappa\right\} \tag{5.23}$$

$$U_1 = \max\left\{0, \rho(\bar{s}_1)(v - [\psi + (1 - \psi)p]\, H)\bar{q}_1 - c(\bar{q}_1) - c_I - (1 - \rho(\bar{s}_1))\kappa\right\}, \tag{5.24}$$

which is equivalent to:

$$U_0 = \begin{cases} 0 & : U^*(\hat{q}_0) < 0 \\ \rho(\bar{s}_0)(v - pH)\hat{q}_0 - c(\hat{q}_0) - pc_F - (1 - \rho(\bar{s}_0))\kappa & : U^*(\hat{q}_0) \geqslant 0 \end{cases}$$

$$U_1 = \begin{cases} 0 & : U^*(\hat{q}_1) < 0 \\ \rho(\bar{s}_1)(v - \left[\psi + (1 - \psi)p\right] H)\hat{q}_1 - c(\hat{q}_1) - c_I - (1 - \rho(\bar{s}_1))\kappa & : U^*(\hat{q}_1) \geqslant 0 \end{cases}$$

Let U_{max} denote maximum utility. Then:

$$U_{max} = \max\left\{U_0, U_1\right\}. \tag{5.25}$$

The constrained level of drone activity, $\bar{q}$, is given by:

$$\bar{q} = \begin{cases} 0 & : \quad U_{max} = 0 \\ \hat{q}_0 & : \quad U_{max} = U_0 \\ \hat{q}_1 & : \quad U_{max} = U_1 \end{cases}. \tag{5.26}$$

5.2.6 Welfare

Following the analysis in Chapter 4, let c_E denote the cost of the effort of attempting to identify the drone if it was not detected by the detection system: the probability of such detection is p, and the total cost of effort to identify the drone is independent of the activity level.

Welfare is the sum of the operator's utility, harm suffered by the bystander, the cost of effort of identifying the drone, and the cost of administering the registration scheme. Let W_0 denote welfare if an identifier is not carried, and W_1 denote welfare if an identifier is carried. Then:

$$W_0 = \begin{cases} -r & : U^*(\hat{q}_0) < 0 \\ \rho(\hat{s}_0)(v - H)\hat{q}_0 - c(\hat{q}_0) - (1 - \rho(\hat{s}_0))\kappa - c_E - r & : U^*(\hat{q}_0) \geqslant 0 \end{cases}$$

$$W_1 = \begin{cases} -c_I - r & : U^*(\hat{q}_1) < 0 \\ \rho(\hat{s}_1)(v - H)\hat{q}_1 - c(\hat{q}_1) - (1 - \rho(\hat{s}_1))\kappa - c_I - (1 - \psi)c_E - r & : U^*(\hat{q}_1) \geqslant 0 \end{cases} \tag{5.27}$$

The expected fine is a cost to the operator but is also a benefit to society:

the two effects cancel out so the expected fine does not appear in the welfare function. If the drone is carrying an identifier then effort only needs to be exerted to identify the drone when it is operating beyond the range of the detection system, hence the cost of effort is $(1-\psi)c_E$. The cost of administering the registration scheme is incurred regardless of whether or not the drone operator chooses to register her drone and carry an identifier.

Let W^{RS} denote welfare with the registration scheme when self-defence is also allowed. Then:

$$W^{RS} = \begin{cases} -r & : \quad U_{max} = 0 \\ W_0 & : \quad U_{max} = U_0 \\ W_1 & : \quad U_{max} = U_1 \end{cases} . \tag{5.28}$$

5.3 Numeric Analysis

This section provides a numeric analysis of welfare with both registration and self-defence in comparison to the other policy options considered. Section 5.3.1 compares registration and self-defence with the status quo where there is no registration and destruction of drones is prohibited. Section 5.3.2 then compares registration and self-defence with registration only. Section 5.3.3 compares registration and self-defence with self-defence only. Section 5.3.4 compares registration only with self-defence only. Section 5.3.5 identifies the optimal policy across the (p, H) space.

Following Chapter 3 and Chapter 4, parameters for the cost function are $\alpha = 2$ and $\eta = 0.5$, the unit value from the drone operation is $v = 10$, and the cost of the registration regime is $r = 1$. To simplify the exposition, charts are only presented for the case where the drone spends half the time within range of the detection technology ($\psi = 0.5$).

Also to simplify the exposition, I only present charts of the policy regime boundaries for the selected policies; I do not show the construction of the policy regime boundary. To distinguish between policy regime boundaries, the colour convention in table 5.1 is adopted.

Table 5.1

Colour convention for Policy Charts

Policy 1	Policy 2	Math	Colour
self-defence	status quo	$W^{SD} = W^{SQ}$	red
registration	status quo	$W^{R} = W^{SQ}$	green

Table 5.1

Colour convention for Policy Charts

Policy 1	Policy 2	Math	Colour
registration	self-defence	$W^R = W^{SD}$	orange
registration & self-defence	status quo	$W^{RS} = W^{SQ}$	blue
registration & self-defence	self-defence	$W^{RS} = W^{SD}$	brown
registration & self-defence	registration	$W^{RS} = W^R$	magenta

5.3.1 Comparison with the Status Quo

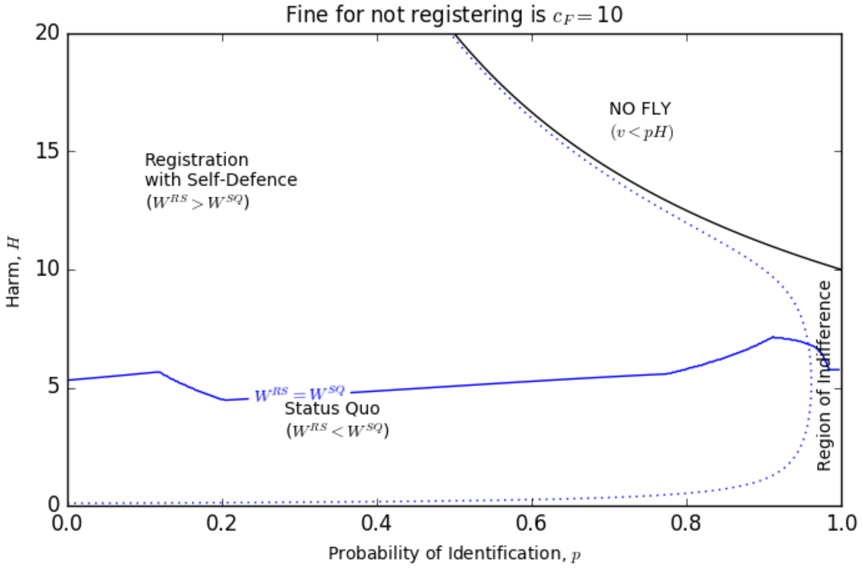
In this section I compare welfare under registration with self-defence to welfare under the status quo with neither registration nor self-defence.

Figures 5.2 and 5.3 show the policy regime boundary for registration with self-defence compared to the status quo with neither registration nor self-defence. Above the blue policy regime boundary welfare is higher with registration and self-defence; below the curve welfare is higher under the status quo. The two figures show a fine of $c_F = 10$ (figure 5.2), and voluntary registration ($c_F = 0$, figure 5.3), respectively. In both figures the cost of the identifier is $c_I = 5$.

The policy regime boundary in figure 5.2 shows that compared to the status quo, registration with self-defence is welfare-enhancing at moderate to high levels of harm, but is welfare-reducing at low levels of harm. The boundary does not have a constant slope, but instead has several changes in slope which reflect changes in underlying behaviours.

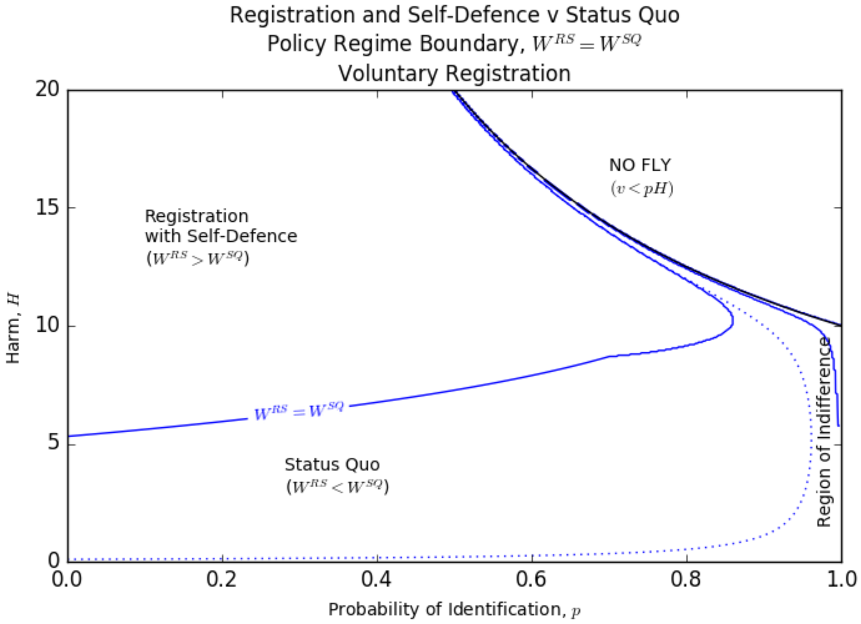
Figure 5.3 shows the policy regime boundary when registration is voluntary ($c_F = 0$). The upward slope of the curve slowly increases as the probability of identification increases. At higher levels of harm and a high probability of identification the policy regime boundary becomes backward sloping as it converges with the dotted line signifying the boundary of the region where we are indifferent to self-defence. Above and to the left of the policy regime boundary (the upper left quadrant of the chart) it is welfare-enhancing to allow registration with self-defence, and below the policy regime boundary it is optimal to retain the status quo.

Registration and Self-Defence v Status Quo
Policy Regime Boundary, $W^{RS} = W^{SQ}$
Fine for not registering is $c_F = 10$



Blue line is the regime boundary at which welfare under registration with self-defence, W^{RS}, equals welfare under the status quo without registration or self-defence, W^{SQ}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 5$; $c_F = 10$; $C_E = 10$; $r = 1$.

Figure 5.2. Policy Regime Boundary for Registration + Self-Defence v Status Quo; fine = 10


Registration and Self-Defence v Status Quo
Policy Regime Boundary, $W^{RS} = W^{SQ}$
Voluntary Registration

Blue line is the regime boundary at which welfare under registration with self-defence, W^{RS}, equals welfare under the status quo without registration or self-defence, W^{SQ}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 5$; $c_F = 0$; $C_E = 10$; $r = 1$.

Figure 5.3. Policy Regime Boundary for Registration + Self-Defence v Status Quo; Voluntary Registration ($c_F = 0$)

5.3.2 Comparison with Registration Only

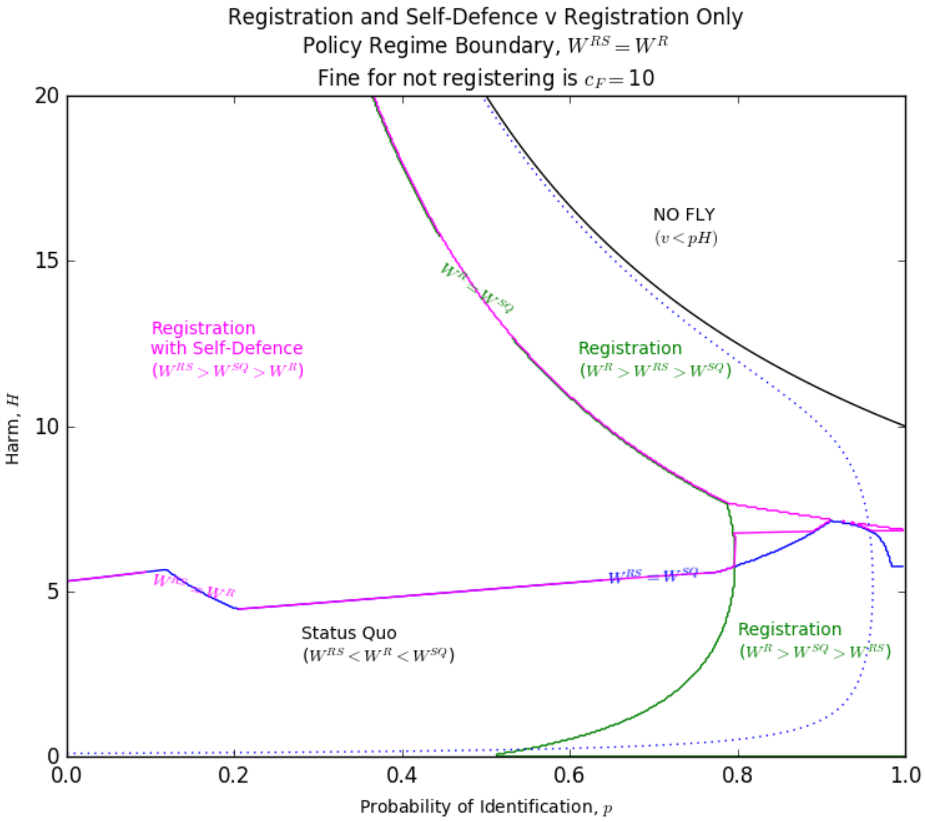
In this section I compare welfare under registration with self-defence to welfare with registration only. This identifies the circumstances in which allowing self-defence will enhance the efficiency of registration.

Figures 5.4 and 5.5 compare the policy regime boundary for registration with self-defence (blue) to the policy regime boundary for registration without self-defence (green), and plot the boundary of the region where registration with self-defence has higher welfare than both the status quo and registration only (magenta). The two figures show a fine of $c_F = 10$ (figure 5.4), and voluntary registration ($c_F = 0$, figure 5.5), respectively. As before, in both figures the cost of the identifier is $c_I = 5$.

Figure 5.4 shows the policy regime boundaries when there is a positive fine for not carrying an identifier ($c_F = 10$). The green curve is the policy regime boundary for registration relative to the status quo. In the area to the left of the green curve the status quo has higher welfare than registration ($W^{SQ} > W^R$), but to the right of the green curve registration has higher welfare than the status quo ($W^R > W^{SQ}$).

The blue policy regime boundary shows the boundary for registration with self-defence versus the status quo, as presented in the previous section. In the area above the blue curve registration with self-defence has higher welfare than the status quo ($W^{RS} > W^{SQ}$), but below the blue curve the status quo has higher welfare than registration with self-defence ($W^{SQ} > W^{RS}$).

The magenta policy regime boundary demarcates the area where registration with self-defence has higher welfare than both registration only and the status quo. Perhaps the most striking feature of figure 5.4 is that although there is an overlap between the region where registration is optimal relative to the status quo (to the right of the green curve) and the region where registration with self-defence is optimal relative to the status quo (above the blue curve), in the area of the overlap registration by itself almost always dominates registration with self-defence. That is, if registration only has higher welfare than the status quo *and* registration with self-defence has higher welfare than the status quo, then registration only almost always has higher welfare than registration with self-defence. Where the magenta policy regime boundary is the envelope of the region to the top left of the blue and green curves, registration with self-defence is not optimal if registration by itself is optimal. The exception to this occurs as



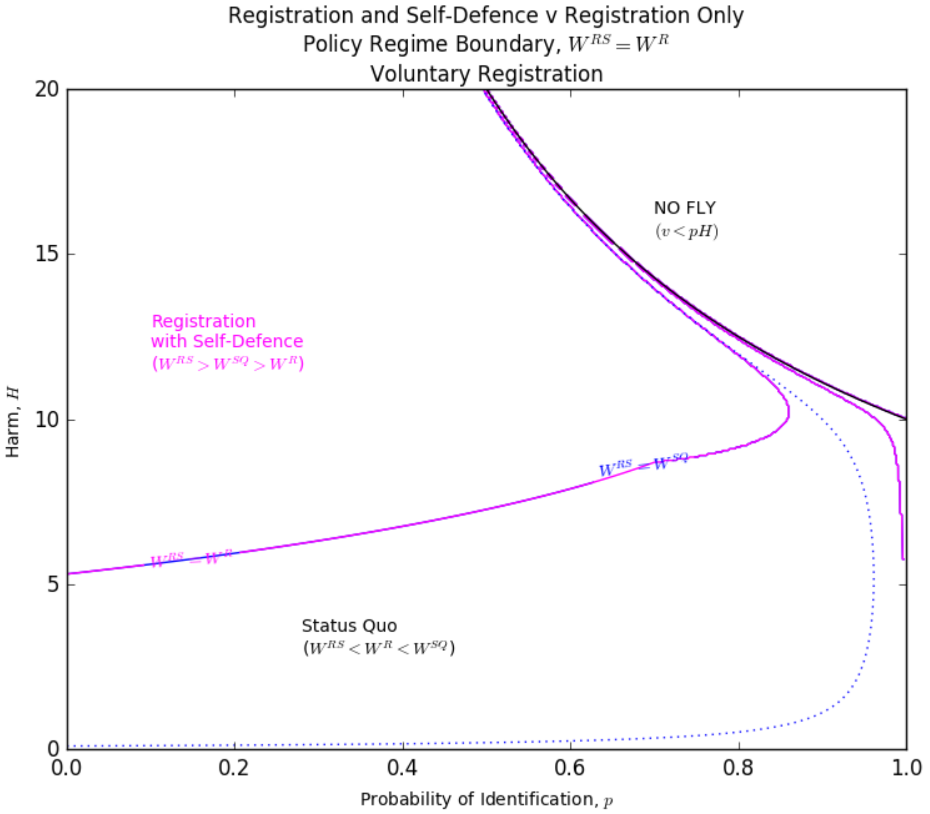
Registration and Self-Defence v Registration Only
Policy Regime Boundary, $W^{RS}=W^{R}$
Fine for not registering is $c_F=10$

Green line is the policy regime boundary at which welfare with registration, W^{R}, equals welfare under the status quo, W^{SQ}. Red line is the policy regime boundary at which welfare with self-defence, W^{SD}, equals welfare under the status quo. Magenta line is the policy regime boundary at which the welfare from registration with self-defence, W^{RS}, equals welfare from registration only without self-defence, W^{R}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v=10$; $\kappa=3$; $\psi=0.5$; $c_I=5$; $c_F=10$; $C_E=10$; $r=1$.

Figure 5.4. Policy Regime Boundary for Registration + Self-Defence v Registration Only; fine = 10

a narrow ‘sliver’ of magenta at a moderate level of harm and a high probability of identification: in this narrow sliver registration with self-defence has higher welfare than either registration by itself or the status quo.

Figure 5.5 shows the policy regime boundaries when registration is voluntary ($c_F = 0$). The green curve is absent from figure 5.5, because registration by itself is never optimal if registration is voluntary. Furthermore, because registration by itself is never optimal, the boundary of the area where registration with self-defence has higher welfare than registration by itself (magenta curve) is coincident with the boundary of the area where registration with self-defence has higher welfare than the status quo (blue curve). Above this curve it is welfare-enhancing to allow registration with self-defence, and below this curve it is optimal to retain the status quo with


Registration and Self-Defence v Registration Only
Policy Regime Boundary, $W^{RS} = W^{R}$
Voluntary Registration

Green line is the policy regime boundary at which welfare with registration, W^{R}, equals welfare under the status quo, W^{SQ}. Red line is the policy regime boundary at which welfare with self-defence, W^{SD}, equals welfare under the status quo. Magenta line is the policy regime boundary at which the welfare from registration with self-defence, W^{RS}, equals welfare from registration only without self-defence, W^{R}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 5$; $c_F = 0$; $C_E = 10$; $r = 1$.

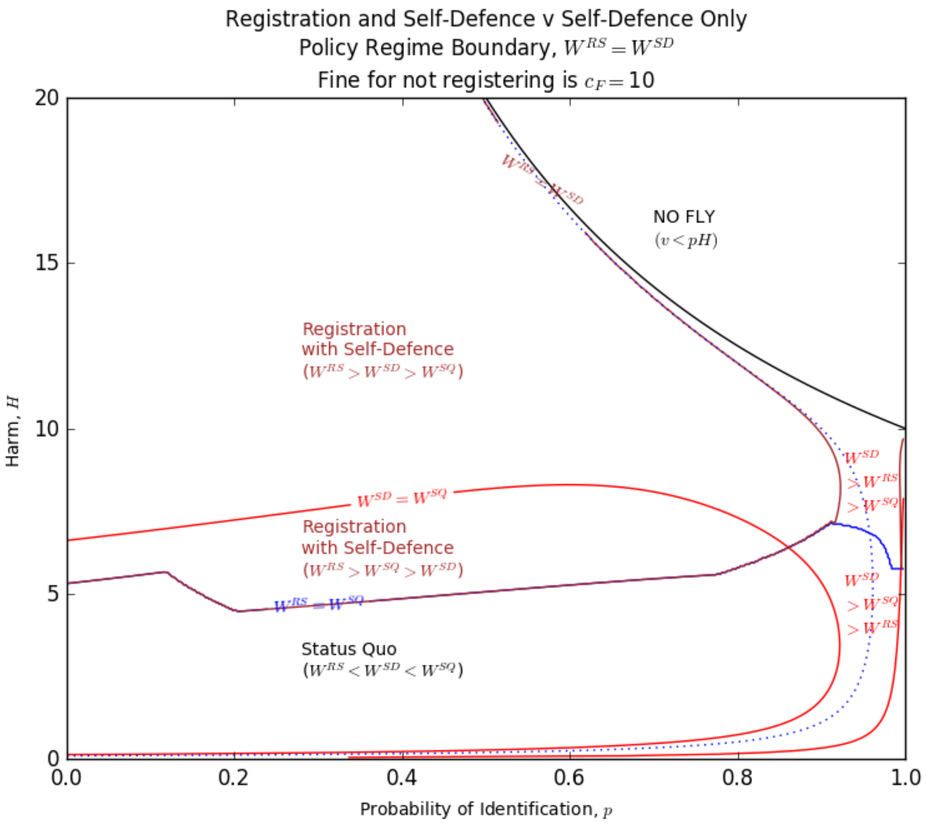
Figure 5.5. Policy Regime Boundary for Registration + Self-Defence v Registration Only; Voluntary Registration ($c_F = 0$)

neither registration nor self-defence.

5.3.3 Comparison with Self-Defence Only

In this section I compare welfare under registration with self-defence to welfare with self-defence and no registration. This identifies the circumstances in which registration enhances the efficiency of self-defence.

Figures 5.6 and 5.7 compare the policy regime boundary for registration with self-defence (blue) to the policy regime boundary for self-defence without registration (red), and plot the boundary of the region where registration with self-defence has higher welfare than self-defence only (brown). The two figures show a fine of $c_F = 10$ (figure 5.6) and voluntary registration ($c_F = 0$, figure 5.7), with the cost of the identifier being $c_I = 5$.



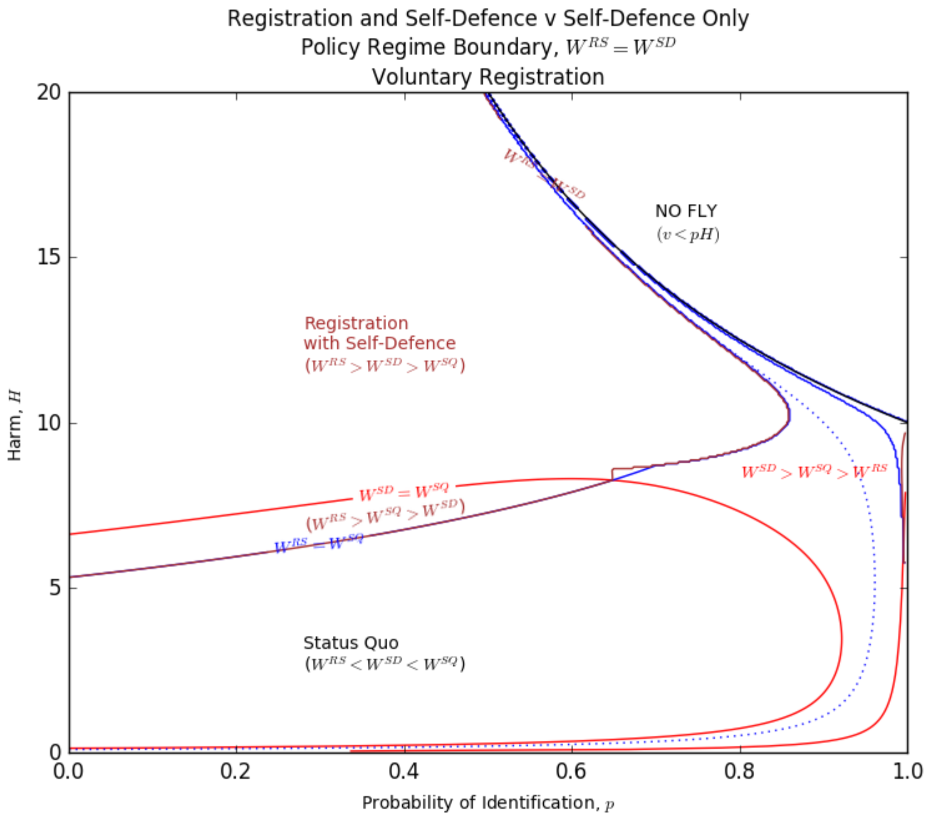
Blue line is the policy regime boundary at which welfare under registration with self-defence, W^{RS}, equals the status quo, W^{SQ}. Red line is the policy regime boundary at which welfare with self-defence, equals the status quo. Brown line is the policy regime boundary at which the welfare under registration with self-defence, W^{RS}, equals welfare from self-defence only, W^{SD}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v=10$; $\kappa=3$; $\psi=0.5$; $c_I=5$; $c_F=10$; $C_E=10$; $r=1$.

Figure 5.6. Policy Regime Boundary for Registration + Self-Defence v Self-Defence Only; fine = 10

Figure 5.6 shows the policy regime boundaries when there is a positive fine for not carrying an identifier ($c_F = 10$). In the range $p = [0, 0.85)$ the blue curve lies below the red curve, which indicates that registration expands the region in which self-defence in welfare-enhancing, allowing self-defence at lower levels of harm. This is because if a drone is carrying an identifier and is in range of the detection technology, then the bystander will be able to obtain legal redress for harm, so it is less likely that self-defence will be used to destroy a drone. This in turn means that the costs arising from self-defence are lower and hence self-defence remains welfare-enhancing at lower levels of harm. In this range the brown curve is coincident with the blue curve, which means that above this curve registration with self-defence has higher welfare than both the status quo (blue curve) and self-defence by itself (brown curve).

The blue and brown curves extend beyond the red $W^{SD} = W^{SQ}$ boundary until $p = 0.9$. At that point the blue $W^{RS} = W^{SQ}$ boundary curves down, but the brown line curves up to join and then follow the dotted boundary of the area where we are indifferent to self-defence. The area demarcated by the brown curve takes up the majority of the area of the chart, indicating that for all of that area of the chart registration with self-defence has higher welfare than both the status quo and self-defence only. Self-defence only is relegated to a small area at the right-hand side of the chart, where the probability of identification is high and registration will not provide a significant increase in the ability to attribute liability.

Figure 5.7 shows the policy regime boundaries when registration is voluntary. The blue curves - showing the boundary of the region where registration with self-defence has higher welfare than the status quo - are identical to the blue curves in figure 5.3. The area in which registration with self-defence has the highest welfare is reduced relative to figure 5.6 and the area in which self-defence has the highest welfare is increased. However, in broad terms, the regions in figures 5.6 and 5.3 are similar, with both figures indicating that at a low probability of identification registration with self-defence is a welfare-enhancing policy if harm is moderate to high, but the status quo is optimal if harm is low.



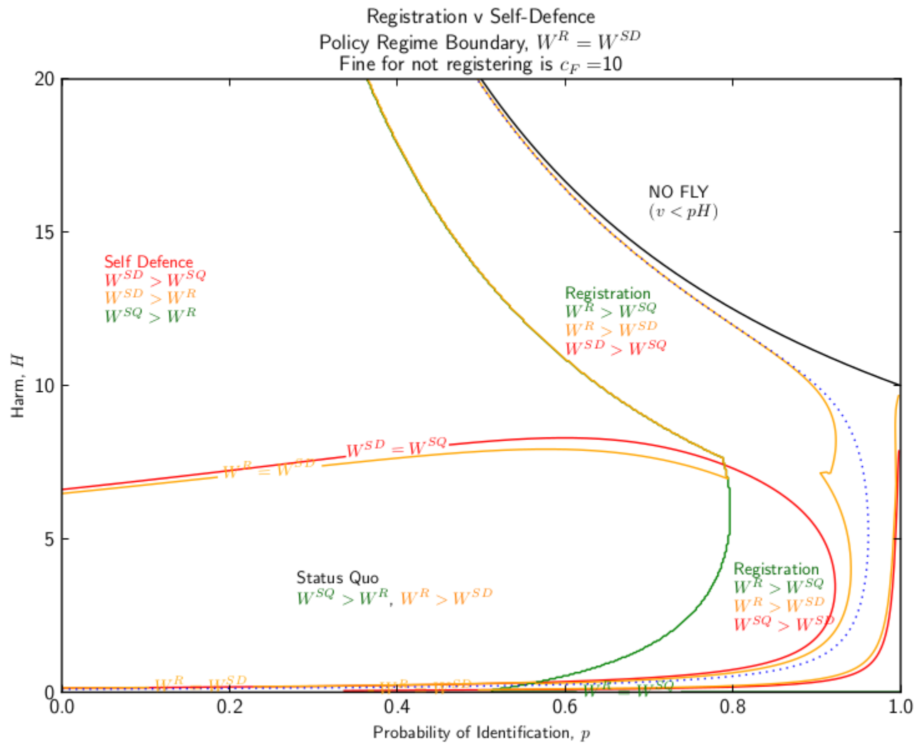
Blue line is the policy regime boundary at which welfare under registration with self-defence, W^{RS}, equals the status quo, W^{SQ}. Red line is the policy regime boundary at which welfare with self-defence, equals the status quo. Brown line is the policy regime boundary at which the welfare under registration with self-defence, W^{RS}, equals welfare from self-defence only, W^{SD}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 5$; $c_F = 0$; $C_E = 10$; $r = 1$.

Figure 5.7. Policy Regime Boundary for Registration + Self-Defence v Self-Defence Only; Voluntary Registration ($c_F = 0$)

5.3.4 Comparison of Registration with Self-Defence

In this section I compare welfare under registration with no self-defence to welfare with self-defence and no registration. Figures 5.8 and 5.9 compare the policy regime boundary for registration (green) to the policy regime boundary for self-defence (red), and plot the boundary of the region where registration has higher welfare than self-defence (orange).

The green curve is the policy regime boundary for registration relative to the status quo. In the area to the left of the green curve the status quo has higher welfare than registration ($W^{SQ} > W^R$), but to the right of the green curve registration has higher welfare than the status quo ($W^R > W^{SQ}$). The red curve is the policy regime boundary for self-defence only. In the

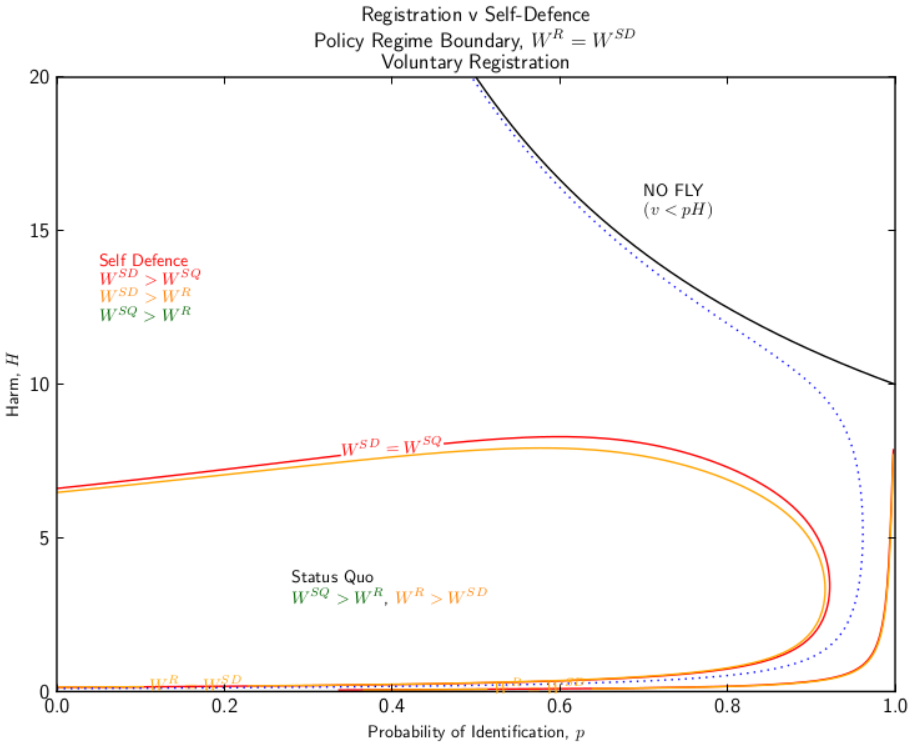


Red line is the policy regime boundary at which welfare with self-defence, W^{SD}, equals welfare under the status quo, W^{SQ}. Green line is the policy regime boundary at which welfare with registration only, W^R, equals welfare under the status quo, W^{SQ}. Orange line is the policy regime boundary at which welfare with registration, W^R, equals welfare with self-defence, W^{SD}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: v =10; κ =3; ψ =0.5; c_I =5; c_F =10; C_E =10; r =1.

Figure 5.8. Policy Regime Boundary for Registration Only v Self-Defence Only; fine = 10

area above the red curve self-defence has higher welfare than the status quo ($W^{SD} > W^{SQ}$), but inside the area demarcated by the red curve the status quo has higher welfare than self-defence ($W^{SQ} > W^{SD}$). The orange policy regime boundary demarcates the area where registration has higher welfare than self-defence. This area includes most of the area where registration has higher welfare than the status quo, but (a) also includes most of the area where the status quo has higher welfare than self-defence, and (b) excludes a small area at the far right hand side of the chart where self-defence has higher welfare than registration.

Figure 5.9 shows the policy regime boundaries when registration is voluntary. As with earlier comparisons, the green curve is absent from figure 5.9 because registration by itself is never optimal when registration is voluntary. This chart essentially collapses to the optimal policy chart for self-defence only.



Red line is the policy regime boundary at which welfare with self-defence, W^{SD}, equals welfare under the status quo, W^{SQ}. Green line is the policy regime boundary at which welfare with registration only, W^R, equals welfare under the status quo, W^{SQ}. Orange line is the policy regime boundary at which welfare with registration, W^R, equals welfare with self-defence, W^{SD}. Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $v = 10$; $\kappa = 3$; $\psi = 0.5$; $c_I = 5$; $c_F = 0$; $C_E = 10$; $r = 1$.

Figure 5.9. Policy Regime Boundary for Registration Only v Self-Defence Only; Voluntary Registration ($c_F = 0$)

5.3.5 Optimal Policy

My analysis so far has considered welfare with registration and self-defence relative to: the status quo with neither registration nor self-defence (section 5.3.1); registration only (section 5.3.2); and self-defence only (section 5.3.3). In section 5.3.4 I also considered welfare with registration only relative to welfare with self-defence only. I now address the question of when each of the four policy options is optimal. I first consider the optimal policy when the drone spends half of the time in range of the detection technology, and then consider when the drone spends only ten percent of the time in range of the detection technology.

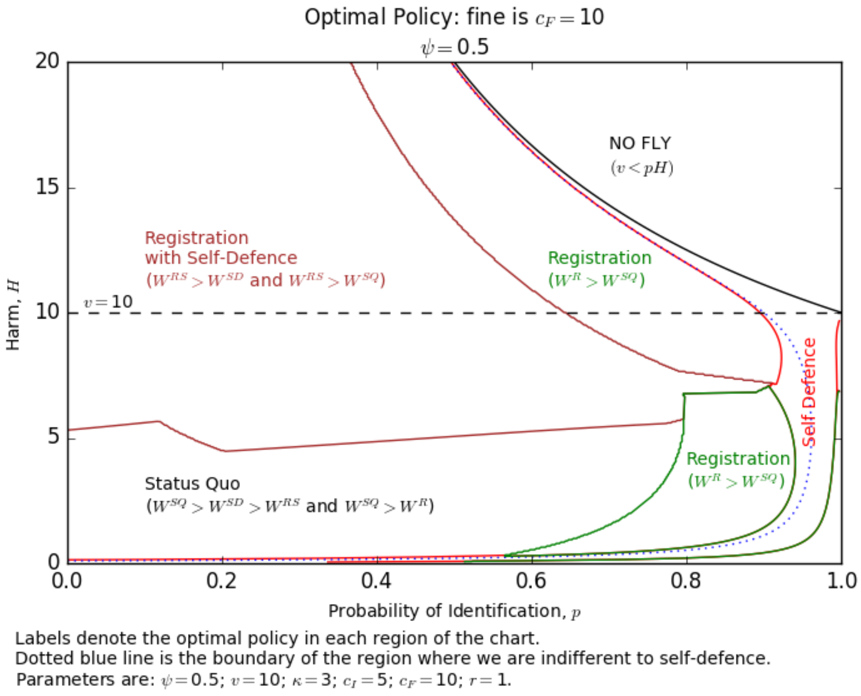
In range of the Detection Technology Half of the Time ($\psi = 0.5$)

Consider, first, when the drone spends half of the time within range of the detection technology ($\psi = 0.5$). Figures 5.10 and 5.11 show the optimal policy charts for a fine of $c_F = 10$ (figure 5.10) and voluntary registration ($c_F = 0$, figure 5.11) respectively. As with the analysis in sections 5.3.1, 5.3.2, and 5.3.3, the cost of the identifier is $c_I = 5$.

The brown curve is the boundary of the region where registration with self-defence is optimal. In the area to the left of the chart, and above harm of approximately $H = 5$, registration with self-defence is the optimal policy. There are two areas where registration only is the optimal policy; these correspond to the areas in figure 5.4 where registration was optimal, subject to the restriction on the far right hand side of the chart in figure 5.8 where self-defence has higher welfare than registration.

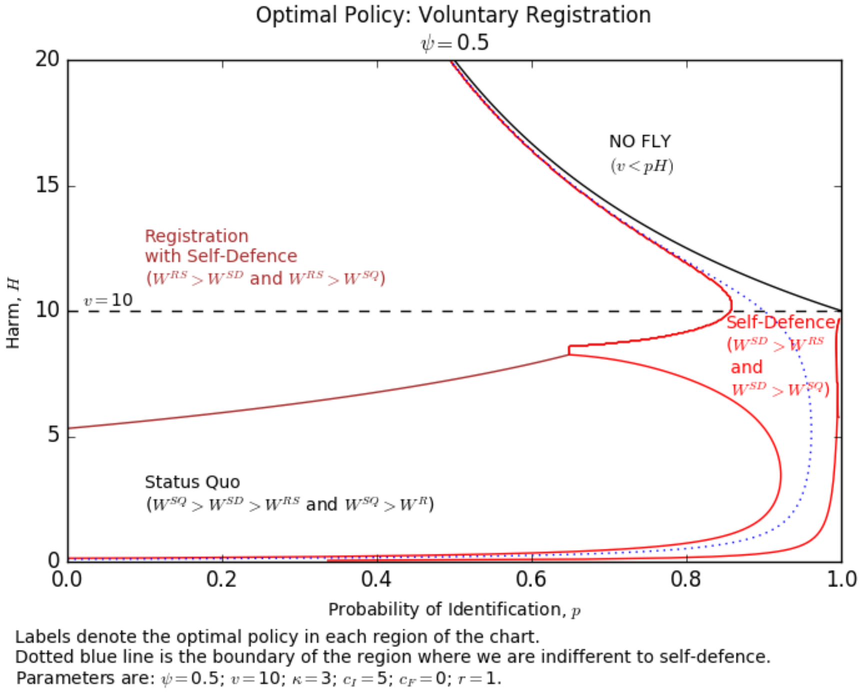
If the probability of identifying a drone that is not carrying an identifier is relatively low ($p < 0.4$) then there is a simple policy prescription: for low levels of harm the status quo with neither registration nor self-defence should be retained; but at moderate-to-high levels of harm registration should be utilised, with bystanders also able to act in self-defence against drones. In this range neither registration by itself nor self-defence by itself is optimal.

If the probability of identifying a drone that is not carrying an identifier is higher ($p > 0.4$) then any of the four individual policies may be optimal depending on the specific combination of p and H. Registration without self-defence is only optimal if registration is not voluntary, the probability of identifying the drone is relatively high, and harm is relatively low.



Labels denote the optimal policy in each region of the chart.
Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $\psi = 0.5$; $v = 10$; $\kappa = 3$; $c_I = 5$; $c_F = 10$; $r = 1$.

Figure 5.10. Optimal Policy; fine for no identifier = 10



Labels denote the optimal policy in each region of the chart.
Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $\psi = 0.5$; $v = 10$; $\kappa = 3$; $c_I = 5$; $c_F = 0$; $r = 1$.

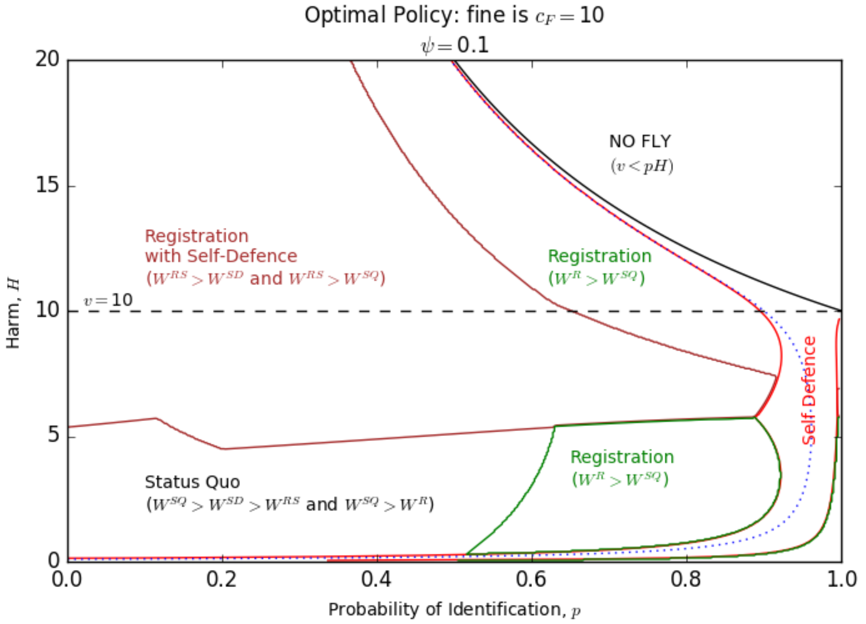
Figure 5.11. Optimal Policy; Voluntary Registration $c_F = 0$

In range of the Detection Technology Ten Percent of the Time ($\psi = 0.1$)

Consider now when the drone only spends ten percent of the time in range of the detection technology. Figures 5.12 and 5.13 show the optimal policy curves for a fine of $c_F = 10$ (figure 5.12) and voluntary registration ($c_F = 0$, figure 5.13). As with the previous sections in this chapter, the cost of the identifier is $c_I = 10$. All curves are coloured as in the analysis for $\psi = 0.5$.

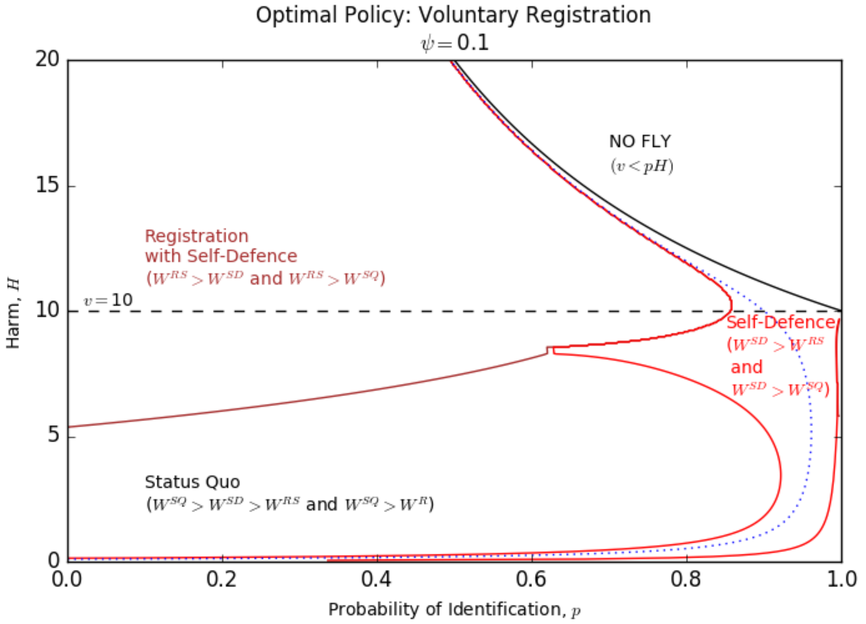
Figure 5.12, with the fine for not carrying an identifier, is similar to figure 5.10 for $\psi = 0.5$. The most notable difference between the two figures is that the region in which registration by itself is optimal has changed in shape and size. By inspection, the lower region where registration is optimal has a larger overall area, whereas the upper region where registration is optimal has been reduced by an expansion in the area where registration with self-defence is optimal.

Figure 5.13, with voluntary registration, is very similar to figure 5.11 for $\psi = 0.5$. If the probability of identifying a drone that does not have an identifier is relatively low ($p < 0.4$) then reducing the proportion of time that the drone spends within range of the detection technology from $\psi = 0.5$ to $\psi = 0.1$ does not alter the policy prescription. As before, for low levels of harm the status quo with neither registration nor self-defence should be retained; but a moderate-to-high levels of harm registration should be utilised, with bystanders also able to act in self-defence against drones.



Labels denote the optimal policy in each region of the chart.
Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $\psi = 0.1$; $v = 10$; $\kappa = 3$; $c_I = 5$; $c_F = 10$; $r = 1$.

Figure 5.12. Optimal Policy; fine for no identifier = 10



Labels denote the optimal policy in each region of the chart.
Dotted blue line is the boundary of the region where we are indifferent to self-defence.
Parameters are: $\psi = 0.1$; $v = 10$; $\kappa = 3$; $c_I = 5$; $c_F = 0$; $r = 1$.

Figure 5.13. Optimal Policy; Voluntary Registration $c_F = 0$

5.4 Discussion and Conclusions

The analysis in this chapter has analysed which of the registration, self-defence, registration with self-defence, and the status quo with neither registration nor self-defence is optimal. Registration with self-defence was compared against each of the other three policy options, and the optimal policy across all four options was considered.

When the probability of identifying the operator of a drone that is not carrying an identifier is relatively low ($p < 0.4$), which reflects the reality for drones, then the optimal policy is the status quo for low levels of harm but registration with self-defence for moderate-to-high levels of harm. This is true whether the drone spends half of the time within range of the detection technology or only ten percent of the time within range of the detection technology. It is also true whether there is a positive fine for registration or whether registration is voluntary.

This result suggests that it would be reasonable to either specify a range of circumstances in which harm is likely to be at least moderate and hence self-defence against drones may be used, or alternatively to generally allow self-defence against drones but specify the circumstances in which harm is likely to be low and self-defence must not be used. In conjunction with the allowance for self-defence, a *voluntary* registration scheme should be provided. Both a voluntary registration scheme and a compulsory registration scheme backed by a fine achieve the same result, so there is no advantage in making registration compulsory.

Registration by itself is only optimal in a relatively narrow range of circumstances, most notably when there is a relatively high probability of being able to identify the drone operator even if an identifier is not carried. Thus, given the characteristics of drones, a compulsory registration scheme by itself is not likely to be efficient.

Appendix 5.A Mathematical Appendix

5.A.1 Voluntary Identifier with Self Defence: Derivation of $\hat{s}$

Substituting equation (5.5) into equation (5.9) provides

$$\begin{aligned}
s^*(m,H) &= \left[(1+s^*)^{-n}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)}}[n(1-m)H]^{\frac{1}{n+1}}-1\\
\Rightarrow 1+s^* &= (1+s^*)^{\frac{-n}{(n+1)(\alpha-1)}}\left[n(1-m)H\left(\frac{v-mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}}\\
\Rightarrow (1+s^*)(1+s^*)^{\frac{n}{(n+1)(\alpha-1)}} &= \left[n(1-m)H\left(\frac{v-mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}}\\
\Rightarrow (1+\hat{s})^{\frac{(n+1)(\alpha-1)+n}{(n+1)(\alpha-1)}} &= \left[n(1-m)H\left(\frac{v-mH}{\eta}\right)^{\frac{1}{\alpha-1}}\right]^{\frac{1}{(n+1)}}\\
\Rightarrow \hat{s} &= \left[(n(1-m)H)^{(\alpha-1)}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{(n+1)(\alpha-1)+n}}-1.
\end{aligned} \tag{5.29}$$

5.A.2 Voluntary Identifier with Self Defence: Derivation of $\hat{q}$

If $\hat{s} > 0$ then from equation (5.9) $1+\hat{s} = [n(1-m)Hq]^{\frac{1}{n+1}} \Rightarrow \rho(\hat{s}) = (1+\hat{s})^{-n} = \left[\frac{1}{n(1-m)Hq}\right]^{\frac{n}{n+1}}$. Substituting this expression for $\rho(\hat{s})$ into equation (5.5) and solving for $\hat{q}$ then provides:

$$\begin{aligned}
q^* &= \left[\left(\frac{1}{n(1-m)Hq^*}\right)^{\frac{n}{n+1}}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}}\\
&= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}}\left(\frac{1}{q^*}\right)^{\frac{n}{(n+1)(\alpha-1)}}\\
\Rightarrow \hat{q}^{\frac{(n+1)(\alpha-1)+n}{(n+1)(\alpha-1)}} &= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{1}{\alpha-1}}\\
\Rightarrow \hat{q} &= \left[\left(\frac{1}{n(1-m)H}\right)^{\frac{n}{n+1}}\left(\frac{v-mH}{\eta}\right)\right]^{\frac{(n+1)}{(n+1)(\alpha-1)+n}}.
\end{aligned} \tag{5.30}$$

References

Privacy Act 1993. (1993). New Zealand Statutes. Retrieved from http://www.legislation.govt.nz/act/public/1993/0028/latest/whole.html

Shelley, A. V. (2016). Proposals to address Privacy Violations and Surveillance by Unmanned Aerial Systems. *Waikato Law Review*, *24*(1), 142–170.

Chapter 6

Policy Implications

Synopsis

This chapter proposes a policy framework that would enable the practical implementation of drone-detection and counter-drone systems in New Zealand.

6.1 Introduction

Although this thesis has identified circumstances in which self-defence against drones and the consequential potential destruction of drones should be allowed, there are legal impediments to the use of both drone detection systems (which could allow a non-destructive effort towards self-defence) and to the use of of counter-drone systems (which could potentially result in the destruction of drones).

This essay is structured as follows. Section 6.2 summarises my theoretical analysis, both for privacy regulation and for self-defence and registration generally. Section 6.3 then discusses a policy framework that would allow use of counter-drone systems with safeguards to avoid potential misuse. Section 6.4 then concludes with an analysis the legal impediments to the implementation of drone-detection and counter-drone systems in New Zealand.

6.2 Research Summary

6.2.1 Privacy Regulation

Chapter 2 provides a legal analysis of issues surrounding trespass and privacy violation by drones. That chapter recommended a package of policy measures: tort law reform, the promulgation of a “Code of Practice for Drone Operations” under the Privacy Act 1993, an encoded radio frequency beacon to identify approved operators, provision for aerial trespass by unmanned aircraft, provision for the destruction of unmanned aircraft committing trespass, and the clarification of what constitutes a privacy violation by broadcast or closed-circuit television and video systems. Allowing the destruction of an unmanned aircraft committing trespass or causing other harm can be justified by legal argument, but that does not necessarily mean that such destruction will be efficient.

6.2.2 Self-Defence and Registration

Chapter 3 provides a detailed economic analysis of when a bystander should be allowed to exercise a right to self-defence and take action to destroy a drone. That analysis considered simultaneous interaction between the drone operator and a bystander, as well leader-follower variants with the drone operator as leader and with the bystander as leader. The analysis showed that it can be efficient to destroy a drone engaged in an activity that causes some form of harm to a bystander. For typical consumer drones the analysis supports a policy of allowing the destruction of drones whenever the operation of the drone reduces welfare, assuming that the expected liability of the drone operator is low. The analysis also suggested that it is never efficient to allow the destruction of manned aircraft, a conclusion which reflects existing law.

A potential alternative to allowing the destruction of drones is to register drones and utilise the legal and regulatory system to attribute liability to the drone operator. Chapter 4 therefore analyses the circumstances in which registration would be efficient. I find that a necessary condition for registration to be welfare-enhancing is that the cost of an identifier is less than the fine for not carrying an identifier. Furthermore, registration is generally welfare-enhancing when the probability of identifying the drone operator in the absence of an identifier is relatively high. When the probability of identifying the drone operator without an identifier is low then a very high fine is required to incentivise compliance. Even a perfectly reliable remotely-readable identifier will be ineffective, and registration inefficient, if there is a low probability of identifying the operator of a drone that is not registered.

There is a partial overlap between the region in which self-defence with destruction of drones is welfare-enhancing and the region in which registration of drones is welfare-enhancing. Chapter 5 analyses the interaction between registration and self-defence, and identifies the regions in which each policy individually is optimal, and when both policies together are optimal. Given the low probability of identifying the operator of a drone that is not carrying an identifier, I find that it is optimal to allow self-defence against drones when harm is moderate-to-high, coupled with registration scheme. Both a voluntary registration scheme and a compulsory registration scheme backed by a fine achieve the same result, so there is no advantage in making registration compulsory. When harm is low then the optimal policy is the status quo, with neither registration nor self-defence.

A clear outcome from my research is that parties should be able to engage in self-defence against drones, at least when harm has reached at least a moderate threshold.

6.3 Proposed Policy Framework

In the first instance, the analysis in Chapter 5 finds that there should be voluntary registration of drones, coupled with the ability to exercise self-defence against drones when harm is at least at a moderate level. Self-defence may take the form of either drone-detection systems or counter-drone systems. Given the current legislative framework, enabling legislation is required to create a positive right to utilise drone-detection and counter-drone systems. The analysis in Chapter 4 can be applied to determine whether the use of drone-detection systems and counter-drone systems should each be subject to registration requirements.

Consider, first, drone-detection systems. These systems will have a very low level of harm, if there is in fact any harm at all. Rather, it seems likely that such systems can be used without causing any harm. As such, the right to use drone-detection systems should be generally available to all persons. Furthermore, in many instances it will be difficult to identify whether a person has a drone detection system. There are, for example, proposals to utilise WiFi networks to detect drones. Given the potentially low probability of identifying that a drone-detection is in operation, and consequently the low probability of attributing liability for whatever harm we might imagine is caused by the operation of such a system, the analysis in Chapter 4 indicates that such systems should not be registered.

Consider, now, counter-drone systems. These systems do have the potential to cause harm beyond just stopping the errant drone: radiocommunications jamming may interfere with legitimate uses of radio spectrum, and drones that are disabled may crash on to third parties causing harm. A counter-drone system could also be used to disrupt the legitimate operation of drones. Given the potential harm from the misuse of counter-drone systems, it is appropriate to consider whether such systems should be regulated. There is a relatively high probability of identifying the location and operator of many counter-drone systems. The drone operator will know where her drone was when it encountered the counter-drone system. Even with jamming technology, an effective regulatory regime already exists that for the most part detects and prevents the use of such systems. It therefore seems likely that the probability of identifying the use of counter-drone systems is relatively high. Given the potential for harm from collateral damage and the high probability of identifying the party causing the harm, my analysis in Chapter 4 indicates that counter-drone systems *should* be registered. It may be appropriate to limit the right to use counter-drone systems to people and organisations who can demonstrate that they have the training and organisational management systems to appropriately manage the associated risks. One option would be to promulgate a Civil Aviation Rule for the licensing of counter-drone system operators, in a similar manner to the other organisational licensing rules discussed in section 4.2.1. The right to use counter-drone systems could then be limited to those persons and organisations that have been licensed under the counter-drone rule.

6.4 Legal Impediments to Drone-Detection and Counter-Drone Systems[1]

6.4.1 Aviation Crimes Act 1972

Drones are defined as "aircraft" and as such are subject to the general prohibitions in the Aviation Crimes Act 1972 against taking actions that would damage an aircraft or render it incapable of flight. The relevant provisions of s5 of the Aviation Crimes Act 1972 state:

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[1] The analysis in this section was first published in Shelley (2018) *Enabling Counter-UAS and UAS-Detection Systems in New Zealand*, Aviation Safety Management Systems Ltd.

> **S5 Other crimes relating to aircraft**
> Everyone commits a crime, and is liable on conviction to imprisonment for a term not exceeding 14 years, who, whether in or outside New Zealand,—
> (b) destroys an aircraft in service; or
> (c) causes damage to an aircraft in service which renders the aircraft incapable of flight or which is likely to endanger the safety of the aircraft in flight[.]

Any action taken which renders a drone incapable of flight, damages it, or destroys it, is prima facie contravening this section.

The wording of this clause reflects Montreal Convention (United Nations, 1975), but omits the Convention's qualification that acts are performed "unlawfully". The qualification that the acts are performed unlawfully should be included in the Aviation Crimes Act 1972. This would then allow counter-drone actions to be taken, so long as those actions were lawful.

6.4.2 Crimes Act 1961

Some counter-drone systems rely on a technique called "protocol manipulation" which essentially hacks into the computer running the drone to issue it with new instructions to either land in place, land in a safe area, or return to its origin. Taking such action would appear to contravene s250 of the Crimes Act 1961, which has a prohibition against interfering with or impairing any data or software in a computer system, and s252 of the Crimes Act 1961, which has a prohibition against accessing a computer system without authorisation. Furthermore, any person that makes or sells such a system would contravene s251, which prohibits the "making, selling, or distributing software that would enable another person to access a computer system without authorisation."

Importantly, the prohibitions in ss250 and 252 relate to a person who does so "without authorisation". Authorisation is defined in s248 as including "an authorisation conferred on a person by or under an enactment or a rule of law, or by an order of a court or judicial process." This suggests that there is no need to alter the anti-hacking provisions of the Crimes Act 1961; but also that legislation is required to define when a person is authorised to utilise counter-drone technology.

6.4.3 Radiocommunications Act 1989

The radio signals used to control a drone are detected by some systems and used to identify the drone, determine the location of the drone, and determine the location of the transmitter that is controlling the drone. These systems enable defensive measures to be taken, from diverting aircraft away from the drone to enabling law enforcement officials to be dispatched to the location of the transmitter. However, such systems appear to contravene s133A(1)(a) of the Radiocommunications Act 1989:

> **133A Offence to disclose contents of radiocommunications**
> (1) Every person commits an offence against this Act who receives a radiocommunication and who, knowing that the radiocommunication was not intended for that person,—
> (a) makes use of the radiocommunication or any information derived from that radiocommunication; or ...

The radiocommunication is clearly not intended for any person, but rather for the drone that the signal is controlling. Therefore making use of that radiocommunication, or any information derived from it, is a prima facie breach of this section.

The same section does include some exceptions, most notably:

> (b) by a constable, a Customs officer, or any other class of law enforcement official listed in regulations made under this Act for the purpose of avoiding prejudice to the maintenance of the law, including the detection, prevention, investigation, prosecution, and punishment of offences; or ...
> (c) by an employee of an intelligence and security agency for the purpose of performing the function under section 10 of the Intelligence and Security Act 2017; or
> (d) by a member of the New Zealand Defence Force, in connection with any of the purposes specified in section 5(a) to (d) of the Defence Act 1990...

There are also a number of other specific exemptions referenced in subsection (e):

> (e) by a person acting under, and in accordance with, any authority conferred on him or her by or under—

(i) Part 1 of the Telecommunications (Residual Provisions) Act 1987; or
(ii) Part 4 of the Intelligence and Security Act 2017; or
(iia) [Repealed]
(iii) the Misuse of Drugs Amendment Act 1978; or
(iv) the International Terrorism (Emergency Powers) Act 1987.

None of the provisions provide a general power enabling the private sector to intercept radiocommunications used to control drones and then utilise those signals or the information contained in the signals. Thus all of the following situations would contravene this section:

- a private security firm hired to deploy drone-detection systems at a sports arena;
- air traffic control deploying these systems at airports; and
- the owner of the national electricity transmission network deploying these systems at its major substations.

The private sector use of counter-drone systems and drone-detection systems would be facilitated by an additional exception under s133A(e). If there was specific enabling legislation for counter-drone systems then the additional exception in s133A(e) would refer to an authority conferred under that enabling legislation.

6.4.4 Prohibition against Jamming

The 'Radiocommunications Regulations (Prohibited Equipment - Radio Jammer Equipment) Notice 2011' prohibits the "use of radio jammer equipment other than by a permitted person." There is no general process for becoming a permitted person. The only entity with formal permission is the Department of Corrections, with qualified permission granted by way of s189B of the Corrections Act 2004. This permission includes the qualification that there must not be "harmful interference outside prison boundaries."

The effects of jamming are potentially widespread and can have an adverse effect on a wide range of unintended targets. Drones typically use General Use Radio Spectrum, so jamming the control frequencies used by a drone can interfere with the proper operation of other devices legitimately utilising the spectrum. It is therefore recommended that the anti-jamming provisions remain, with the power for parliament or the Secretary to declare a person a permitted person for the purpose of the 'Radiocommunications Regulations (Prohibited Equipment - Radio Jammer Equipment) Notice 2011'.

6.5 Conclusion

There is merit in providing for a voluntary registration scheme for drones, but there should not be a compulsory registration scheme. Alongside this should be a positive right to utilise drone-detection systems, which should not be registered. There should also be a positive right to utilise counter-drone systems, but the use of such systems should be restricted to those who are licensed and registered under appropriate regulations.

Having established a right for specified classes of people to use drone-detection and counter-drone systems, and promulgated the relevant Civil Aviation Rule, the remaining changes required to legislation to allow the implementation of drone-detection and counter-drone systems are small. As discussed above, the Aviation Crimes Act 1972 requires a very minor amendment to accurately reflect the wording of the Montreal Convention that the prohibited acts are performed "unlawfully". No specific changes are required to the Crimes Act 1961, but the enabling legislation should provide a positive authorisation for accessing computer systems for the purpose of operating a counter-drone system. Section 133A(e) of the Radiocommunications Act 1989 should be amended to include persons authorised by the counter-drone enabling legislation as exempt from the offence of disclosing the contents of a radiocommunication.

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Chapter 7

Conclusion

This thesis set out to answer the following questions:

1. Under what circumstances will the use of self-defence against drones be efficient?
2. Under what circumstances will the registration of drones be efficient?
3. What combination of registration and self-defence is optimal?

A secondary research question was whether there are any other regulatory instruments that will aid in achieving efficient harm reduction. Each of these questions has been answered.

A clear outcome from my research is that parties should be able to engage in self-defence against drones, at least when harm has reached at least a moderate threshold. Registration by itself is unlikely to be welfare-enhancing for drones, but voluntary registration may be welfare-enhancing in conjunction with self-defence.

7.1 Contribution

The literature has very few analyses of self-defence. This may be because self-defence is an extra-legal action, so does not fit neatly within the discipline of law and economics. It is, however, a remedy that is at times legally justified. This thesis has contributed a formal economic model of self-defence which has potentially broad application: it is capable of explaining both why a manned aircraft should not be shot down, but also why a wandering dog that is worrying stock may be shot. Applied to drones, the model identifies the circumstances in which self-defence against drones is justified, primarily because of the difficulty of obtaining legal redress for harm caused.

The literature also lacks a formal model of registration when it is used to attribute legal liability. This thesis contributes a formal model of registration and identifies the circumstances in which registration is welfare-enhancing, and the circumstances in which the ease of bypass means that registration is not welfare-enhancing.

Finally, this thesis also contributes a formal model to study the interaction between self-defence and registration. There would seem to be broad applicability of the principle that if there is a low probability of identifying a party potentially causing harm then self-defence should be allowed, but voluntary self-identification should also be allowed to enable the party potentially causing harm to signal their intentions and potentially allow the bystander to seek redress through the legal system if required. Compulsory registration alone is ineffective when there is a low probability of identifying a party causing harm. Perhaps one of the most generally accepted applications of this principle is the concept of trespass to land, but with the implied licence to enter on to private property to make reasonable enquiry (Aitkin, 2016): this enables a person who would like to go on to the land of another to go on to that property and seek permission, thus effectively voluntarily self-identifying.

7.2 Future Research

One avenue not explored in this thesis is the extent to which the probability of identifying a drone is a function of the level of effort exerted by regulatory authorities. As the level of effort by enforcement authorities increases, it would be reasonable to expect that both the probability of identification would increase and the cost of enforcement would increase. It seems likely that there would be an optimal level of enforcement effort, and that optimal level of effort may change with each policy.

A further avenue for future research is the whether the existence of asymmetric information would alter the outcome of the games, and hence the location of the boundary between policies. In particular, asymmetric information might exist in relation to the potential harm caused by a drone, with the drone operator potentially under-estimating the harm and the bystander potentially over-estimating the harm.

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Appendix A

Sources of Harm

This appendix surveys the major sources of harm potentially arising from the use of drones. Appendix A.1 surveys invasions of privacy and surveillance. Appendix A.2 surveys instances of physical harm to individuals. Appendix A.3 discusses the potential harm from collision with manned aircraft. Appendix A.4 surveys damage to electric power infrastructure. Appendix A.5 discusses malicious use, such as use in the commission of crime, security incidents, and terror attacks.

A.1 Privacy and Surveillance

Many people are concerned at the prospect of being observed by an unknown surveillor via the medium of a drone. In New Zealand, there have been news articles about drones being used to film into another person's property (Harris, 2015), taking photographs of children at a public swimming pool (Bonnallack & Young, 2015), and frightening animals in backyards (Wells, 2015). In one case a woman confronted a real-estate drone photographer about invasion of privacy only to have her fears confirmed when the pilot informed her that she had an external door open upstairs (Dillane, 2017). In Australia, a woman discovered that real estate advertisements, including a large billboard, carried an image of her sunbathing in her backyard (Panahi, 2014). In another Australian case, a woman in Darwin was swimming naked in her private backyard swimming pool when a small drone began hovering overhead (Gogarty, 2017). In Sydney, a couple discovered a drone observing them inside their apartment (Patterson, 2017).

Drone technology also provides an avenue for surveillance by both private parties and State agencies. Private entities utilising drones for legitimate activities, such as pizza delivery or responding to burglar alarm activations, could collect significant surveillance imagery. A New Zealander recently demonstrated a flight of 7 hours 48 minutes by a low cost fixed-wing drone flying in large circles (Robinson, 2016), an activity that could legally be employed over population centres and seems tailor-made for surveillance. The Police in Baltimore have already engaged a private contractor to undertake city-wide surveillance using manned aircraft (Friedersdorf, 2016), and the low cost of drones makes this more likely to occur in future.

An additional value closely related to privacy is autonomy, which is the ability to make life decisions free from the influence or control of others (Thompson, 2015). Autonomy is a privacy value that may be threatened by widespread use of drones, as individuals feel that they must change or moderate their private behaviour in the face of potential surveillance (Martin, 2013, p. 13). The Sydney couple who discovered a drone watching them in their fifth-floor apartment started shutting and dead-bolting the door to their patio, and keeping their blinds shut (Patterson, 2017). The perceived need to alter behaviour was demonstrated by the Helsinki Privacy Experiment, which studied the effects on ten volunteer households of ubiquitous surveillance within the home over a period of six months (Oulasvirta et al., 2012). The Helsinki Privacy Experiment demonstrated that even individuals who consent to surveillance will actively alter their behaviour in order to regulate what the surveillors perceive, and the surveillance system was "a cause of annoyance, concern, anxiety, and even rage" (Oulasvirta et al., 2012).

Surveillance activities may also have more insidious long-term effects than other forms of privacy violation, potentially undermining basic trust and thereby contributing to poor economic performance. Lichter, Loeffler and Siegloch (2015) analyse the effects of surveillance by the East German Ministry for State Security (Stasi) using county-level data. They show that "higher levels of Stasi surveillance led to lower levels of social capital as measured by interpersonal and institutional trust in post-reunification Germany", and that a higher spy density is associated with "lower self-employment rates, fewer patents per capita, higher unemployment rates and larger population losses throughout the 1990s and 2000s". Of note, the spies in the Lichter et al. study were primarily citizen informers, so the results are potentially relevant to any situation where one's fellow citizens may be conducting surveillance.

A.2 Physical Harm to Individuals

Several instances of drone-related physical harm have been reported by the news media. In early April 2014, a drone struck a female athlete during a triathlon in Geraldton, Western Australia (Taillier, 2014). She received lacerations to her head, and ambulance personnel removed a piece of the propeller from her head (Grubb, 2014). In May 2017, an errant drone crashed during a cycle race and parts of the drone become lodged in the spokes of one of the riders, causing the rider's bicycle to flip in the air and crash (Smith, 2017).

In May 2015 a drone flying above a crowd at a Memorial Day parade in Marblehead, MA hit a building and crashed, causing minor injuries to two people (Molinet, 2015). A month later, a woman was knocked unconscious at the Seattle Pride Parade by a small drone that hit a building and then fell on her (CBS News, 2015). In May 2017, a drone crashed into the front of a car travelling at 70km/h on the Sydney Harbour Bridge (O'Sullivan, 2017); no harm occurred in this instance, but the potential exists for a crash if a driver swerves to avoid a drone.

Notwithstanding the above accidents, the events likely to raise most public concern are those involving small children. In September 2015, an 11-month old baby was injured by debris from a drone that crashed at a public event in Pasadena, CA (Henry, 2015). In another accident in 2015, an 18-month old British boy was blinded in one eye when his eyeball was cut by a small drone that crashed after clipping a tree (Steafel, 2015). In August 2018, a 1-year old child received cuts to the face from a drone while playing in a public playground (Ta, 2018).

Small drones are considered to be a class of model aircraft. There have been at least seven reported fatalities arising from the use of model aircraft and drones.[1] In April 2003 an out-of-control model aircraft killed a 14-year-old girl in England (Sapsted, 2003). In November 2003 a 41-year-old man was killed while providing flight instruction to the operator of a radio-controlled model helicopter (dennis@deetee, 2003). In August 2009 a man was killed while operating a Yamaha R-max drone in Korea (ARAIB, 2010). In March 2013, a radio-controlled helicopter crashed in Borneo, Malaysia, killing an 18-month-old baby ('Baby killed by remote control helicopter', 2013). In July 2013, a man was killed in Japan when the rotor blades

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[1] The majority of this list was first published in Shelley (2016). The third accident listed, (ARAIB, 2010), was not included in that publication.

of the Yamaha R-max drone he was operating hit him in the head ('Man killed by RC helicopter while spraying agricultural chemicals', 2013). In September 2013, a 19 year old in New York was killed when his remote-controlled helicopter "plummeted from the sky," inflicting severe head and neck injuries (Zennie, 2013). In Switzerland in 2013, a radio-controlled helicopter struck the 41-year-old man who was operating it, inflicting what was described as "severe head and arm injuries" (Curtis, 2013).

A.3 Collision with Manned Aircraft

In addition to the above examples of individual harm, pilot associations (New Zealand Airline Pilots Association [NZALPA], 2012) and regulators express concern at the potential for fatal accidents that could arise if there was a collision between a drone and manned aircraft. Small drones are reported to have come within feet of passenger jets (Guynn, 2015; Messing, Moore & Perez, 2016; Shelley, 2018; UK Airprox Board, 2016), rescue helicopters (Australian Transportation Safety Bureau [ATSB], 2014b; NZ Herald, 2018), agricultural aircraft (Australian Transportation Safety Bureau [ATSB], 2014a), and glider tow aircraft (Fagan & Slade, 2015).

In the event of a collision between a manned aircraft and a drone, a range of damage could be occur to the manned aircraft, some of which will be survivable, and some of which may not. Small drones have a mass similar to birds, and thus might be expected to cause similar damage to a manned aircraft as occurs with a collision between birds and aircraft (known as "bird-strike"). A 2014 study by the Federal Aviation Administration (FAA) and the US Department of Agriculture (USDA) reported that in the period 1990-2013 there were 12 bird-strikes causing 26 human fatalities (FAA & USDA, 2014). Of note, 8 fatalities arose from a single strike by a red-tailed hawk, a species with a mass of between just 690g and 1,460g (Cornell Lab of Ornithology, 2015a). In comparison, the DJI Phantom 2 has a mass of 1,000g, and the DJI Phantom 3 has a mass of 1,280g. Over the same period there were 196 bird-strikes causing 348 injuries. Canadian geese were associated with 15 bird-strike incidents causing 117 injuries, and vultures of various species were associated with 32 bird-strike incidents causing 39 injuries. Canadian geese weigh from 3kg to 9kg (Cornell Lab of Ornithology, 2015b), and vultures have a mass between 1,600g and 2,200g (Cornell Lab of Ornithology, 2015c, 2015d). These figures should, however, be put in context: over the same period there were a total of 138,257 reported bird-strikes, of which just 12 (0.009%) caused a fatality and 196 (0.14%) caused injury.

Drones have characteristics that might be expected to cause more damage than occurs with a bird-strike. The drone is a mechanical device with hard components rather than a biological organism with soft body parts that will "splatter" on impact. Simulation results suggest that a 3.6kg drone could fracture the turbine blades of a jet aircraft, rapidly destroying the entire engine (Mackay, 2015; Wasserman, 2015). Known as an "uncontained engine failure", such an event can cause significant structural damage to the aircraft (ATSB, 2013) and even a catastrophic fire (Gates, 2015).

The *Small Remotely Piloted Aircraft Systems (drones) Mid-Air Collision Study* (2017) report the results of a study of the impact of a drone against the windscreen of a helicopter and an airliner. Helicopter windscreens not certified against bird strike were shown to have a "low resistance" to all classes of drone tested, including that in the 400g weight class. Airliner windscreens are certified against bird strike; although windscreens would be "substantially damaged" in an impact with a drone, they "could retain integrity during impacts with drones up to speeds typically flown at during the aircraft landing and later stages of the approach". At higher altitudes and speeds complete structural failure of the windscreen could occur with a 4 kilogram weight class quadcopter.

If a drone did "penetrate" an aircraft windscreen, then the hard components in a drone are more likely to injure a person than will occur with a bird strike. The hard components are also more likely to damage an aircraft wing.

The *Small Remotely Piloted Aircraft Systems (drones) Mid-Air Collision Study* (2017) also examined drone strike against helicopter tail rotors and concluded that "they would be vulnerable to impacts with all types of drones". Loss of tail rotor in a helicopter can in some instances result in severe spinning of the helicopter and in any event requires an autorotative emergency landing (FAA, 2012, pp. 11–16).

A.4 Electric Power Infrastructure

Electric power infrastructure, particularly overhead power lines and outdoor switch yards, are vulnerable in the event of a drone crash. Careless rather than malicious use of small drones has resulted in power outages of varying severity. Some examples include:

- In 2015 a drone being used to take photographs of a commercial property in Whangarei, New Zealand, crashed into overhead electricity lines "causing a power cut to about 200 properties and the loss of at least 1000 man-hours of productivity for the businesses affected" (Dinsdale, 2015).
- Approximately one month later a drone crashed into power lines in Los Angeles, causing a power outage to approximately 700 people and lasting about 4.5 hours (Farivar, 2015; Serna, 2015).
- In June 2017 a drone crashed into high voltage power lines causing a power outage to approximately 1,600 people for about 2 hours (Green, 2017).
- In August 2017, a drone crashed into a power line in Moore, Oklahoma, causing a power outage, a small fire, and damaging two cars (Brilbeck, 2017).

The economic cost of an interruption to electric power supply is measured by the "Value of Lost Load" (VOLL). The New Zealand Electricity Authority (2013, pp. 2–3) reports values of VOLL for a number of scenarios, with estimates of the weighted average VOLL across consumer types ranging from \$9.38/kWh to \$18.69/kWh.

A.5 Malicious Use - Crime, Security, and Terror Attacks

Small drones have been used to deliver contraband - particularly drugs, weapons, and mobile phones - to prisons in both the United Kingdom (Brandes, 2015) and the United States (Glanfield, 2015). In the United Kingdom, it was reported that 120 drones were seized flying contraband into prisons over a 23 month period (Drury, 2017). Drones have also been used to aid criminal activity, such as reconnaissance for potential burglaries (Barrett, 2015).

Drones have been used to conduct numerous unauthorised flights over French nuclear plants (Lichfield, 2014), raising questions about whether the flights are a pre-cursor to ground-based attack (Baylon, 2014). While such attacks apparently did not eventuate, these flights highlight the ease with which drones might be used to obtain information on the security at what might be considered “critical infrastructure”.

The Syrian civil war and the subsequent war against ISIS in Syria and Iraq has seen the use of small drones to drop improvised explosives and grenades (Gibbons-Neff, 2017; Watson, 2017). However, the planned use of drones by non-state insurgent groups pre-dates the Syrian civil war. Ballard, Pate, Ackerman, McCauley and Lawson (2001) report that in early 1994 the Japanese cult Aum Shinrikyo attempted to use a remote control helicopter Bunker to deliver the nerve agent sarin against a target, although the helicopter crashed during testing (Bunker, 2015). Bunker (2015) also reports that al-Qaida leaders had considered using drones equipped with improvised explosive devices since before 2001. These uses of drones have highlighted concerns that similar attacks could be conducted in the West (Hughes, 2015). In August 2018, two drones with on-board explosives were used in an attempt to assassinate President Maduro of Venezuela (Waters, 2018). In October of that year, the Director of the Federal Bureau of Investigation stated in testimony before the Senate Homeland Security and Governmental Affairs Committee that (Wray, 2018):

> The FBI assesses that, given their retail availability, lack of verified identification requirement to procure, general ease of use, and prior use overseas, [drones] will be used to facilitate an attack in the United States against a vulnerable target, such as a mass gathering. This risk has only increased in light of the publicity associated with the apparent attempted assassination of Venezuelan President Maduro.

Underscoring the realistic nature of this threat, in September 2019 a man in Pennsylvania was arrested for allegedly using a drone to drop explosive devices on his ex-girlfriend’s house (Hall, 2019).

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