Greener Aviation Take-off (Delayed): Analysing Environmental Transitions with the Multi-Level Perspective

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In the past fifty years, long-range commercial airliners have changed only incrementally from the paradigmatic design – a tube fuselage with swept wings and mostly-aluminium construction. Reducing the environmental impact of airliners may require radical innovations and a new paradigm, but the transition to a new paradigm is fraught with risks. This paper analyses how key risks have shaped and limited efforts to transition toward three types of radical innovations that would significantly improve airliner fuel efficiency. We use these three cases to reassess the dominant framework for analysing sociotechnical transitions – the multi-level perspective (MLP) – in light of methods and theoretical perspectives drawn from Science and Technology Studies (STS). We argue that if the MLP is to provide a robust framework for analysing sociotechnical transitions, it must be refined in three ways. First, it must 'open the black box' to account for the ways that technologically-specific risks shape the transition process. Second, rather than predefining particular innovations as radical or conservative, 'mature' or 'immature,' it should attend to how actors conceive of such terms; an innovation which appears 'mature' to one group may appear 'immature' to another. Third, the MLP would be strengthened by additional case studies such as ours, which examine incomplete or failed transitions.

Keywords: Green Aviation, Transitions, Multi-Level Perspective

Introduction

At the beginning of the 21st century, amid growing concerns about anthropogenic climate change, an authoritative study concluded that two innovations – laminar flow control (LFC) and a 'flying wing' aircraft design – offer "the greatest aerodynamic potential for reducing the contribution of air travel to climate change" (Greener by Design, 2003: 9). Remarkably, one of the UK's then leading aircraft manufacturers, Handley Page, had proposed precisely the same thing nearly fifty years earlier – a flying wing with LFC. The Handley Page 117 (HP, 117) would have consisted of nothing but wings carrying passengers inside, rather than wings with a fuselage for passengers. It would also have used LFC to reduce drag. Handley Page claimed that together the flying wing design and LFC would have maximized the lift to drag ratio and increased fuel efficiency, cutting operating costs in half.[1]

However, today both the flying wing and LFC remain technologies of the future. In fact, for over fifty years, long-range commercial airliners have changed only incrementally from the paradigmatic design – a tube fuselage with swept wings, mostly-aluminium construction, and turbofan engines – despite considerable work on more fuel-efficient designs. For example, lightweight materials such as carbon fibre have been under development since the 1970s, but only recently began to displace aluminium in large structural components. Advanced turboprop engines could nearly match the speed of turbofans while operating much more efficiently, but despite decades of development, such engines have not seen operational use in airliners.

Why haven't any of these innovations become operational, even after decades of interest in reducing fuel consumption and carbon emissions? Many other approaches to greener aviation are possible, including the use of biofuels, solar power, airships, and improved air traffic management (Cohen, 2010: 460). Moreover, improving fuel efficiency may not increase sustainability, as more efficient and thus cheaper-to-operate airliners may make flying less expensive and more common (the Jevons paradox, see, for example, Owen, 2012). As Ozzie Zehner (2012) has argued, behavioural changes will be needed to achieve sustainability. Nonetheless, we focus on three technologies for improving energy efficiency – more fuel-efficient engines, lighter aircraft, and more aerodynamic designs – because they dominate contemporary studies of greener airliners (Greener by Design, 2005; Green, 2009). Why, despite growing interest in energy efficient aircraft, have these technologies not been widely adopted?

Lack of radical change in airliner technology reflects the persistence of what evolutionary economists have called a *technological regime*: a rule-set that governs decisions about how to develop and produce new technologies. As initially described by Nelson and Winter (1977, 1982), technological regimes encourage engineers to pursue incremental improvements along a technological trajectory rather than radical innovation (see also Dosi, 1982). Kemp and Rip expanded the notion of regime to include the rules shared by technology's selection environment (Rip & Kemp, 1998), while Geels has used 'sociotechnical regime' to describe a broader set of relationships and investments "embedded more widely in the knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics" (Geels, 2002b: 1260). This paper defines sociotechnical regimes broadly to include artifacts and organizations, a usage that is common in the literature (see e.g. Kemp et al.,1998), and explicit in Gabrielle Hecht's notion of 'technopolitical regimes' (Hecht, 2001; Allen & Hecht, 2001).

The dominant framework for understanding how regime transitions occur is the Multi-Level Perspective (MLP) (Geels, 2002b, 2005; van Driel & Schot, 2005). The MLP conceptualizes transitions according to three levels: niche, regime, and landscape. Because regimes tend to pursue incremental innovation, radical innovations are nurtured only in small market niches. The landscape includes economic, political, and environmental pressures that are beyond the direct influence of regime or niche actors, but that may encourage regimes to nurture and adopt niche technologies.

The MLP explains transitions as a result of "linkages between co-evolutionary dynamics at multiple levels", rather than seeing them as driven by price/performance improvements (Geels, 2006: 1014). It characterizes transition pathways by two aspects of interactions between the levels: i) the timing of niche, regime, and landscape developments (especially whether or not the niche technology is mature relative to landscape pressures), and ii) the degree to which niche and landscape developments threaten or reinforce the regime (Geels & Schot, 2007).

Thus, the MLP would explain slow, incomplete, or non-existent transitions such as those explored here as a consequence of immature niche innovations and/or insufficient landscape pressures. But this explanation leaves deeper questions unanswered. How do regime actors decide whether or not a niche technology is sufficiently mature? What does it mean for landscape pressures to be sufficiently large, and for whom? And what happens when key actors related to different dimensions (Lettl et al., 2006: 252) of an innovation frame technology differently?

This paper addresses these questions through the core principles and methods of science and technology studies (STS), as exemplified by Stewart Russell's work (e.g. Russell, 1993; Russell & Williams, 2002). Indeed, Russell's emphasis on the ways in which complex interdependencies affect sociotechnical change anticipated the MLP (see discussion in Weber, 2014). We argue that STS can extend the MLP in three ways.

First, we follow STS's injunction to 'open the black box' of technology by considering how the inner workings of technology shape social outcomes, and vice versa (Pinch & Bijker, 1987). Although the injunction to open the black box is not new, the MLP has yet to fully incorporate this perspective into its framework. As Russell and Williams (2002: 81) note, close attention to "the *specificity* of processes in different areas of technology and different domains of application" (italics in original) is crucial to a full understanding of the social shaping of technology. However, the MLP does not account for the content of technological design in any systematic way.

For example, the MLP's typology of transition pathways specifies transition pathways solely in terms of the maturity of niches relative to landscape pressures, and the degree to which the niche innovation threatens or reinforces the niche. Yet we have reason to expect that transition pathways will be shaped by aspects of technological design. For example, many communications technologies, by their very design, are exhibit in strong economies of scope, or positive network externalities. Because products which capture an early market share enjoy increasing returns if the network grows, firms have strong incentives to introduce products early as well as to invest in them heavily only if the network then grows. It is also riskier to introduce a product late than to introduce it with a few glitches.[2] By contrast, the consequences of failure for technologies such as airliners and nuclear power plants are extremely high. Because such large physical systems confront huge start-up costs, a commercial failure is enormously expensive. Additionally, technological failures in such systems can cost not only money but also hundreds or thousands of lives. Thus, from the perspective of an aircraft manufacturer, the risks of introducing a new airplane before its safety is demonstrated are far greater than the risks of being rendered obsolete by a competitor while research and development continues.

The differences between technologies such as computer network protocols and airliners illustrate that technological specificity can shape transition pathways by giving meaning to the notion of technological maturity. Accordingly, the MLP would be strengthened by incorporating some dimensions of technological design into its conception of how transitions occur. Here we suggest that the type of risk associated with innovation is one key facet, but other aspects are undoubtedly important.

Second, STS explains technological change in part by the unique ways that social groups frame technology—that is, the assumptions that they bring to bear upon new artifacts. This agent-oriented approach has been criticized (with some justification) by MLP advocates, who argue that the MLP "is strong in combining STS sensitivities about micro-processes with long patterns and processes" (Geels & Schot, 2010: 35). However, these authors also acknowledge that the global theory of the MLP "needs to be complemented by local theories which help to analyse how actors navigate, struggle and negotiate on specific alternatives" (Geels & Schot, 2010: 101). Similarly, MLP advocates acknowledge that the structuralist approach of the MLP needs to be complemented "with an actor-oriented approach working 'from the inside out' " (Geels, 2004: 43).

The need to work both 'from the inside out' and 'from the outside in' was advanced much earlier by Russell and Williams (1988: 4, 11). Adopting such an 'inside out' approach, Höyssä and Hyysalo (2009) and Hyysalo (2010) argue that an understanding of how specific actors perceive 'innovativeness' – including the degree to which specific technologies are novel, the dimensions of its novelty and how they relate to different actor groups, and the locus of innovation around the new products – is critical to understanding transitions. Here we build on this argument by considering how different actors – such as design engineers, operators, business analysts – understand what it means for a new innovation to be 'radical' or 'conservative,' 'mature' or 'immature.' We argue that achieving an appropriate balance between agency and structure requires analysts to not predefine particular innovations as radical or immature, but rather to study how different actors themselves conceptualize these terms with respect to specific technologies and their dimensions of novelty. While advocates of the MLP acknowledge the importance of agency, they do not generally consider how actors construct concepts such as 'radical' innovation or 'mature' technology. As we will see, an innovation that seems radical to one group may seem quite conservative to another.

Third, we help to correct a bias in MLP studies by following STS's 'symmetry principle,' in which success and failure both require sociological explanation (Pinch & Bijker, 1987). The MLP has tended to treat success, but not failure, as a matter for sociological analysis (for a recent exception, see Wells & Nieuwenhuis, 2012). Although aspects of the MLP framework have been used to assess on-going transitions (see e.g. Hofman & Elzen, 2010; Elzen et al., 2011; Grünewald et al., 2012), the MLP framework has been developed primarily using historical case studies of successful transitions. Geels and Schot (2010: 79) acknowledge the need to "correct the bias towards winners and novelty". Russell's (1986, 1993) early work on combined heat and power in Britain exemplifies STS accounts that focus on failure, and thereby help to correct the bias towards success stories. This paper builds on Russell's legacy by examining transitions that have, we might say, stalled.

In what follows, we first discuss how a very low tolerance for risk shapes innovation within the aviation regime. We then provide three historical case studies of innovations for more fuel-efficient airliners, showing how the 'maturity' of the innovation is socially constructed by actors that may have different tolerances for risk, and by different conceptions of what constitutes 'radical' innovation.

Risk in the Aviation Regime

In commercial aviation, radically new technology entails many risks. The process of moving from early stage technology development to a marketable product is very expensive. For example, the Boeing 787 airliner is estimated to have cost around $16 billion to develop (Gates, 2011). By contrast, the Toyota Prius cost about $1 billion, a typical cost for new cars (Taylor, 2006). The sizable majority of mobile apps cost less than $100,000 to develop (Furnas, 2013). High airliner development costs, along with the difficulties of entry have produced an oligopoly in which a very small number of manufacturers (just Boeing and Airbus for large airliners) participate in the design of new aircraft. Competition between these manufacturers is fierce, but the high stakes of new aircraft development leave companies favouring incremental innovation.

The (potentially) large risks associated with airliner innovation – including the reputational damage that could ensue from a major crash – are exacerbated by high uncertainties. In early stages of research and development, feasibility, producibility, regulatory acceptance and market appeal are all uncertain. High technological complexity amplifies these uncertainties. While computer simulations are helpful for predicting likely performance, the performance of new designs can ultimately be determined only by building and operating a full-scale product. Airline manufacturers try to minimize uncertainties through an extremely conservative innovation strategy. Since deductive models are of limited value for predicting future performance, manufacturers base judgments about the feasibility of future aircraft on extrapolation from decades of engineering experience – data on wind tunnel testing, operational performance of existing airplanes, and the tacit knowledge and intuition of experienced engineers.

Regulators also rely heavily upon past data and conservative innovation. American aircraft certification is carried out by the Federal Aviation Administration (FAA) (working in conjunction with its European counterpart). The certification process has become increasingly challenging as the complexity of aircraft design has increased. In 1998, a study by the U.S. National Research Council noted:

> A major airframe manufacturer may employ as many as 8,000 engineers, flight test pilots and inspectors to design, develop, and certificate a new wide-body passenger jet. These large staffs are necessary to investigate the design complexities of modern aircraft. The number of labour hours invested by a manufacturer in designing a large new jet may be several hundred times greater than the number of labour hours the FAA has available to verify the safety of the aircraft design. (NRC, 1998: 38)

As the National Research Council (NRC) noted, these disparities raise questions "about the FAA's ability to analyse independently new aircraft designs and locate safety-related design flaws" (NRC, 1998: 38).

The FAA attempts to manage this problem by co-opting the aircraft engineers themselves to self-regulate, and by drawing on the past record of the aircraft manufacturers and of the aircraft that they built (Downer, 2010). As Downer notes:

> Reliability assessments of new civil aircraft lean very heavily on inferences from the – statistically well-established – data from earlier, different, aircraft designs. This is viable because the architects of new aircraft are highly conservative when developing new models. […] Innovations are extremely modest, with new technologies being withheld until their reliability has been well-established in other contexts (in military aircraft, for instance). (Downer, 2011: 279).

In short, the main barrier to the development of radically more fuel-efficient airliner technology is the extremely conservative innovation process that is particular to the aviation regime. This conservative approach is rooted in socially and technologically specific views on what it means for innovations to be radical or disruptive of the airliner regime, and thus calls for the analytic framework and methods of STS.

In what follows, we analyse how this conservatism has shaped three approaches to making airliners more fuel-efficient. The first approach is to replace turbofan engines with more efficient turboprop or propfan engines. The second is the adoption of carbon fibre composites, a transition that is now finally underway despite having been feasible for decades. The third approach is to achieve greater aerodynamic efficiency through LFC and/or flying wings. In each case, the MLP provides a partial explanation of how these innovations gained a niche. However, to explain why these approaches have not caused a regime change, we adopt a more micro-level perspective. We show how different social groups adopted varying views of what 'radical' or 'mature' innovation meant, and how these different framings ultimately limited the adoption of more fuel-efficient technologies.

The Turbo Revolution: The Birth of the Modern Airliner Regime

Edward Constant's (1980) study of the 'turbojet revolution' is often cited as an example of how radical innovations can transform a stable regime. Thus Geels (2002a, 2006) illustrates the MLP through the shift from the propeller piston-engined, straight-wing regime (e.g. the Douglas DC-3), to the turbojet-engined, swept-wing regime (e.g. the Boeing 707). A 'landscape' development – the looming threat of war in the 1930s – nurtured the turbojet niche because the higher speed of turbojets was identified as a valuable asset for fighter aircraft. Fighters with turbojets could be rapidly 'scrambled' from ground stations when enemy aircraft were spotted. Although only a few turbojet fighters saw action in WWII, turbojets were preferred in post-war fighters.

Military applications thus provided a niche in which turbojets could mature sufficiently to be considered for civil applications. After WWII, many manufacturers continued with incremental improvement of piston-engined airliners, but the turbojet provided an opportunity for new entrants to gain competitive advantage. For the UK, building a turbojet-engined airliner was a way of overcoming the growing US dominance of the industry, and the De Havilland Comet was the world's first jet airliner to enter commercial service in 1952. The initial success of the Comet quickly dissipated due to fatal crashes in 1954 (as discussed further below). Nonetheless, the Comet demonstrated that there was public demand for such a technology. The interest stimulated in airline operators led Boeing to convert its Dash-80 refuelling jet into the Boeing 707 airliner, which entered service in 1958 (Geels, 2006: 1012).

The development of turbofans – a variation of turbojets which reduces noise and increases efficiency – further increased commercial aviation's interest in 'jet' engines. As Geels (2006) has discussed, several adaptations in the aviation regime (such as longer runways, pilot training, and new aircraft control methods) enabled turbojets to displace piston-propeller aircraft. However, Geels provides only a partial historical account because he does not explain how another engine technology – turboprops – flourished alongside turbojets and turbofans, albeit on a lesser scale.

From an engineering perspective, turbofans and turboprops are both incremental innovations upon turbojets, both of which aim to optimize the mass and final velocity of the air moved. Because the energy consumed in an engine scales with the mass of the air multiplied by the velocity squared (mv^2), while the momentum produced by the engine is equal to mv, engines can produce momentum most efficiently by moving larger masses of air more slowly (i.e. increasing m while decreasing v). A 'pure' turbojet gains all of its propulsion from high-speed gases produced by combustion in the engine core. By contrast, turbofans use the jet's combustion to power a fan, which accelerates a larger volume of air to a lower velocity. The air accelerated by the fan bypasses the engine, so the ratio of this slower air mass to the faster air mass accelerated by engine combustion is called the *bypass ratio*. Efficiency increases as the bypass ratio grows. Because noise tends to increase with higher velocity air, the high bypass ratio of turbofans offers not only more efficiency, but also less noise than pure turbojets.

Closely related to the turbofan is the turboprop. Whereas the turbofan uses a gas turbine to spin a ducted fan, a turboprop uses the gas turbine to spin a propeller more slowly than the turbine. Turboprops are most efficient at low speeds because they can move larger masses of air more slowly than turbofans. But at high speeds, turboprops become less efficient than turbofans because the tips of the propellers are moving close to the speed of sound, generating shock waves that increase drag and friction. Turboprops are typically slower and noisier, but much more fuel-efficient than turbofans.

The first turboprop to fly was the British Rolls-Royce Trent, which was tested on a Meteor I aircraft in 1944 (Anonymous, 1950: 489). Although turbofans became dominant in long-range aircraft, the greater fuel efficiency of turboprops soon made them the preferred engine for short-range aircraft, where passengers were unlikely to notice the lower speed. By the 1960s turboprops were completely dominant in aircraft with less than 50 seats, and had approximately an equal share of aircraft with 51–90 seats. The oil crisis of the early 1970s made energy efficiency an even greater priority, encouraging further demand for turboprops. Additionally, the deregulation of the US market in 1978 encouraged the hub-and-spoke model for airline operations, thereby increasing the number of short-range flights and the associated demand for turboprops (Bonaccorsi & Giuri, 2000: 855–857).

Thus, the commercial aviation regime developed a mixed character with respect to engines, with both turbofans and turboprops establishing patterns of incremental innovation. In this sense, it might be more accurate to discuss a 'turbo revolution' than a 'turbojet revolution.'

High oil prices enabled an even more fuel-efficient 'advanced turboprop,' or propfan, to find an R&D niche during the 1970s and 1980s. The propfan consisted of thin swept blades that resembled a pinwheel, and aimed to achieve similar efficiencies to conventional turboprops, but without generating the turbulence that eroded efficiency at high speeds (Ethell, 1983). Although fast and efficient propfans posed several engineering challenges, they represented an incremental innovation from standard turboprops. Propfans were first suggested in the 1950s, but the materials at that time were not strong enough to create propfan blades, and the low cost of fuel meant that efficiency was not a priority.

In what follows, we show that while the MLP partially explains how propfans found an R&D niche, it does not fully explain why propfans have not been adopted by airlines. To explain this non-transition, we show how specific social groups – airlines, and passengers – framed propfans as too revolutionary and immature for operational use, despite the fact that they represented a kind of incremental innovation.

Propfans and the Advanced Turboprop Project

The dominance of the turbofan in long-range aircraft was such that NASA had ceased research into propeller technology by the early 1970s (Hager & Vrabel, 1988: 1). However, the 1973–1974 oil crisis saw aviation fuel prices increase from twelve cents a gallon to over a dollar in the U.S., and fuel increased as a proportion of airline operating costs from about a quarter to over half (Bowles & Dawson, 1998: 326). Responding to this changing landscape, NASA began investigating propfans in 1974, and accelerated work after February 1976, when the U.S. Congress funded NASA's new Aircraft Energy Efficiency (ACEE) programme. Three of the six projects funded concerned propulsion systems, and were managed by NASA's Lewis (now Glenn) research centre in Cleveland, Ohio. NASA and several industry studies all agreed that the Advanced Turboprop Project (ATP), which focused on propfans, had the highest potential payoff of the three propulsion projects, with estimates of fuel savings ranging from 30% to 50% (Bowles, 2010: xii, 13; Hager & Vrabel, 1988: 3). The challenge was to develop a propfan that could match the speed and altitude of the turbofans used on most airliners – 0.8 Mach at 30,000 feet – whilst maintaining satisfactory levels of noise, comfort and reliability.

The ATP's initial funding was held up, according to John Klineberg, later director of Lewis Research Center, "because it was considered too high risk and too revolutionary to be accepted by the airlines" (quoted in Bowles & Dawson, 1998: 329).

Table 1. Comparison of different types of turbine-based engines

Type	Source of Propulsion	Efficiency and Noise
Turbojet	Combustion gases	Least efficient below Mach 1
Turboprop	Combustion gases turn a propeller, which moves air	Most efficient below Mach 0.6[3]
Turbofans	Combustion gases turn a ducted fan, which moves air	More efficient than turboprops above Mach 0.6
Advanced Turboprop; Propfan; Unducted fan	Combustion gases power specially-designed propeller, which moves air	Most efficient above Mach 0.6

In February 1975, NASA's newly formed Aircraft Fuel Conservation Technology task force noted that aircraft manufacturers were disinclined to develop high-speed turboprops (or propfans) because of the "perception of turboprops as an old-fashioned, troublesome device with no passenger appeal" (quoted in Bowles & Dawson, 1998: 328). Studies by Boeing, McDonnell Douglas, and Lockheed also raised questions about noise, potential maintenance costs, and whether the propeller could remain efficient at speeds exceeding 0.6 Mach (Hager & Vrabel, 1988: 5).

Significantly, the propfan was too 'high risk' and 'revolutionary' primarily from a passenger and marketing perspective. From an engineering perspective, the ATP represented an incremental improvement upon lower-speed turboprops. As proof of the viability of high-speed turboprops, engineers could point to the Soviet development of long-range turboprop aircraft such as the Tupolev TU-95 'Bear' bomber, which had a 0.75 Mach cruise speed. This Soviet achievement was used to gain support for the ATP by raising concerns about the Soviet Union being ahead in the Cold War technology race (Bowles, 2010: 19, 125). Although the TU-95 (and its civil airliner derivative, the TU-114) demonstrated the feasibility of achieving high speeds and altitudes with turboprops, they were reportedly very noisy and relied on complex gear-systems for the contra-rotating propellers with consequent high maintenance requirements.

By the time the ATP was formally launched in 1978, NASA had demonstrated high efficiency at Mach 0.8 in a scale model (Hager & Vrabel, 1988: 8). However, it remained to be seen whether such performance could be achieved with acceptable cabin noise levels. Since the addition of acoustically insulating materials to reduce noise would add weight and thereby reduce the efficiency of turboprops, there appeared to be a trade-off between noise and efficiency.

The ATP research programme also aimed to alleviate industry anxieties about safety. For example, at a meeting of the Industrial Advisory Board at NASA, an air accident advisor expressed concern about the "safety aspect of propellers breaking away from the engine and the damage caused by their impingement into the fuselage" (quoted in Bowles & Dawson, 1998: 333). To dispel these anxieties, engineers at NASA Lewis carried out and commissioned studies into propeller damage, concluding that turboprops posed no unique safety risks (Bowles & Dawson, 1998: 333).

As NASA's project continued, another spike in fuel prices influenced developments at General Electric (GE), one of the world's big three engine producers (the others being Pratt & Whitney and Rolls Royce). The Iran-Iraq war that began in September 1980 led to an even more dramatic increase in oil prices than that of 1973. GE's internal predictions were for aviation fuel to rise to $2 or $2.20 a gallon by the mid to late 1980s (Sweetman, 2005). As a result, GE set up a team in 1981 to investigate more efficient engine designs, including its own version of a propfan.

First announced in 1983, GE's unducted fan (UDF) engine came as a surprise to the ATP team. The UDF was bigger and more powerful than NASA's effort, and was planned to be ready sooner, in late 1986 (Sweetman, 2005). A non-functioning mock-up of GE's UDF engine was unveiled to the public at the 1985 Paris Air Show, and first ground-tested in August that year (Sutcliffe, 1987: 11). It was the key to greater fuel efficiency in Boeing's proposed 150-seat 7J7 airliner, slated for delivery within seven years. Boeing promised that the 7J7 would be twice as fuel-efficient as the

Airbus A320 that was then almost ready for delivery (Sweetman, 2005).

The first test flight of the UDF, carried out on a Boeing 727 airframe, came on August 20, 1986, with the first public flight on a McDonnell Douglas MD81 following in September 1988 at the Farnborough air show. The test flights were considered encouraging: noise levels were higher than desirable, but manageable: 'acceptable and certifiable', according to GE (Anonymous, 2007). The way forward appeared clear, as a 1987 *Washington Post* article stated: "The aircraft engine of the future has propellers on it" (Hamilton, 1987).

Advanced Turboprops Stall

Thus, by the mid-1980s, major landscape changes had apparently destined propfans for widespread adoption. However, a key risk-averse social group – airlines – viewed propfans as too uncertain, and therefore too immature, against the changing landscape. Boeing's attempts to market its proposed 7J7 – a 727 employing the UDF instead of turbofans – were not successful. In order to reduce noise from the UDF, the engines would be installed in the back of the plane. However, this increased the weight of the plane, and maintenance costs for a novel engine remained uncertain. Thus, operations engineers were cautious. Bob Conboy, a market analyst at GE recalls: "We'd talk to the planning people and they'd say 'When can we have it?' But we never got an enthusiastic response from the operations people" (quoted in Sweetman, 2005).

Future fuel prices also remained uncertain, and were another reason (in addition to the potential maintenance and weight issues) that Airbus did not adopt the UDF. Airbus' chief planner, Adam Brown explained that the advantages of the UDF "depended very much on the price of fuel […] . With the projections that we were most comfortable with at the time, they couldn't beat the A320." (quoted in Sweetman, 2005). Although the A320 could not offer the fuel efficiency claimed for the 7J7, it used more familiar turbofan engine technology while still improving over the previous generation of midsize airliners.

One of Boeing's own aircraft also undermined support for the 7J7. The 737 was a late-1960s midsize airliner that struggled to achieve decent sales during the 1970s. But in 1981, a new version, the 737-300, was introduced with a more efficient and quiet CFM56 turbofan engine developed by GE and the French SNECMA engine developer. Sales of the 737-300 grew rapidly, with over 1000 sold by the end of 1987 (Sweetman, 2005). With the CFM56 engine becoming the dominant engine in this important and growing airliner sector, GE saw little need to pursue the UDF development. According to Brian Rowe, then GE's senior vice president in charge of engine development: "When the CFM56 took off, we thought, What the hell? All we'd be doing [by launching the UDF] is killing our own business" (quoted in Sweetman, 2005).

The other main potential user of the UDF was McDonnell Douglas, whose rear-engined MD-80 was proving uncompetitive with the Boeing 737 and Airbus A320. A UDF engine was tested on an MD-80 airframe in late 1987, and McDonnell Douglas had plans to launch UDF-fitted models the following year. The UDF-equipped MD-80 was flown to the Farnborough Air Show in September 1988,[4] but without firm orders, GE was unwilling to commit to further development (Sweetman, 2005). The MD-80 was also flown with an ATP-inspired engine developed by Pratt & Whitney and Allison, but again there was insufficient commercial interest.

Wither the propfan? By the late 1980s, the landscape conditions that had led to the ATP and to GE's UDF had ameliorated.

Using non-inflation adjusted dollars, the cost of oil had soared from $3.39 per barrel in 1970 to $37.42 per barrel in 1980; by 1988 it was down to only $14.87 per barrel (Bowles, 2010: 134). In inflation-adjusted 2012 dollars, this did translate into a significant increase – from approximately $11 in 1970 to $35 in 1988 (BP, 2013: 15). But the commercial aviation regime viewed these prices as tolerable, and the risks of further increases as survivable. The commercial case was thus undermined. The manager of NASA's ATP, John R. Facey, believed that the manufacturing costs would exceed operational fuel savings: "An all new aircraft with advanced avionics, structures and aerodynamics along with high-speed turboprops would be much more expensive than current turbofan-powered aircraft, and fuel savings would not be enough to offset the higher initial cost" (quoted in Bowles, 2010: 134).

Facey's comments represent a risk calculus – a belief that extra manufacturing costs would probably outweigh future fuel savings. These financial risks make propfans radical from a business perspective. Yet from an engineering perspective, the physical concepts behind propfans are not radically different from those behind the well-established turbofan and turboprop.

In the past decade, growing pressures for more energy efficient aircraft have reinvigorated research into propfans. Europe's Clean Sky Joint Technology Initiative, a partnership between the European Union and industry, has continued to pursue propfan research and development (Clean Sky, 2013). GE continues to develop propfans, and currently anticipates reducing the noise to acceptable levels by 2030 (Croft, 2012).

In sum, landscape changes – spikes in oil prices – nurtured development of propfans. However, these pressures were too transient to overcome the risk aversion of some of the key actors in the civil aviation regime – business concerns about image and initial manufacturing costs, and operational concerns about maintenance and noise. By examining propfans from an STS perspective that focuses on the technologically and socially specific risks associated with new engine designs, we can better assess obstacles to a transition. In particular, the adoption of propfans may depend on locating airports further away from urban centres or a significant shift in public attitudes towards aircraft noise, which until recently has been *the* key environmental driver for aero engine development (Greener by Design, 2005: 5).

Lighter Materials: The Development of Carbon Fibre

Whereas more efficient engines are stuck in laboratory development, lighter materials (most notably carbon fibre) have found a substantial market niche. Although the MLP helps to explain how lighter materials have seen growing use, it does not fully explain why a more complete transition to composite construction has not occurred. In what follows we use the MLP to frame the initial adoption of carbon fibre, and then show how an actor-oriented understanding of what it means for innovative materials to be 'mature' is necessary to explain the limits of adoption.

High strength carbon fibre was first developed in the 1960s and quickly found application in rocket casings and military aircraft (Spinardi, 2002). Military aircraft, and the gradual introduction of composite components such as tailfins and control surfaces in airliners, provided a niche for developing stronger, lighter-weight, and more reliable composites. Carbon fibre was first used for airliner secondary structures (such as spoilers, airbrakes, rudders, and wing edges) in the early 1980s. Sharp rises in oil prices nurtured the carbon fibre niche, and in 1981, one production engineer predicted that aircraft would be more than 50% composite construction by the end of the 1990s (King, 1982). Similarly, in 1983, the Dutch aircraft company Fokker announced that its next commercial aircraft, to be introduced in 1992, would consist of 50–65% composite materials by weight (Feazel, 1983). Yet by the turn of the millennium, no commercial airliner had more than 20% carbon fibre construction.

Why was carbon fibre not adopted more widely earlier? The MLP would suggest that landscape pressures were insufficient, or that carbon fibre was not yet mature. But to understand what it means for landscape pressures to be large enough or for carbon fibre to be mature enough, we must adopt an STS 'inside out' perspective, and consider how different regime actors framed different kinds of risks associated with novel materials.

The *safety* risks of new aircraft materials are well illustrated by the experience of the Comet, the first aluminium pressurized fuselage to enter service. On three separate occasions in the mid-1950s, Comets broke up in mid-flight as the pressurized fuselage explosively decompressed (Marks, 2009). Although the Comet had been subjected to the most rigorous safety testing available to that time, engineers did not fully understand how the process of pressurization and depressurization would fatigue the metal, leading to cracks around the plane's square windows, and eventually structural failure (Hansard, 1955).

The Comet experience led to better testing procedures because it "stimulated enormous research efforts aimed at understanding and avoiding fatigue cracking" (Vlot, 2001: 11). It also heralded a shift towards conservatism in the airliner innovation system. Technological advances in aviation had been rapid over the first half of the twentieth century, with clear benefits in the speed and comfort of long-distance travel, but there were trade-offs between these benefits and the risks involved in pushing new technology. Once turbo-powered aircraft such as the Boeing 707 came into service, and large aircraft such as the 747 made long-range mass transit economical, it was not clear that further leaps forward in airliner technology were worth the risks associated with novelty. Notwithstanding experiments with faster aircraft such as the Concorde, most airline manufacturers and operators agreed that the paradigmatic 707-type aircraft was good enough.

The adoption of carbon fibre thus proceeded very incrementally. It was not until 2002 that Boeing announced that its next generation airliner would use unprecedented levels of carbon fibre – nearly 60% (Wallace, 2001 Smith, 2001; Staff, 2001). What eventually became the Boeing 787 is the first airliner to use carbon fibre for large structural components (i.e. fuselage and wings).[5] Concerns about the safety of such large composite components became very public after engineer Vincent Weldon claimed that Boeing fired him over his criticisms of carbon fibre. Boeing claimed that he was fired because of threatening and racist comments he made towards a manager, but Weldon nonetheless drew public attention to the risks of new materials. In a 2007 letter to the FAA, Weldon warned that aluminium has "far fewer failure modes" than carbon fibre.

Significantly, Weldon's criticisms centred on the risks generated by a relative lack of experience with carbon fibre, noting that "there is far less proven knowledge than for aluminum structure," and that "the less mature composite structure data base, compared to that of aluminum, is of concern". A 2011 investigation by the US General Accounting Office echoed these concerns, acknowledging "limited in-service experience with composite materials used in the airframe structures of commercial airplanes and, therefore, less information [...] on the behavior of these materials than on the behavior of metal" (GAO, 2011: 28). However, the GAO report concluded that the FAA's certification process had been satisfactory, citing expert opinion "that while not every risk can be known, the use of composites is not revolutionary; rather, it is a new application of technology that has a history in military and general aviation applications" (GAO, 2011: 28).

Although government regulators concluded that carbon fibre was mature enough from a *safety* perspective, Boeing discovered new *manufacturing* risks when it attempted producing those structures. While aluminium components are produced by cutting the metal and then assembling parts, carbon fibre components are fabricated at one and the same time that the composite is created. Carbon fibre components are typically made through a labour-intensive process: a tool modelling the shape of the part is created; carbon fibre plies that are pre-impregnated with resin are carefully placed on the tool, using a precise alignment that is designed to optimize the final strength of the part; the entire assembly is carefully covered with materials to ensure that the plies lay flat; and then the entire part is cured under heat and pressure (Younossi et al., 2001). Composite components can reduce the need for assembly processes, but they are often slower and more expensive to produce. Furthermore, because composites cannot be reshaped after fabrication, they must be produced to very precise tolerances (Vosteen & Hadcock, 1994).

Because the composite material does not exist apart from the part that it constitutes, a much larger component is effectively a different material. Boeing discovered this the hard way in June 2009, when ground tests simulating the stresses of flight showed unexpected structural weaknesses. When pressure was applied to the wings of the test aircraft, titanium fasteners did not transfer the load properly, causing delamination of the carbon fibre plies and deflection inside the fuselage. The failure was especially troubling because computer models had not predicted it. The data that was the basis for engineering the entire aircraft suddenly appeared to be flawed (Mecham, 2009). The 787 finally entered service in 2011, years late and over budget, largely because of unexpected difficulties that came with new fabrication processes.

Although the Boeing 787 appears to be on its way to commercial success, the transition to carbon fibre remains incomplete. In 2008, Mitsubishi Heavy Industries, the company responsible for manufacturing the 787 carbon fibre wing box, announced that it would be manufacturing a lighter-weight, more fuel efficient regional jet (the Mitsubishi Regional Jet). But Mitsubishi chose not to use composites for the fuselage or wings, because it did not expect the weight savings on a smaller-sized airplane to justify the risk of higher manufacturing costs (Tabuchi, 2013).

Thus, the current commercial aviation regime remains mixed between carbon fibre and aluminium, and it is unclear whether a transition to carbon fibre will be completed. This incomplete transition cannot be fully explained by the MLP, which would suggest that the carbon fibre niche is immature relative to landscape pressures. By contrast, the methods of STS explain this partial transition by reminding us that the maturity of carbon fibre is a matter of perspective. While regulators have deemed carbon fibre to be safe, manufacturers continue to be wary of production-related risks and uncertainties related to recouping costs.

Radical Aerodynamics: Flying Wings and Laminar Flow Control

A third area in which aircraft can be made more efficient lies in aerodynamic advances that maximize the amount of lift that can be obtained from a given amount of power. The aerodynamics of the classic 707-type aircraft has changed only incrementally since their development in the late 1950s. Considerable advances in aerodynamic efficiency have been achieved by fine-tuning this design through wind-tunnel testing and computational fluid dynamics. Additionally, winglets – small, nearly vertical wing extensions which increase the lift-to-drag ratio – have produced small improvements. However, far greater improvements have long been known to be possible through flying wings and laminar flow control (LFC). Consistent with the MLP, these 'radical' innovations have been nurtured in the niches of military research and development. However, to understand why flying wing designs and LFC have yet to become operational, we must again move beyond the structural approach of the MLP and consider how specific actors – most notably airlines and passengers – construct the 'maturity' of these innovations.

Flying Wings

A flying wing seeks to get rid of any aircraft structures (in particular the fuselage) that do not provide lift, thus maximizing the overall lift to drag ratio of the airframe. The flying wing concept is almost as old as aviation itself. Hugo Junkers patented a wing-only aircraft concept in 1910 (Pletschacher & Junkers, 2004: 144). The closest Junkers came to realizing this ideal was the 1930 G-38 airliner whose all-metal structure involved a huge 148 feet wide and six foot deep wing (with space for passengers to sit in the wing space next to the fuselage looking forward). However, the G-38 had a long fuselage after the wing leading to a biplane tail, and a stub of a fuselage at the front. *Flight* magazine noted that the aircraft "does not realize the ideal of the 'flying wing,' although it goes some way towards it" (Anonymous, 1929).

Others in Germany and the UK experimented with flying wing designs, but the concept found its fullest expression in the USA, where Jack Northrop was an avid supporter. Military aviation – a sector with greater risk-tolerance than civil aviation –provided a niche for Northrup's designs, starting with the 1940 N1-M. The aerodynamic efficiency predicted for such designs would enable bombers to fly longer distances and/or to fly faster – goals, which had great appeal during WWII. With feasibility demonstrated, in 1941 Northrop won a contract from the Army Air Corps to develop a large flying wing bomber. Known as the XB-35, the first aircraft was due to be delivered in 1943 (Baker, 2001: 201).

Northrup promoted the XB-35 for having "considerably less drag than a conventional airplane, which means that the same comparative speed can be obtained with less horsepower or that the speed may be considerably increased using the same horsepower."[6] It also claimed 'extensive' cost savings, "as the Northrop aircraft consists essentially of a thick wing in which there are virtually no structural complications, and in which there is ample room for the installation of the many auxiliary component parts which make up the modern airplane."[7]

However, Northrop's optimistic sales talk proved wide off the mark. The XB-35 programme was plagued by production and technical problems. The first XB-35 did not fly until June 1946, three years late and 400% over budget (Baker, 2001: 202). Much of the XB-35's difficulty stemmed from its counter-rotating propeller engines, and after 1947 Northrop focused on the YB-49, a modified

XB-35 in which the propeller engines were replaced by turbojets. Again production proved challenging, and the resulting aircraft had much less range than planned (mainly because the of the fuel-hungry turbojet engines), had insufficient payload capacity, and suffered from instability in pitch and yaw that made bombing much less accurate than conventional aircraft. Even worse, a test flight on June 5, 1948 provided fatal evidence of the YB-49's propensity to stall (Baker, 2001: 205). Northrop was unable to meet the production schedule, and the RB-49 was cancelled in 1949 due to budgetary constraints and a preference for more proven technology (Baker, 2001: 210).

Thereafter, advocates of flying wing aircraft struggled to argue that the benefits would surpass the extra costs and risks in comparison to conventional designs. In January 1947 *Flight* magazine predicted that: "Some day the flying wing will emerge as the accepted form of a passenger air liner" (Anonymous, 1947), but in 2015 that day still appears some way off. The technical maturity of a flying wing design is no longer in doubt; the US B2 'Stealth' bomber proves that stability problems can be managed using complex computer algorithms. Flying wings have survived in the niche of military aviation, with military support demonstrating the feasibility of the flying wing.

To understand why flying wings have not been widely adopted, we must move beyond the MLP to consider technologically specific features of commercial aviation – in particular, risk aversion in commercial dimension of the regime. Commercial airlines continue to view flying wings as too radical and high-risk because of concerns about cabin pressurization and the integration of passengers in a flying wing (i.e. passengers like to look out of windows). Instead, recent work has focused on a compromise approach known as a 'blended wing' which retains some fuselage blended into a large wing in order to provide windows (Greener by Design, 2005: 19–20).

Laminar Flow Control

The other much-touted aerodynamic innovation – laminar flow control (LFC) – likewise has a long, frustrating history. When an aircraft moves through air, friction with the surface causes a thin boundary layer of air to be dragged along with the surface. This boundary layer is laminar when it is comprised of thinner layers that slide past one another with no mixing, thus creating minimal drag. However, flow over large surfaces tends to become turbulent, dramatically increasing drag. Approximately half of fuel consumed in commercial aircraft goes into overcoming this turbulent drag (Bowles, 2010: 114).

The goal of LFC or 'laminarisation' is to keep this boundary layer laminar rather than turbulent. When leading edge surfaces are angled such that pressure decreases as the boundary layer moves towards the trailing edge, laminar flow occurs naturally. However, to keep the flow laminar near the rear portion of the surface, pressure must increase as air moves towards the trailing edge. This requires active LFC, which is typically obtained using suction through small perforations in the surface of the airfoil.

The efficiency gains of active LFC were first discussed by Griffith and Meredith of the UK Royal Aircraft Establishment in a 1936 paper.[8] They calculated that LFC by suction could reduce five-sixths of the power loss caused by friction between the aircraft's skin and air.[9] In the 1950s and the 1960s, the rapid growth of air travel (a 'landscape development') prompted some companies to study LFC as a means of reducing costs and further expanding markets. In June 1960, Handley Page acknowledged that supersonic air travel was "a new and inevitable development", but argued that high costs would only make it more exclusive: "passenger air transportation can be expected to remain the preserve of the expense account traveller or the wealthy, and a significant increase in air passenger traffic is unlikely without a correspondingly significant reduction in fares."[10] Thus, Handley Page proposed the HP 117 aircraft as a way to enable long-range air travel for the masses. The HP 117 design used two techniques for reducing drag: laminarisation and a flying wing design, thus affording "the full exploitation of low drag associated with laminar flow in combination with the low structure weight of the all-wing aeroplane."[11]

Although Handley Page gained government support for early research on the HP 117, it could not obtain funding to build a full-scale operational LFC aircraft. The sociotechnical landscape – notably the low cost of aviation fuel and efficiency gains from high-bypass turbofan engines – did not favour LFC in the 1960s. Crude econometric studies suggested that LFC would only offer a worthwhile benefit for very long-range aircraft, and with no such requirement envisaged, UK funding was stopped in the late 1960s.

Notably, this decision was not based upon a clear-cut cost-benefit analysis. Rather, it involved judgments about the probable costs and benefits of LFC. Deliberations by the Aeronautical Research Council's Aerodynamics Committee regretfully noted that this decision was based on "purely arbitrary estimates and so, as on many occasions in the past, the discussions have highlighted the difficulties of making any accurate assessment of the possible performance advantages from laminarisation in the absence of reliable and substantiated data on manufacturing and maintenance costs."[12] This decision illustrates a typical catch-22 for radical innovations: they present high uncertainties until they are developed and operated, but these same uncertainties deter sufficient investments in development to provide operational data.

Support for LFC was more substantial in the USA. In the early 1960s, Northrop obtained Air Force funding for a flight test programme with an X-21 aircraft. This initially revealed several difficulties associated with LFC, including unexpectedly high levels of turbulence across wing surfaces, and the loss of LFC in certain weather conditions due to the formation of ice crystals. The X-21 eventually achieved laminar flow over 95% of its laminarised surfaces, but the project was cancelled in the late 1960s, reportedly because of dwindling Air Force support and the distractions of Vietnam (Braslow, 1999: 12).

Interest in LFC was revived by the 1973 oil crisis. Although many at NASA believed that earlier research had demonstrated the impracticality of LFC, a 1974 workshop by the American Institute of Aeronautics and Astronautics (AIAA) indicated that progress in related technologies warranted renewed attention to LFC. In September 1975, a NASA-sponsored task force published their conclusion that LFC should be supported, and a Laminar-Flow Control Working Group was immediately established at NASA Langley Research Center (Braslow, 1999: 14). The LFC project eventually became one of the six projects to be supported by NASA's ACEE.

The task of the 1970s LFC group was even more challenging than that of the 1960s LFC researchers because NASA aimed to develop technology for the civil airliner industry, where costs are more important than they are in military applications (Braslow, 1999: 15). A wide range of activities, from basic research to flight-testing, sought to establish the practicality of LFC. Key concerns included insect contamination and the consequent in-flight loss of laminarisation, along with extra maintenance costs. Flight tests on a relatively small aircraft demonstrated that LFC could be maintained over a portion of the wings under operational conditions that were typical of commercial airliners: “during four years of flight testing from November 1983 to October 1987, no dispatch delays were caused by LFC systems” (Braslow, 1999: 25).

Despite these findings, the risks of extra maintenance costs and in-flight loss of LFC have deterred airliner manufacturers from using LFC operationally (Braslow, 1999: 1). Both Boeing and Airbus have flight-tested hybrid LFC, in which a combination of natural and active laminar flow control provides a more reliable, though less efficient solution than active LFC. This has now been implemented on the latest derivative of the 787 (Kingsley-Jones, 2014 Mecham, 2012). Nonetheless, an airliner with extensive suction-LFC does not appear to be a near-term prospect.

In sum, while landscape pressures such as high oil prices have helped to provide a niche for LFC research and development, they have been insufficient to cause a regime change. To explain this insufficiency, we must go beyond the structural MLP analysis to consider how specific social groups conceive of ‘maturity’. While engineers have proven that LFC can operate reliably on small aircraft, manufacturers and commercial airlines require more experience and full-scale demonstrations before they consider LFC to be mature.

Discussion and Conclusions

Why do some innovations enable transitions, while others find only limited market niches, and still others remain in the research and development phase? The case studies described above illustrate both the utility and limitations of the MLP in answering such questions. The MLP provides insight into how the timing of landscape, regime, and niche dynamics allowed the turbofan to displace propeller-pistons in long-range aircraft. The landscape pressures of WWII nurtured the military turbojet niche and made it sufficiently mature to replace the propeller-piston regime when new landscape pressures – the U.S.-British post-war rivalry in commercial aviation and the rapid expansion of air travel – grew sufficiently strong.

Yet the mere presence of niche resources and landscape pressures is insufficient to explain how or why transitions occur. As we have seen, other radical aviation technologies – including advanced turboprops, flying wings, and laminar flow control – have been supported in niches and nurtured by landscape developments, but have not caused transitions. Cold War technological competition created a niche for both carbon fibre and flying wings. Propfan and laminar flow control niches were nurtured by the landscape development of the oil crisis and consequent government R&D programmes. In recent years, concerns about a new landscape pressure – climate change – have continued to nurture all of these niches.

Why, then, have niche and landscape developments not caused a transition towards these more fuel-efficient innovations, as they did for the (extremely inefficient) turbojet? The MLP provides a preliminary answer: the niche was not mature enough, and/or the landscape pressures have not been sufficiently strong or sufficiently consistent to lead to full market introductions and maturation of innovations. But to understand why some innovations cause transitions while others do not, we must consider what it means for a niche development to be sufficiently mature, what it means for landscape pressures to be sufficiently large, and for whom. We also need to follow the 'symmetry' principle by analysing a spectrum of outcomes (success, failure, and partial adoption), rather than focusing solely on past successful transitions. Future work on the MLP framework could benefit from a more comparative approach that considers successful, partial and failed transitions within the same regime and between different types of regime.

What our case studies show is that different social groups could evaluate the same innovation as 'conservative' or 'radical,' 'mature' or 'immature.' In the engineering dimension of innovation, propfans were not very radical, but in a business and consumer dimension, they represented significant departures from what had come to be accepted as the appropriate speed, noise level, and appearance of a long-range airliner to the social groups primarily concerned with these aspects of air travel. The case of carbon fibre is just the opposite: the engineering and manufacturing of carbon fibre components is radically different than that of aluminium components, but a carbon fibre airliner such as the 787 looks nearly identical to other Boeing or Airbus aircraft. Similarly, laminar flow remains a 'radical' engineering challenge, and its development poses significant economic risks, though consumers would hardly notice it in operation. Flying wings are radical from virtually all dimensions of innovation – engineering, business, policy, and consumer acceptance – and this is a principle reason that they are not even on the drawing board for any near-term airliner.

These cases suggest that technologies which are more radical in the engineering dimension of innovation than from a business or consumer dimension are likely to find a niche in research and development laboratories, but will be slower to find a market application. Such technologies include cold fusion nuclear reactors and carbon sequestration technologies. Markets for cheap, safe electricity and carbon footprint reductions exist, but the engineering of such systems remains stuck in the laboratory. By contrast, technologies, which are primarily radical in a business or consumption dimension, but are conservative from an engineering dimension, are more likely to find a market niche. Examples of innovations in this latter category include car sharing schemes (such as Zipcar, RelayRides, and Getaround) and 'smart' electrical meters. In these latter cases, regimes may take on a mixed character, in which two or more technologies see a pattern of incremental development.

These conclusions have implications for policy as well as for future research. As we have seen, the transition from niche to regime is often limited by actors' risk tolerances, but these tolerances vary greatly. Simply nurturing a niche is far from enough, even when landscape pressures appear to be supportive. Instead, the specific concerns of specific regime actors need to be addressed. Manufacturers find it safer to build upon established consumer preferences than to enter radically different markets. Consumers are wary of new and unproven products. The process of taking early-stage research into the market is long, arduous, and above all else, risky. In the case of high-risk technologies such as laminar flow and flying wings, neither increasing landscape pressures nor nurturing niches is likely to enable a transition. Rather, policies should aim to reduce or disperse the specific engineering, business, and regulatory risks associated with different technological options for radically green aviation.

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Notes

1 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd, June 1960. UK National Archives [NA], DSIR 23/28151.

2 This is one reason that computer software is often put on the market with glitches and security flaws (Anderson, 2006).

3 See 1992 Figure from Rolls Royce: http://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion3/UnifiedPropulsion3.htm

4 A short clip of it flying can be found here: https://www.youtube.com/watch?v=1BMNaXc1rL8

5 Carbon fibre comprises 50% of the Boeing 787 by weight, and enables over 3% of the 787's 20% fuel savings. Weight savings contribute to 3% of the efficiency gains, and carbon fibre also enables aerodynamic streamlining and systemic efficiency improvements. Combined with more efficient engines, these material-related savings make the 787 20% more fuel efficient than previous comparable aircraft.

6 Official Northrop Press Release, enclosed with letter from British Air Commission, October 31, 1941. NA, AVIA 10/363.

7 Official Northrop Press Release, enclosed with letter from British Air Commission, October 31, 1941. NA, AVIA 10/363.

8 Royal Aircraft Establishment, 'The possible improvement in aircraft performance due to the use of boundary layer suction,' by A. A. Griffith and F. W. Meredith, March 1936. NA, AVIA 6/8595.

9 Royal Aircraft Establishment, ‘The possible improvement in aircraft performance due to the use of boundary layer suction’, by A. A. Griffith and F. W. Meredith, March 1936. NA, AVIA 6/8595.

10 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd June 1960. NA, DSIR 23/28151.

11 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd June 1960. NA, DSIR 23/28151.

12 Aeronautical Research Council, Aerodynamics Committee, One-Hundred-and-Third Report of the Performance Sub-Committee, 7 May 1968. NA, DSIR 23/35788.

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