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Up in the air: Barriers to greener air traffic control and infrastructure lock-in in a complex socio-technical system

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ABSTRACT

Greater automation of air traffic control (ATC) could reduce aviation's climate change impacts, but improvements predicted long ago have been slow to happen. This resistance to ATC modernisation is framed as an issue of lock-in, and the detailed case study described here enables an analysis of the factors involved in slowing change. Although the classic lock-in effects of 'increasing returns' and 'network externalities' are important, a major barrier to modernisation is due to the political and organisational challenges of coordinating change across a large, complex socio-technical system. However, lock-in effects are crucial with respect to the perceived increasing returns accrued from experience with manual ATC operations, and the difficulty of quantifying the risks of automation (particularly as regard the use of complex software) is a major barrier to further improvements. Overcoming this obstacle to further automation depends on finding ways to test and operate new ATC software and procedures without compromising safety.

1. Introduction

In early 2010 the Obama Administration set out a new vision for NASA, with, amongst other changes, a refocusing towards 'green aviation', and a budget request that allocated $20 million per year 'to support NASA's environmentally responsible aviation program' [51]. The green aviation label encompassed many activities, including work on aerodynamics, engine technology and biofuels, as well as on air traffic control (ATC).

Although ATC improvements only offer modest environmental benefits, they have the advantage that they could be implemented without the need to replace current aircraft. Such ATC-driven reductions in aviation's climate change impact could thus *in principle* be implemented relatively quickly. The two main alternative approaches will take decades to have significant impacts. Aviation biofuel could be developed to make air travel sustainable, but the sheer amount required, along with the problematic nature of most current sources, make a rapid transition unlikely. Likewise, although greener aircraft with markedly better fuel-efficiency are feasible [33], their commercial viability is less certain [50]. Moreover, even if radically greener airliners can be built that are socially acceptable, it would be many years before the current aircraft inventory is completely replaced, whereas improvements in ATC efficiency would provide environmental benefits with both current *and* future aircraft.

Advances in ATC technology have long been predicted. A 1981 RAND report [70, p. 2] noted that:

> The prospect of almost total automation is no longer only science fiction. Computers are powerful and fast enough to project aircraft flight paths far into the future, to automatically correct them when they conflict with the anticipated flight profiles of nearby aircraft, and to digitally transmit the revised clearances up to the aircraft. Machines can continuously compute and update delay predictions, so that aircraft can be slowed at fuel-efficient higher altitudes when airports are operating at peak capacities.

However, over three decades later such levels of automation are still not implemented. Drawing on interviews with key personnel at NASA, and on analysis of NASA documentation, as well as of the trade and secondary literature, this paper describes the first major use of automation in the US ATC system, the Traffic Management Advisor (TMA) developed by the NASA Ames Research Center. Set in the context of broader US ATC developments, this case study is used to address three questions. What are the obstacles to the implementation of more automated ATC? Can these obstacles be understood in terms of 'lock-in' of the existing socio-technical system? And what measures could be used to overcome such lock-in?

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2. Aviation, climate change, and air traffic control

Aviation contributes to climate change by increasing levels of greenhouse gases such as carbon dioxide, ozone and water vapour, and by stimulating the creation of cirrus cloud around ‘contrails’ (condensation trails) that reflect more energy back to the earth than they reflect away from the earth. Total ‘radiative forcing’ – simply put, atmospheric warming – due to aviation is thought to be about three times that due to aircraft carbon dioxide emissions alone [60, p. 18]. Using biofuels (assuming that these can be sourced in a way that is both environmentally and economically desirable) would thus only be a partial solution.

More efficient ATC offers a ‘win-win’ outcome, with both environmental and economic benefits. For example, a 2000 report on aviation and the environment by the US Government Accounting Office (GAO) noted that:

> Operational improvements in such areas as communications, navigation, surveillance, and air traffic management could also lead to reductions in aircraft emissions. . . . improvements in air traffic management worldwide could reduce the annual consumption of aircraft fuel by 6 to 12 percent over the next 20 years [26, p. 22].

The potential environmental benefits lie in two areas. First, better ATC could make air travel more fuel-efficient. The ideal flight path for an aircraft would be for it to be able to operate as if there were no other aircraft around, and so no potential conflicts that would force it to take a sub-optimum flight path. An optimum flight path, in terms of fuel efficiency, would not only take the shortest route, and involve no ‘stacking’ while waiting for a landing slot, but it would also fly at the optimum (high) altitude for most of the journey, with a continuous ‘cruise climb’ after take-off, and land following a continuous ‘idle thrust’ descent. In particular, enabling aircraft to utilise idle thrust descents, with low engine power, is a key challenge for ATC because of the complexity and time pressure of many different types of aircraft converging on a limited landing space at an airport. ATC automation enables trajectories to be predicted, and adjustments made, further from the airport so that the final descent can be smooth and energy efficient.

Second, greater ATC automation could enable aircraft to avoid areas most likely to produce contrails, thus minimising the radiative forcing resulting from cloud formation, although there would be trade-offs involved in not flying the most direct routes [64]. Aviation-induced cirrus cloud formation has a potentially large impact on radiative forcing that cannot be ameliorated by the use of biofuels or improved aircraft efficiency [72, p. 743]. Sophisticated ATC might also enable aircraft to fly below contrail-prone altitudes although again there would be a trade-off with fuel-efficiency, and maybe objections on grounds of comfort and safety.

3. The challenge of lock-in

There are many obstacles to the fundamental transitions in energy production and use that are required to limit climate change. Technological innovation is necessary, but it is not sufficient to bring about these transitions. As Sovacool ([63], p. 1; see also [62]) notes, much research on energy has had too narrow a focus on technology and economics, while downplaying ‘the human dimensions of energy use and environmental change.’ At the level of economics it is clear that market forces alone will not bring about transitions quickly enough, and that economic instruments such as carbon taxes or emissions trading are often poorly focussed [23] and hard to implement without unintended consequences [39]. At the individual level, exhortations to adopt greener lifestyles have limited success, are inappropriate for much of the world’s population that live in poverty [3], and flounder due to inertia even when the financial payback is clear [65] or because of the lack of social acceptance of novel solutions.

With regard to US ATC technology the key question is why it has not made the transition to the greater levels of automation that would enable greener air travel. It is thus appropriate to address this question through the conceptual lens of lock-in theory. The idea that the adoption of more environmentally desirable technologies is prevented by lock-in builds on work by Arthur, David and others on ‘path dependency’. Arthur [2, p. 116] argues that technologies get locked in because ‘the more they are adopted, the more experience is gained with them, and the more they are improved’, and thus ‘a technology that by chance gains an early lead in adoption may eventually “corner the market” of potential adopters, with the other technologies becoming locked out.’

Alongside this ‘increasing returns’ effect, a second concept underpinning the idea of lock-in hinges on the role of ‘network externalities’. Although he did not use this term in his 1985 paper, this idea is central to David’s iconic, though contested (see [46]), QWERTY keyboard example. David [10, p. 334] argues that the history of QWERTY shows that what many consider an inferior technology remains locked in because of ‘*technical interrelatedness*, *economies of scale*, and *quasi-irreversibility* of investment’ (his italics). In other words, there was a strong linkage between the typewriter keyboard design and the expertise to type on it quickly. Thus, the more that one keyboard design dominated, the more it paid to be skilful in its use, and once such a large stock of keyboards and of people skilled in their use existed, it became increasingly hard for a competitor to gain traction.

Increasing returns and network externalities provide mechanisms for understanding how an inferior technology might persist in the face of superior alternatives. Previous studies of technological lock-in have focussed both on particular artefacts – e.g., the light water nuclear reactor [7] and the gasoline car [8] – and on large technological systems [66]. Lock-in has been highlighted as a particular concern for infrastructure-dependent vehicle technologies because of ‘high infrastructure investment costs and the presence of network externalities’ [67, p. 98]. With automobiles or other vehicles, lock-in can be conceptualised as hinging on consumer or operator choice, and potential policy options include whether to support more R&D on new vehicle technologies or to support infrastructure development [67]. However, such an analysis focuses on the way that the infrastructure inhibits transitions in vehicles, but ignores the possibility that infrastructure improvements may themselves be inhibited by lock-in.

Unlike with vehicles, ATC technology cannot be understood as a single technical artefact, amenable to technological substitution based on consumer or operator choice; rather, it is part of the infrastructure that makes air travel possible. ATC is a large technological system with capabilities stemming from the interactions of many elements, including radars, communications systems, software, and human operators. Thus, there are not only lock-in issues to consider, but also the challenges of implementing change in large socio-technical systems [38] involving complex products and systems [36], often requiring large investments from both public and private sources [32]. The nature of the technology and its organisational and political context are thus likely to make radical innovation difficult, as is the emphasis in aviation on ‘high reliability’ [43] and risk minimisation [15]. These factors present challenges to the explanatory utility of an approach based solely on economics-derived lock-in theory. Accordingly an interdisciplinary approach is adopted here, because, as noted by Sovacool [63, p. 26], ‘the energy problems facing society cut across academic disciplines.’