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A fuel-payload ratio based flight-segmentation benchmark

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ABSTRACT

Airlines and their customers have an interest in determining fuel- and emissions-minimizing flight segmentation. Starting from Küchemann's Weight Model and the Breguet Range Equation for cruise-fuel consumption, we build an idealized model of optimal flight segmentation for maximizing fuel efficiency and minimizing emissions under the assumption that each leg is operated with an aircraft of segment-length-matching design range. When a multi-leg ($\geqslant 2$) itinerary is most efficient, legs are ideally of equal length. Instrumental to the parsimony of this flight-segmentation benchmark is a new efficiency metric: Fuel-Payload Ratio (FPR). The FPR approach has a one-to-one correspondence with the standard microeconomic cost-curves framework, which avails the standard tools of microeconomic analysis for cost-efficient design-range determination and optimal flight segmentation. This makes it possible to make direct comparisons between (i) technically efficient design-range and flight-segmentation solutions and (ii) their economically efficient counterparts. Even modest fixed-cost components cause the latter to diverge non-trivially from the former.

1. Introduction

Air transportation is caught between two converging fronts. The first is increasing demand for air transportation, driven by income growth – notably, at a rate faster than income growth itself – during an era of consistently increasing world Gross Domestic Product (GDP).[1] The second is accelerating anthropogenic climate change, and the consequent need to reduce greenhouse gas (GHG) emissions drastically in order to avoid global-ecosystem-altering climate change. Technological innovation and far-reaching policy changes will be required in the medium term in order to achieve the targets agreed to in the United Nations Framework Convention on Climate Change (UNFCC COP21).

But in the short run, the GHG footprint of air transportation can be reduced by optimizing aircraft design-and-deployment decisions within the envelope of current technological possibility. This builds upon and makes the most of ongoing technological innovation to improve the efficiency of propulsion technology, improve wing and airframe strength-to-weight ratio by the introduction composite technology, and improve aerodynamic efficiency by e.g. the introduction of winglet technology (Cansino and Román, 2017).

Although several methods exist for calculating the GHG emissions of scheduled air transport, the dominant component common to all methods is *mission fuel* (see e.g. Kaivanto and Zhang, 2017). Nevertheless mission fuel is not the only determinant of GHG

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[1] In the post-1970s era, GDP has consistently grown, with the exception of one year in which the world economy absorbed the fallout from the financial crisis (2009). The empirical income elasticity of demand for air transportation services is widely documented to be greater than 1: for every 1% increase in income (i.e. GDP), demand for air transport increases by *more* than 1% (IATA, 2008; Chi and Baek, 2012; Gallet and Doucouliagos, 2014).

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emissions. Non-fuel-based measures – such as lowering the cruise altitude [2] and rerouting aircraft trajectories in real time to mitigate persistent contrail formation – are potentially important complementary components of emissions-reduction policy packages (Dallara and Kroo, 2011; Campbell et al., 2013). In the present paper however, the focus is on fuel and the possibilities for economizing on fuel burn through optimal flight segmentation.

Whereas route-structure variables are among the many that airlines and air-transport authorities typically optimize jointly (e.g. Dumas et al., 2009; Li et al., 2010; Pita et al., 2014; Dalmau and Prats, 2015), here we tackle the flight-segmentation aspect of route structure in isolation. By doing so, we abstract from the numerous variables and considerations for which fuel burn and GHG emissions are traded off in joint optimization exercises. In this sense, we investigate a pure – and therefore idealized – fuel- and emissions-focused flight-segmentation benchmark.[3]

This problem definition is not without precursors in the literature. Yutko and Hansman (2011) report[4] the frequencies of operations (legs flown) by all US carriers at different fractions of design range (R_1), separately for narrow-body aircraft, wide-body aircraft, an regional jets.[5] The mean of narrow-body aircraft operations was at 41% of R_1; the mean of wide-body aircraft operations was at 61% of R_1; and the mean of regional-jet aircraft operations was at 39% of R_1. Virtually all passenger air-transport movements are therefore sacrificing fuel and emissions efficiency by being operated with aircraft of much greater design range. Zeinali and Rutherford (2010) also document this "inferior environmental performance during actual operation" and suggest that it may be the result of a 'one-size-fits-all' approach in which aircraft are sized to meet extreme missions – presumably to offer the greatest possible scope for flexible deployment – rather than to meet representative payload-range missions. Thus, modern jet aircraft are oversized and consequently less efficient in operation than current technology is capable of delivering. Accordingly Zeinali and Rutherford (2010) identify "aircraft rightsizing" as a means of realizing efficiency improvements and emissions reductions – which they identify as a key challenge for the International Civil Aviation Organization (ICAO).

In turn Perez and Jansen (2014) advocate coupled design optimization, in which the aircraft's design configuration is optimized specifically for taking advantage of Intermediate Stop Operations (ISOs). The question of how ISO routes should be designed to maximize fuel and GHG efficiency is also broached by Green (2002), but his recommendations are couched in preliminary and suggestive language.[6] Poll (2011) revisits this question, and finds that significant fuel- and GHG-related savings are only available for distances greater than 5500 km. Martinez-Val et al. (2013) and Langhans et al. (2013) also begin with this question, but find that there is a tension between the engineering objectives of achieving fuel savings and reducing environmental impact, on the one hand, and economic cost efficiency, on the other hand. Our investigation aims to synthesize and deepen the aforementioned results parsimoniously.

This paper's novel contributions range across three dimensions.

First, the Fuel-Payload Ratio (FPR) efficiency measure – although derived from the same set of equations Green (2002, 2006) employs – has a direct interpretation in the standard microeconomic framework as the lower envelope of Total Variable Input (TVI) curves, which avails all of the standard microeconomic analysis tools. Using this microeconomic framework, we illustrate how Fixed Costs affect Average-Total-Cost-minimizing design range, thereby contributing to our understanding of the empirical disparity between the design ranges of aircraft purchases (and stock thereby created) based on economic drivers and the design ranges of aircraft purchases (and associated stock created) if they were guided purely by technical (fuel, GHG) efficiency.

Second, the present study of flight segmentation aims to sharpen Green's (2002) somewhat vague suggestions concerning efficiency-maximizing stage length. Hence the present study is distinct from, but responds to, complements, and sharpens Green (2002). The advantage of the FPR-based approach is that its mathematical form provides straightforward answers to these types of questions.

Third, the sensitivity analysis reported in this study investigates the effects of perturbations in (i) the 'lost-fuel' fraction λ of takeoff weight that is consumed during takeoff, climb-to cruise altitude and acceleration-to cruise speed, and (ii) the range-performance parameter X, which is a composite of propulsive efficiency and aerodynamic efficiency. In contrast, Green's (2002) sensitivity analysis studies the effects of perturbations in structural constants of proportionality pertaining to maximum take-off weight and payload. Hence the present study is distinct from, but complements Green (2002).

In Section 2 we investigate the impact of design range on commercial air transport fuel efficiency by developing a model drawing on Küchemann's (1978) Weight Model and the Breguet Range Equation for cruise fuel consumption. These two equation families complement each other. Küchemann's (1978) Weight Model is a standard if not classic[7] decomposition of aircraft take-off weight into components that roughly correspond to airframe empty weight, payload, engines, and mission fuel. The Breguet Range Equation in turn allows cruise range to be expressed as a function of (i) aircraft initial weight at take-off, (ii) aircraft 'final weight' upon landing, after mission fuel has been consumed, and (iii) range-performance parameters capturing the calorific energy content of the fuel, the propulsive efficiency of the engine, and the aircraft design's lift-to-drag ratio. Using these equations, Green (2002) derived the

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[2] (i) to reduce the impacts of NO_x emissions and (ii) to reduce the likelihood of persistent contrail formation

[3] Even though there may currently be practical impediments to full implementation of the present idealized flight-segmentation method, shifts toward this benchmark yield efficiency improvements. This is similar in spirit to Dalmau and Prats (2015) proposal, also published in *TRD*, for achieving fuel and time savings by flying continuous-cruise climbs, rather than the constant-cruise-altitude flight levels currently operated under Air Traffic Control (ATC) direction.

[4] in their analysis of 2006 Bureau of Transportation Statistics (BTS) Form 41 T-100 data.

[5] in their Figures 16, 17 and 18, respectively.

[6] For instance: "…the full report …leads to the suggestion that the most environmentally friendly solution might be to break long journeys into sectors not exceeding 7500 km…" (p 61 Green, 2002).

[7] Dietricht Küchemann is thought by some to be the finest aerodynamicist of his generation. His posthumously published (1978) *The Aerodynamic Design of Aircraft* is widely regarded as a classic text in aerodynamics.