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# Aircraft fuel burn performance study: A data-enhanced modeling approach

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ABSTRACT

The rapid growth in commercial air transportation and the price volatility of fuel push for fuel reduction policy to be implemented. Some changes in technology (e.g., improved designs of aircraft and engines), operations (e.g., improved flight routes), or both have shown promising results on fuel reduction in air transportation. Several candidate policy scenarios related to fuel consumption need to be evaluated, which call for fast, efficient, yet accurate fuel burn computation methods, in particular to compute the total aggregate fuel burn given a set of flight missions. While fuel burn evaluation models exist, some are computationally expensive or built based on data that might be outdated. Others suffer from the lack of accuracy due to simplification assumptions and computations. As such, we develop a fuel burn evaluation model by combining a low-fidelity physics-based model with aircraft operation and performance data. For a more accurate fuel burn computation, especially for the climb and descent segments, we integrate the state-of-the-art Base of Aircraft Data (BADA) trajectory simulation results into the fuel burn model. This model offers enhanced accuracy compared to low-fidelity models, yet retains their computational efficiency. In this paper, a fuel burn database corresponding to 40 aircraft types is generated based on the Bureau of Transportation Statistics (BTS) flight missions' database 2015. A sample-based linear regression model is then derived for each aircraft type. The validation results show that the model can estimate the total aggregate fuel burn for each aircraft type with less than 1% prediction errors using flight mission data from 2016, and less than 6% prediction errors when compared with the actual fuel burn data corresponding to three commercial airlines in 2015 and 2016. The developed models are then used to investigate the two common simplifying assumptions in fuel burn evaluation, namely the cruise-only approximation and similar aircraft type mapping (when data pertaining to some specific aircraft types are unavailable). The results provide insight into the inaccuracies caused by these simplifications in fuel burn computation. For instance, the cruise-only approximation shows significant error (mostly >30%) when performed on smaller aircraft, which typically fly shorter routes. The combined computational efficiency and accuracy that these models offer would open doors to perform more computationally intensive analyses, such as sensitivity and uncertainty analyses, as well as optimization. Such analyses could be computationally prohibitive when large-scale models are used.

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## 1. Background and motivation

The advancement of numerical simulation has assisted considerably the study of many complex physical phenomena and is becoming increasingly widespread as a means to support decision-making and policy making processes (Yanto and Liem, 2017). The airline industry, as an example, relies a lot on numerical analyses and modeling in its decision making analyses. In 2006, the number of passengers carried by air transport was around 2,073 billion and it increased to 3,696 billion in 2016 (The World Bank), reflecting the rapid growth in commercial air transportation. With the expected steady increases in the demand of air transportation (ICAO, 2010) and the volatility of fuel prices (International Energy Agency (IEA), 2008), fuel economy and environmental impacts of aviation have become the main drivers in many air transportation policy and decision making processes. Therefore, these policies and decisions need to be carefully analyzed. In 2010, international aviation consumed approximately 142 million metric tonnes of fuel, resulting in 448 million metric tonnes (Mt, 1 kg $\times$ $10^9$) of $CO_2$ emissions and the fuel consumption is projected to multiply by 2.8–2.9 times by 2040 (ICAO, 2016). However, the United States Department of Transportation's Bureau of Transportation Statistics (BTS)[1] has shown a decreasing trend within the period 2006–2009 of the total fuel consumption. This decreasing trend is a result of some changes in technology (e.g., improved designs of aircraft engines), operations (e.g., flight route), or both. To make decisions on the best policy to implement to further reduce the total fuel consumption, several candidate policy scenarios need to be carefully evaluated and compared. For instance, which combination of new engines, improved aircraft designs or structural materials, and operational procedures could reduce the total fuel consumption the most. These evaluations require outputs from flight performance analyses, in particular the amount of fuel burned during any given flight mission (simply referred to as *fuel burn* in the remainder of this paper).

Besides accuracy, computational efficiency is an important consideration in the fuel burn model derivation, for several reasons. First, the scale and complexity of analyzing the fuel burn of the global air transportation system are immense. The simulation of all flights within one year involves over 35 million flights with approximately 350 aircraft types and thousands of input parameters (presented at Deutches Zentrum für Luft- und Raumfahrt (LDR), 2010). Second, to have a realistic evaluation, we need to carefully characterize the effects of uncertainty. To do so, one might wish to perform Monte Carlo simulations, requiring many thousands of simulations to be run. While the uncertainty analysis is beyond the scope of our current paper, computational efficiency is a key performance factor of our proposed model to enable running these simulations, which will become intractable when we use expensive, large-scale models.

There are quite a number of fuel burn prediction models available, spanning from low-fidelity to high-fidelity. The different levels of fidelity are defined based on how closely the models represent the system's physics. In general, the high-fidelity models require modeling of flight mission's detailed trajectory, taking into account the flight condition variations to evaluate the total fuel consumption. The low-fidelity models, on the other hand, may rely on empirical models, or with simplified assumptions. For instance, the cruise segment of flight is typically used to represent the entire flight mission (Kenway et al., 2012; Liem et al., 2015a). There has always been a tradeoff between the accuracy and efficiency in any computational analysis. High-fidelity models for fuel burn computation perform accurately, however, it is typically computationally expensive and time consuming (Liem et al., 2013, 2015b). Low-fidelity models can reduce the computational time, but at the expense of accuracy (Randle et al., 2011).

Some platforms have been developed by government institutions and large organizations, such as the Federal Aviation Administration (FAA) and the European Commission (EC). FAA has led the project to develop the Aviation Environmental Design Tool (AEDT) to assess aircraft fuel burn, emissions, and noise by taking into account detailed inputs such as flight schedules, trajectories, aircraft performance model, and emission factors (AEDT, 2017). The AEDT fuel burn and emissions modules were previously known as the System for assessing Aviation's Global Emissions (SAGE) (Kim et al., 2007). The International Civil Aviation Organisation (ICAO) developed the ICAO Carbon Emission Calculator[2] to estimate the fuel burn and emissions with minimum input variables (ICAO, 2015). The calculation relies on a distance-based approach that is derived based on publicly available data. The European Organization for the Safety of Air Navigation (Eurocontrol) also developed an aircraft performance model which can be used to generate aircraft trajectories and estimate fuel consumption named the Base of Aircraft Data (BADA).[3] We observe, however, the limited number of aircraft and nominal takeoff weights modeled in BADA.

The aforementioned models are typically not free nor publicly available. Moreover, the data used to develop the models are often outdated and might not be available for all aircraft and engine types, especially the newer ones (Wasiuk et al., 2015). Some models are derived based on existing databases, which are not suitable to perform future projections. This will be disadvantageous when we consider the potential future scenarios in policy analysis practices. This particular limitation also applies to the fuel burn evaluation using the quick access recorder (QAR) data, since they only pertain to completed flights. When data are not available, it is common to use data corresponding to another, but similar aircraft type (similar aircraft type mapping), which might compromise the accuracy. Moreover, running the models could be computationally time consuming and inefficient. For instance, for each BADA simulation, the user needs to input the aircraft and flight information one by one (e.g., aircraft type, initial and final altitudes during climb) for each segment. While each simulation takes only a few seconds to run, it is not very practical to run the trajectory simulations for the entire mission profile (including climb, cruise, and descent) thousands of times manually to generate the fuel burn database.

Apart from the detailed models mentioned above, some researchers have developed fuel burn prediction models. These models,

[1] TranStats, Bureau of Transportation Statistics http://www.transtats.bts.gov/.
[2] ICAO Carbon Emissions Calculator http://applications.icao.int/icec.
[3] https://badaext.eurocontrol.fr/.

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