ANNEX E. FUEL EFFICIENCY

The consumption of fuel has increased in importance dramatically over the last decade primarily as a result of a dramatic increase in the cost of fuel as shown in Figure E-1. Up until 1998 there had been a steady decline in fuel price in current terms and a substantial decline in constant terms. This was complemented by a steady improvement in fuel efficiency of aircraft as a result of improvements in both the engines and the airframes (Figure E-2). Fuel consumption is proportional to the weight as well as the coefficients for drag and lift. The introduction of winglets and other design features to reduce drag have produced fuel savings. In addition, improvements in the engines have reduced the fuel consumption per unit of thrust and allowed engines to be configured for greater efficiency during take-off, climbing, and during cruising.

The consumption of fuel of an aircraft is dependent on four factors, the length of the route, the weight of the aircraft, the efficiency of the engines, and the share of the airframe. The length of the route has two impacts on fuel consumption. The first relates to fuel consumed at the cruising altitude, which is directly proportional to the weight of the aircraft and the efficiency of the engines. The second is the fuel consumed for take-off, climb and descent, which is dependent on the weight of the aircraft and the share of the airframe.

Figure E-1. History of fuel charges

Source: DOT BTS
http://www.transtats.bts.gov/rtm91_02.htm

Figure E-2. Normalized energy efficiency of passenger aircraft (MJ/ASK)

proportional to the distance traveled. This distance will include the direct route plus any diversions due to weather of traffic congestion. The second relates to the fuel consumed taxiing to and from the terminal, climbing to the cruise altitude and descending from cruise altitude including any time spent in a holding pattern waiting to land (Figure E-3). A significant amount of fuel is consumed during these operations, especially relative to the distance traveled. The impact is greatest for short trip where ¼ to 1/3 of the fuel for a trip may be consumed in these operations. The impact diminishes with the length of the trip and beyond 4–6 thousand kilometers contributes less than 10 percent. Therefore, for intercontinental or longer regional flights, the fuel consumption can be estimated as proportional to the distance traveled.

**Figure E-3. Typical flight plan**

The shape of the airframe determines not only the carrying capacity of the aircraft but also its aerodynamic drag. Aircraft drag is the sum of zero-lift drag and induced drag due to lift. The former is the sum of drag due to skin friction and pressure. The skin friction occurs at the boundary layer as a result of the viscosity of the air and depends on whether the flow is laminar or turbulent. This drag varies with the shape of the airframe and the speed of travel. Pressure drag depends on the thickness of the boundary layer, which affects pressure recovery at the trailing edge. This is relatively small for subsonic flight. Drag due to lift has two components; induced and viscous. The former is vortex drag, which depends on the distribution of lift across the span of an aircraft. The latter is due to the increase in the boundary layer with the angle of attack.

At a given speed, an increase aircraft weight will increase drag because of changes in the wing to generate sufficient lift. However, the marginal impact is insignificant compared to the impact that an increase in weight has on lift. A more significant impact is the effect of weight on cruising altitude. The heavier the weight, the lower the cruising altitude because the plane requires sufficient air density to provide the necessary lift. The more dense the air, the greater the impact of draft. Thus for our purposes, the increase in thrust and resulting increase in fuel required can be treated as a function of total aircraft weight.

Fuel is consumed while providing the thrust necessary to overcome this drag. The drag in turn depends on the speed of the aircraft. In the last two decades, significant improvements have been
made in reducing draft through changes in the shape of the wing. The aircraft are designed to operate in a specific speed range at cruising altitude so that the drag does not vary due to speed.

Aerodynamic efficiencies of large aircraft have improved approximately 15 percent since 1959 (Lee et al., 2001). Most of these gains were realized after 1980 through better wing design and improved propulsion/airframe integration made possible by improved computational and experimental techniques (IPCC, 1999). Advanced materials such as improved aluminum alloys and composites have been successfully used for control surfaces, flaps, and slats on civil aircraft. However, the current fleet of aircraft is still about 97 percent metallic, with composites used only on relatively few components such as the tail. Furthermore, structural weight reductions have been offset by structural weight increases to enable improvements in aerodynamics and accommodate increased engine weights (IPCC, 1999).

The SAR (Specific air range) model\(^{50}\) is the basic model for describing the physics of aircraft in steady cruise flight, and it quantifies the distance flown per unit of energy consumed. By inverting the equation, the fuel consumption per unit distance is proportional to:

\[
\frac{I \times D \times TSFC}{W \times L \times V}
\]

where:
- \(W\) = \(W_{\text{fuel}} + W_{\text{payload}} + W_{\text{structure}} + W_{\text{reserve}}\) of the aircraft
- \(D\) = drag coefficient for the airframe
- \(L\) = lift coefficient for the airframe
- \(V\) = velocity
- \(TSFC\) = Thrust specific fuel consumption per unit time for the engine

The payload an aircraft is carrying does not have a direct impact on the drag. There will be a slight adjustment in the wing to provide greater lift for heavier payloads but the effect on drag and thus fuel consumption is minimal. A significant increase in payload has a secondary impact on drag because it lowers the cruising altitude in order to provide sufficient air density to provide the necessary lift. The higher density air increases the drag. Therefore, for a given aircraft operating at its cruising altitude, the fuel consumed to overcome drag will be relatively constant regardless of the payload, but the fuel consumption will change along with the optimum cruising altitude for substantial differences in payload.

The efficiency of the engines on the aircraft has a direct impact on fuel consumption. Propulsive efficiencies improved significantly with the introduction of the high-bypass ratio engine. Initially developed for long haul, wide-body aircraft, high-bypass ratio engines contributed to the noticeable increase in fuel efficiency in the early 1970s. However, these engines were not installed on smaller aircraft until more than a decade later. The DC-9-80 and the 737-300 introduced in the first half of the 1980s were still equipped with low-bypass engines.

The loaded weight of the aircraft has a direct relation to the amount of fuel consumed at cruising altitude because of the thrust required to provide the required lift. Ignoring the impact of drag, the

\[\text{SAR} = \frac{Velocity}{TSFC \times h_F} \times \frac{L}{DW}\]

where \(h_F\) = heating value of jet fuel
fuel consumed per kilometer is directly proportional to the full weight of the aircraft. Since that weight diminishes as fuel is consumed during flight, the rate of fuel consumption will gradually decrease over the length of a flight. The longer the flight, the higher the average rate of fuel consumption because the greater the fuel that must be carried. Similarly, the greater the payload, the more the fuel that must be carried because of the need for additional lift.

The combined impact of improvements in technology based on past trends suggests an average annual increase in aircraft fuel efficiency of 2–2.5 percent as shown in Table E-1. The improvement in engine efficiency will derive from advancements already introduced for passenger aircraft that will be converted to freighters in the future as well as the introduction of ultra-high bypass engines. These improvements apply to long-range flights. The shorter flights would show less improvement. The reduction in airframe weight is expected to result from the increase in use of composite materials which will take place in the passenger aircraft over the next 10–15 years and in the air cargo business beginning with new aircraft but accelerating in 15 years when the conversions of passenger aircraft.

The impact on fuel consumption of a change in payload requires an evaluation of both the relationship of aircraft weight to fuel consumption at cruising speed and the change in aircraft weight with a change in payload for a specific route. The first can be addressed using the Brequet range equation, which extends the SAR to include the weight of fuel consumed for steady cruise flight over a specific range.

\[ R = \frac{V (L/D)}{g SFC} \ln \left[ 1 + \frac{W_{\text{fuel}}}{W_{\text{airframe}} + W_{\text{payload}} + W_{\text{fuel reserve}}} \right] \]

Where

- \( V \) = Cruising velocity
- \( L/D \) = lift to drag coefficient
- \( SFC \) = fuel consumption per unit thrust
- \( g \) = gravity constant
- \( W_{\text{fuel}} \) = Weight of fuel consumed during flight
- \( W_{\text{reserve}} \) = weight of required fuel reserves

This equation takes into consideration the variation in weight as the fuel is consumed during the flight.

By moving terms the equation becomes

\[ R \frac{g SFC}{V (L/D)} = \ln \left[ 1 + \frac{W_{\text{fuel}}}{W_{\text{airframe}} + W_{\text{payload}} + W_{\text{fuel reserve}}} \right] \]

By setting the distribution constant, \( R_o \), introducing the exponent and reversing terms, the equation becomes

\[ W_{\text{fuel}} = (W_o + W_{\text{payload}}) e^{R_o} - 1 \]
Where

\[ \alpha = \frac{g \cdot SFC}{V \cdot (L/D)} \]

\[ W_o = W_{\text{airframe}} + W_{\text{fuel reserve}} \]

Assuming that \( \alpha \) is constant and differentiating equation (3) yields the following relation

\[ \frac{\partial W_{\text{fuel}}}{\partial W_{\text{payload}}} = e^{\alpha R_o} - 1 \]

This implies that a uniform amount of fuel is required for each additional ton of payload.