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# First-Order Altitude Effects on the Cruise Efficiency of Subsonic Transport Aircraft

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August 2011

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## Abstract

*Aircraft fuel efficiency is a function of many different parameters, including characteristics of the engines, characteristics of the airframe, and the conditions under which the aircraft is operated. For a given vehicle, the airframe and engine characterteristics are for the most part fixed quantities and efficiency is primarly a function of operational conditions. One important influence on cruise efficiency is cruise altitude. Various future scenarios have been postulated for cruise altitude, from the freedom to fly at optimum altitudes at all times to altitude restrictions imposed for environmental reasons (for example, contrail avoidance). This report provides background on the fundamental relationships determining aircraft cruise efficiency and examines the sensitivity of efficiency to cruise altitude. Analytical models of two current aircraft designs are used to derive quantative results. Efficiency penalties are found to be generally less than 1% when within roughly ±2000 ft of the optimum cruise altitude. Even the restrictive scenario of constant altitude cruise is found to result in a modest fuel consumption penalty if the fixed altitude is in an appropriate range. Penalties begin to grow rapidly when far away from the optimum, however, especially when restricted to low altitude while flying in a low weight condition or high altitude at high weight conditions.*


# 1.0 Introduction

Aircraft fuel efficiency is fundamentally impacted by the altitude at which the aircraft is operated. In the current air traffic management (ATM) system, flight paths (or trajectories) use specific flight altitudes (flight levels) to maintain safe vertical separation and aircraft maintain a constant altitude during cruise unless directed to climb or descend by air traffic control. However, as fuel is consumed the altitude at which the airplane is most fuel efficient increases. If an increase in cruise altitude is desired, the crew can request permission to climb to the next higher flight level available. This “step cruise” is a relatively good approximation to the optimum cruise profile, which is usually a continuous, shallow climb. Aside from trying to improve fuel efficiency, pilots also often ask for permission to change altitude to avoid weather or air turbulence. In this case, the comfort and safety of the passengers may take priority over minimizing fuel consumption. In the future it is envisioned that enhanced traffic surveillance and control technology will enable aircraft to fly more optimum cruise profiles, without the restriction of holding constant altitude. This additional flexibility should result in lower fuel consumption and lower environmental impacts from the resulting emissions. There are, however, environmental impacts which are themselves dependent on the aircraft altitude. The environmental impact perhaps most sensitive to altitude is the formation of persistent contrails. Although the ATM system of the future may enable more efficient cruise, it is also possible that there may be “no fly zones” at certain flight altitudes to mitigate contrail formation and minimize the environmental impacts of aviation.

Persistent contrails are a significant, although very uncertain, contributor to the overall environmental impacts of aviation (ref. 1). Although the fundamental physics of contrails are understood, their influence on the environment depends on the extent of area covered and the optical properties of each contrail. Current observational data is insufficient to determine either of these factors with much certainty. A contrail is effectively a man-made cirrus cloud which reflects some incoming solar radiation (cooling effect) and absorbs some outgoing infrared radiation (warming effect) (ref. 2). The net effect depends on the optical properties of the contrail and where and when the contrail forms (e.g., contrails formed at night have a warming effect, whereas contrails formed midday above a dark surface can have a net cooling effect). Whether or not a given flight will generate persistent contrails, short-lived contrails, or no contrails is dependent on many factors, including the background atmospheric conditions as well as the aircraft operating conditions. As atmospheric measurements and modeling improve in the future, it may be possible to predict when and where contrails will be formed. With this knowledge, it may also be possible to avoid this particular environmental concern by flying in air masses which are not conducive to contrail formation. Recent studies indicate that the layers of air conducive to formation of persistent contrails are relatively thin in vertical height, with a median thickness of 0.7 to 1.2 km (2,300 to 3,900 ft) at an altitude of 9 km (29,500 ft) decreasing to 0.4 to 0.8 km (1,300 to 2,600 ft) at an altitude of 13 km (42,600 ft) (ref. 3). Unfortunately, these layers often occur at the altitudes which are most efficient for aircraft cruise. Avoiding contrail formation by flying higher or lower may increase fuel consumption and the environmental impacts associated with engine emissions, such as $CO_2$. Some studies have attempted to examine the potential trade-offs between higher engine emissions and contrail avoidance to minimize overall environmental impacts (for example, ref. 4 and ref. 5). This type of trade-off is somewhat ill-defined, however, because of the large uncertainty in the direct and indirect environmental impacts of contrail formation and certain engine emissions.

The objective of this report is to provide some fundamental, background information on aircraft cruise efficiency and the sensitivity of efficiency to cruise altitude. No attempt is made in this report to calculate environmental impacts or examine the trade-offs between various types of aircraft environmental impacts as in other studies. Rather, the focus is on the details of aircraft performance. The analysis is limited to two aircraft types, but the results presented provide a rough sense of the potential penalties associated with restricting cruise altitudes, and conversely, the possible improvements from unrestricted cruise. It is hoped that these results can provide some additional data on aircraft cruise efficiency to supplement contrail mitigation studies, which have tended to focus more on overall fuel consumption impacts and less on the underlying aircraft characteristics.

## 2.0 Fundamentals of Cruise Efficiency

In the most general sense, efficiency is defined as the useful output of a system divided by the resources put into the system to achieve that output. There are multiple ways to define aircraft cruise efficiency, depending on how the input and output are measured. In this study, cruise efficiency is defined to be synonymous with specific range (distance flown per pound of fuel consumed, similar to the miles per gallon efficiency metric used for automobiles). For steady, level flight (in zero wind), the instantaneous specific range is given by:

$$\frac{dR}{dW_f} = \frac{V*(L/D)}{(TSFC)*W}$$

where,

| | | |
|---|---|---|
| $dR$ | = | incremental distance flown |
| $dW_f$ | = | incremental fuel consumed (negative of incremental change in aircraft weight) |
| $V$ | = | velocity |
| $L/D$ | = | lift-to-drag ratio (aerodynamic efficiency) |
| $TSFC$ | = | thrust specific fuel consumption (propulsion efficiency) |
| $W$ | = | current aircraft weight |

The parameters in the right-side of the above equation are interdependent. L/D, for a given design, is primarily a function of velocity, altitude, and weight. TSFC primarily depends on velocity, altitude, and the required thrust level (which is in turn dependent on L/D and weight). At any given weight, the aerodynamic and propulsion characteristics of the aircraft dictate the velocity and altitude at which the specific range is maximized. The most efficient cruise profile is to fly at the optimum velocity and altitude at each point in the cruise. Typically this results in a gradual increase in altitude and is often referred to as a “cruise-climb.” Note that although the above equation is based on the assumption of steady, level flight, the climb rate during a cruise-climb is generally small enough that a “quasi-steady” assumption is still valid.

For a given airplane with certain aerodynamic and propulsion characteristics, the specific range is primarily a function of weight, velocity, and altitude. There are secondary effects which can have a small influence. For example, depending on the loading conditions and what comprises the weight (fuel, cargo, or passengers), the center-of-gravity may be different even though the weight is the same. The location of the center-of-gravity can have a small impact on the L/D due to differences in control surface settings necessary to trim the aircraft. These secondary effects are ignored in the current analysis. Under the simplifying assumptions used in this study, for every possible weight of the aircraft, there is a velocity/altitude combination for which specific range is maximized and flying at any other condition while at this weight incurs an efficiency penalty. The magnitude of the off-optimum efficiency penalty, whether due to ATM constraints, contrail avoidance, or other operational reasons, is the focus of this study. (Note that sometimes the theoretical optimum altitude is above the maximum altitude at which the aircraft is certified to operate, or above the maximum altitude at which it is possible to operate the aircraft and maintain sufficient thrust margin to climb at an acceptable minimum rate. In these situations the optimum operational altitude is below the theoretical optimum.)

# 3.0 Modeling and Analysis Methodology

The aircraft sizing and synthesis computer code FLOPS (Flight Optimization System) (ref. 6) was used as the aircraft performance analysis tool for this study. Although FLOPS includes capabilities for aircraft design and optimization, for this study it was used solely for determining performance, more specifically cruise performance, of a given aircraft design under various scenarios. The FLOPS mission performance module includes several different options for cruise. Altitude and Mach number can be independently set by the user or optimized for either range or endurance. Other cruise profiles such as constant lift coefficient and maximum speed cruise (dash) are also available.

## 3.1 Single-Aisle Transport Class Vehicle

The Boeing 737-800 (with winglets) was selected as a representative vehicle in the single-aisle transport class. A FLOPS model of a 737-800 like aircraft was developed using a combination of publicly available data on the 737-800 geometry, weight, and performance characteristics (ref. 7); proprietary aerodynamic data; and a CFM56-7B based engine model developed at NASA Glenn using the NPSS (Numerical Propulsion System Simulation) (refs. 8-10) and WATE (Weight Analysis of Turbine Engines) (refs. 11-13) codes. The FLOPS aerodynamic predictions (drag coefficient, $C_D$, versus Mach number and lift coefficient, $C_L$) were calibrated to 737-800 high speed aerodynamic data. Although it was not possible to exactly match the 737-800 data at all conditions, it was possible to obtain an excellent match around the cruise flight conditions as shown in Figures 1 and 2.

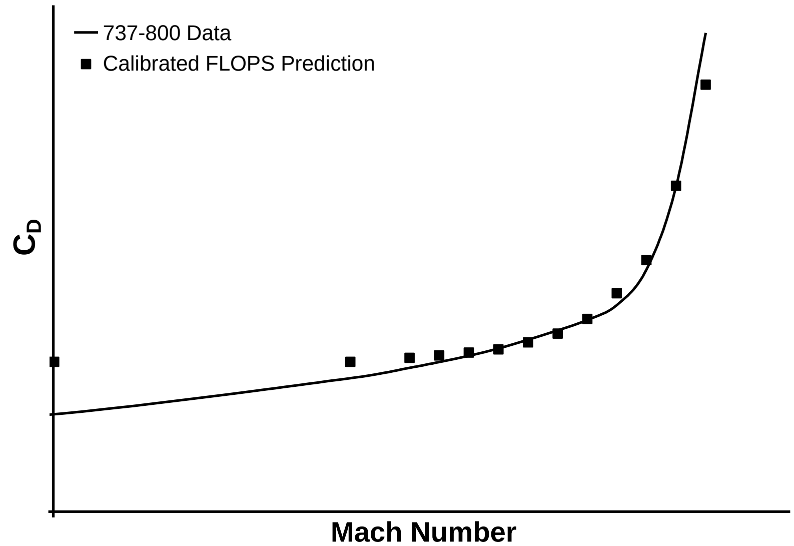



Figure 1. Comparison of predicted and actual $C_D$ versus Mach number for representative cruise $C_L$ condition.

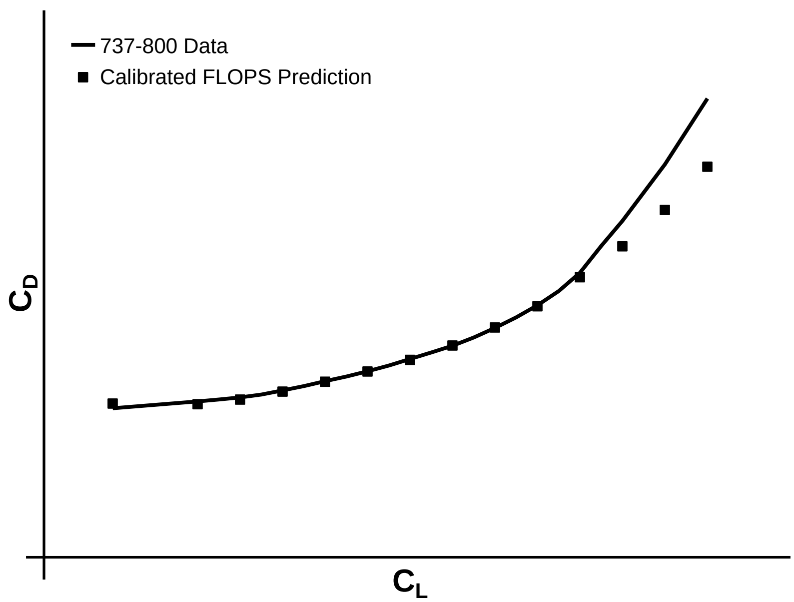



Figure 2. Comparison of predicted and actual drag polars at representative cruise Mach number.

To enhance the accuracy of the analytical model, FLOPS-predicted mission performance was calibrated to a specific point on the 737-800 payload-range diagram provided in reference 7: an operating empty weight plus payload of 124,060 lb at maximum fuel capacity of 46,063 lb. Ramp weight for this calibration mission is 170,123 lb. According to the payload-range diagram, at this operating point the 737-800 range is ~3060 nm (see Figure 3). Although a detailed mission profile is not provided in reference 7, some parameters are specified: 31-35-39,000 ft step cruise, cruise speed at Long Range Cruise Mach, typical mission reserves, and a 200 nm alternate airport. Additional insight into the likely Boeing mission rules was obtained from reference 14, which includes a “typical” mission profile diagram from Boeing. Prior to calibration, the FLOPS predicted range for this mission was 3178 nm (~4% high). Assuming that the mission profile is adequately modeled and the aerodynamic model is accurate, the higher FLOPS range is indicative of an under prediction of engine TSFC. The NASA-developed engine deck was therefore adjusted to match the 3060 nm published range capability. Note that it is not possible to separate the impacts of inaccuracies in mission profile, engine TSFC, and aircraft L/D when matching range performance for a specific total fuel load. Even though adjustment was only made to the engine model, the discrepancy may be due to a combination of differences in engine characteristics, aerodynamic characteristics, and mission parameters.

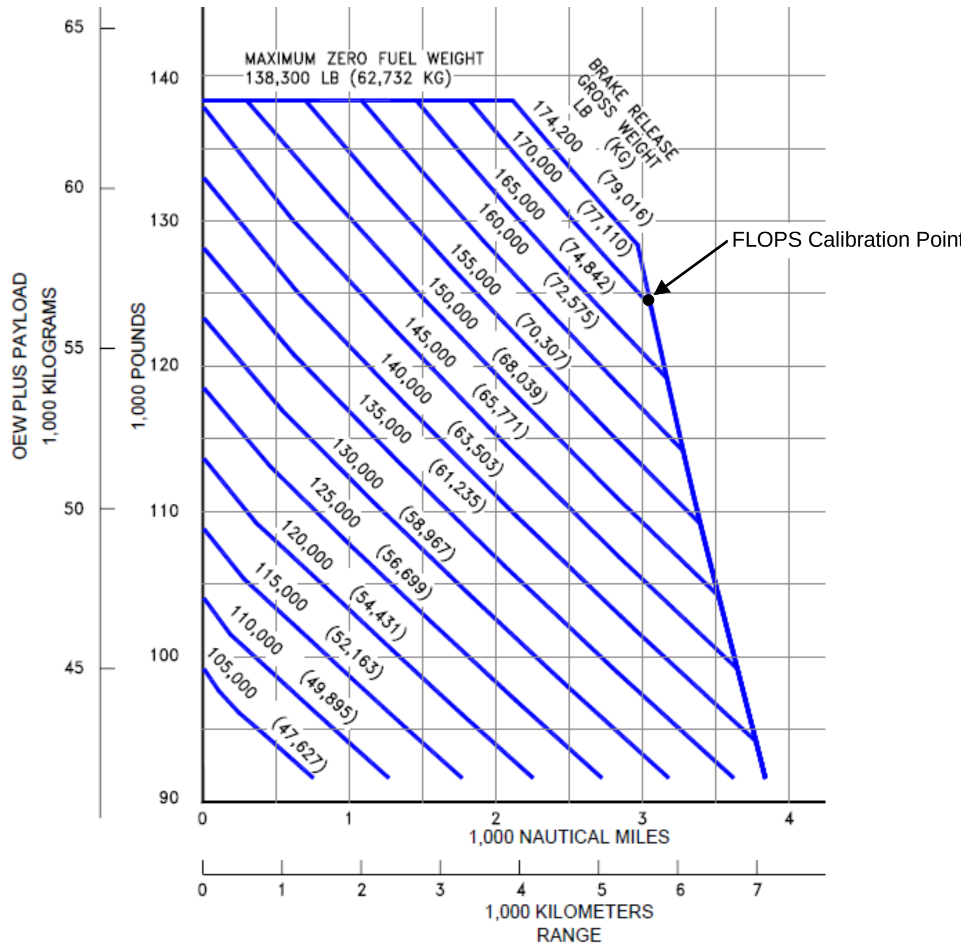



Figure 3. Payload-range diagram for Boeing 737-800 with winglets (from ref. 7).

The ability of the analytical model to accurately estimate fuel consumption was verified by comparing the calculated total fuel weights (including reserves) for several range-payload combinations to those obtained from the range-payload diagram in Figure 3. In Figure 4, the variation of total fuel with payload weight is compared at three different mission distances. In Figure 5, the variation of total fuel with range is compared at two different payload weights. In both cases there is excellent agreement between the FLOPS model and the published data. The accuracy in total fuel weight calculations is assumed to extend to the block fuel (fuel consumed on the main mission) and cruise performance calculations as well, although data are not available to verify that assumption.

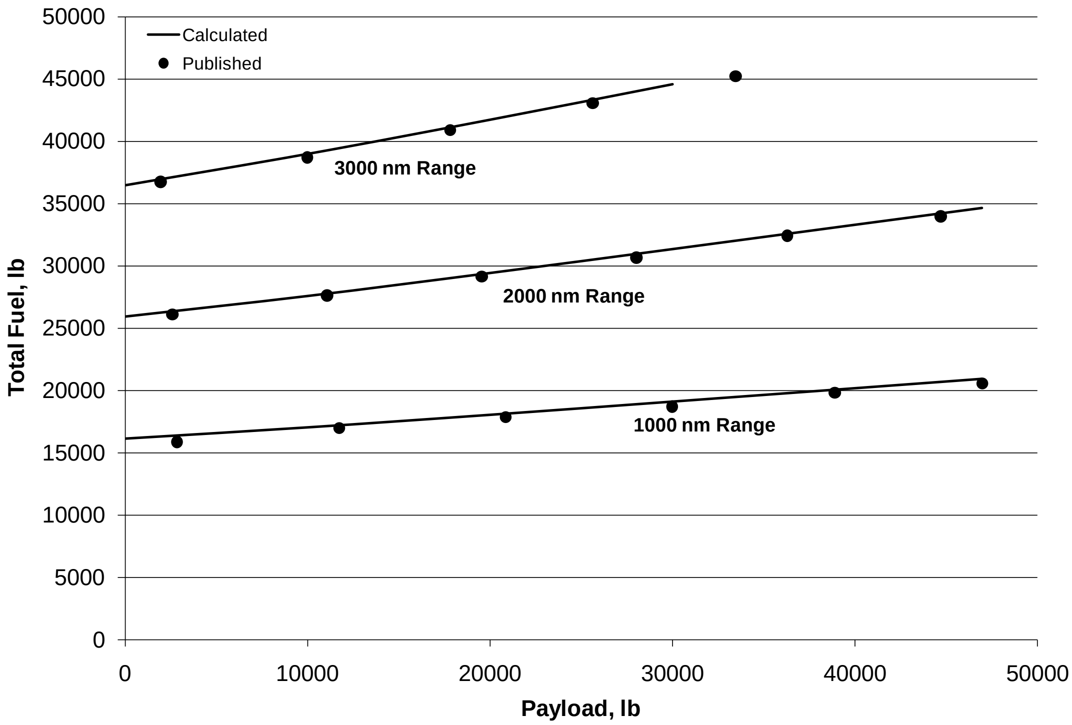



Figure 4. Total fuel weight versus payload weight for various mission distances (Boeing 737-800).

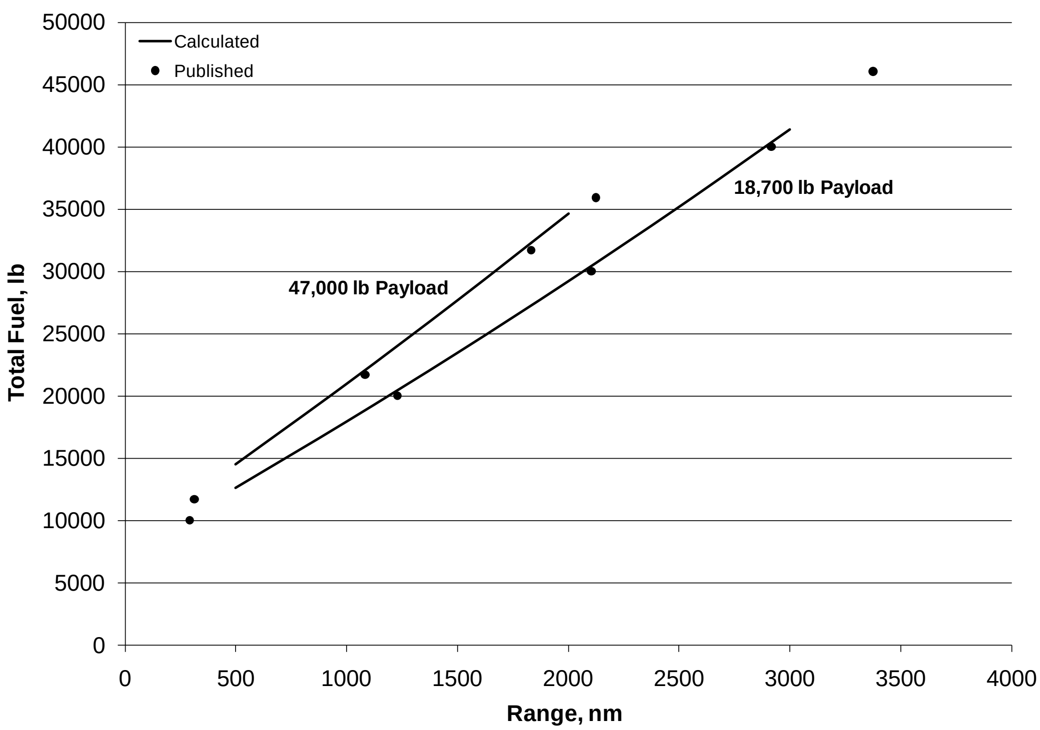



Figure 5. Total fuel weight versus range for various payload conditions (Boeing 737-800).

## 3.2 Large Twin-Aisle Transport Class Vehicle

In addition to the single-aisle transport class vehicle, an analytical model was also developed for a large, long-range twin-aisle vehicle. The Boeing 777-200LR was used as the basis for the representative vehicle in this class. The approach used to develop the model was similar to that described above for the 737-800. A 777-200LR like FLOPS model was developed using a combination of publicly available data on the 777-200LR geometry, weight, and performance characteristics (ref. 15); and a GE90-110B based engine model developed at NASA Glenn using the NPSS and WATE codes. Unlike for the 737-800 model, additional aerodynamic data were not available. FLOPS-predicted mission performance was calibrated to a specific point on the payload-range diagram provided in reference 15: at the maximum zero fuel weight of 461,000 lb and maximum brake release weight of 766,000 lb. According to the payload-range diagram, at this operating point the range is ~7590 nm (see Figure 6). Prior to calibration, the FLOPS predicted range for this mission was only 7100 nm (~6% low). Since there was no additional data available to independently assess the accuracy of the engine model, aerodynamic model, or mission model, equal adjustments were made to the aerodynamic and engine models. Drag and engine SFC were both reduced by 3.2% to increase FLOPS calculated range to 7590 nm.

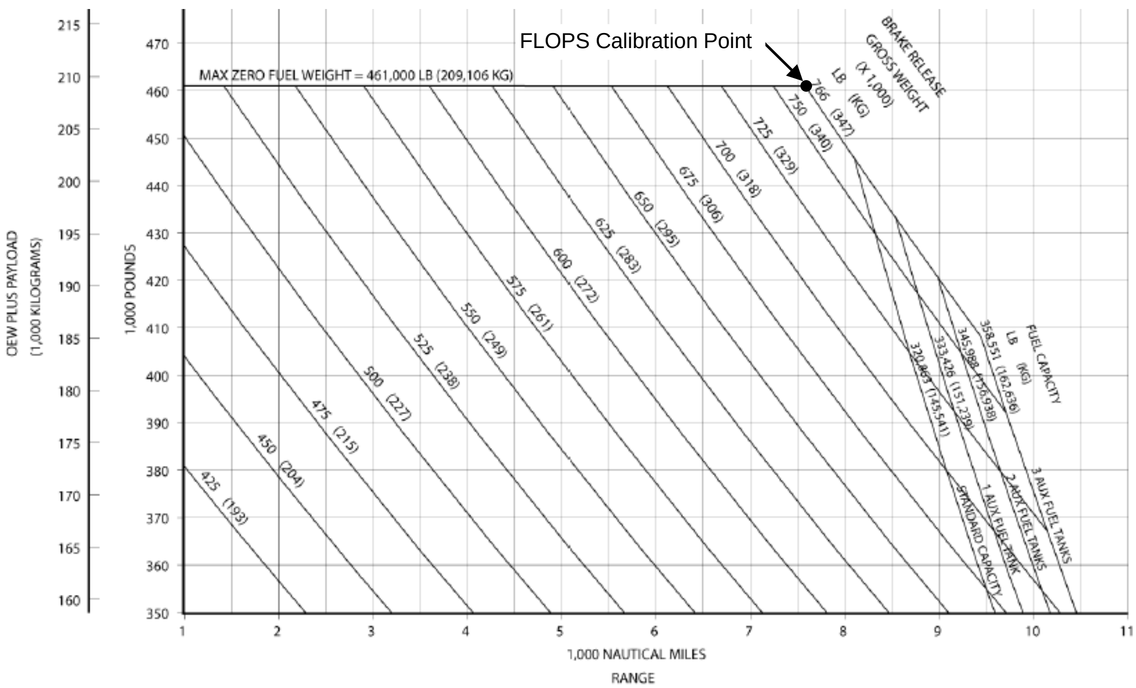



Figure 6. Payload-range diagram for Boeing 777-200LR (from ref. 15).

As with the 737-800 model, the accuracy of the fuel calculations was verified by comparing the calculated total fuel weight (including reserves) for several range-payload combinations to that obtained from the published range-payload diagram. In Figure 7, the variation of total fuel with zero fuel weight (payload weight plus operating empty weight) is compared at four different mission distances. In Figure 8, the variation of total fuel with range is compared at three different zero fuel weights. Again there is excellent agreement between the FLOPS model and the published data for total mission fuel, which is assumed to indicate the model is reasonably accurate at predicting cruise performance characteristics as well.

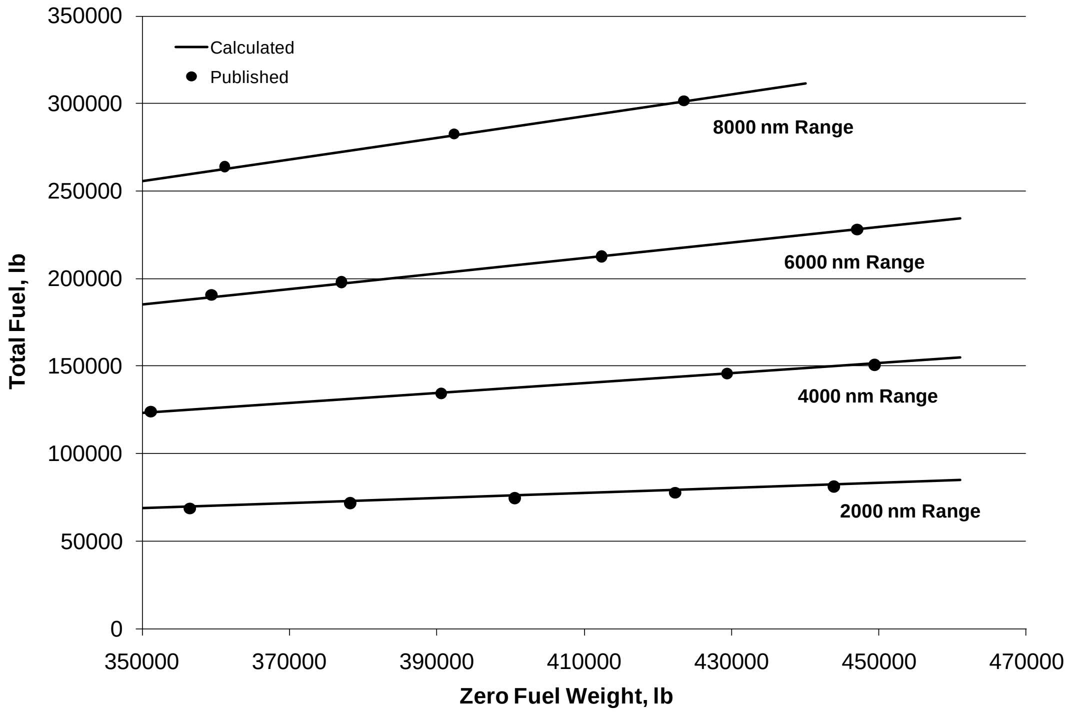



Figure 7. Total fuel weight versus zero fuel weight for various mission distances (Boeing 777-200LR).

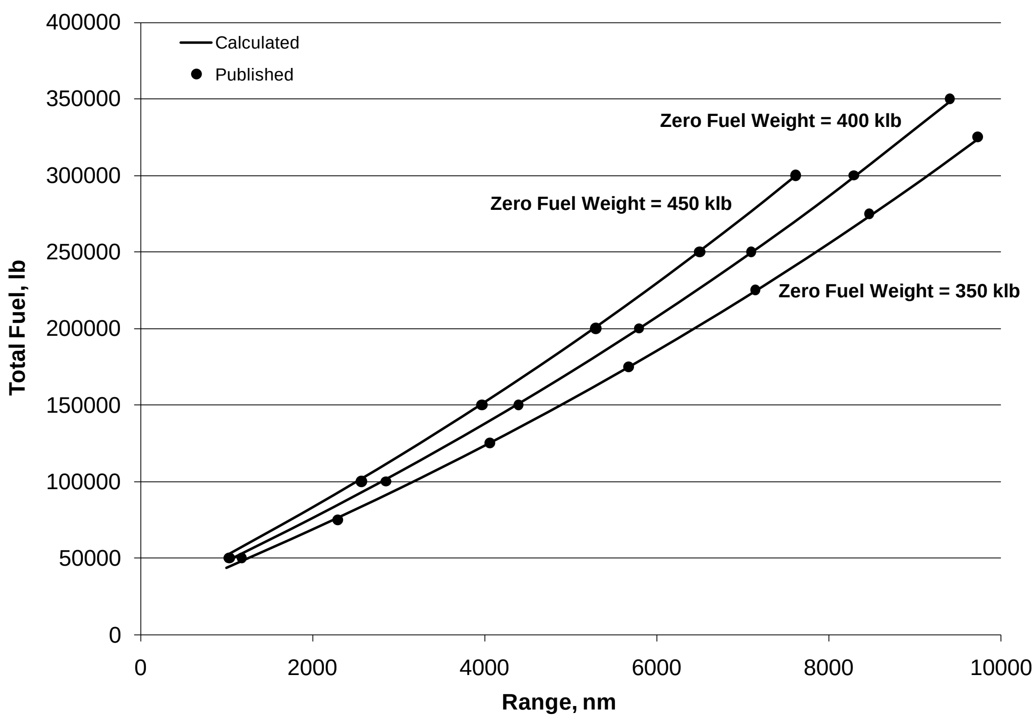



Figure 8. Total fuel weight versus range for various payload conditions (Boeing 777-200LR).

The purpose of the above comparisons is to validate that the FLOPS mission performance module is capable of accurately estimating fuel consumption characteristics for these types of vehicles. Although the good agreement does build confidence in the models, this agreement is obtained for “nominal” conditions.

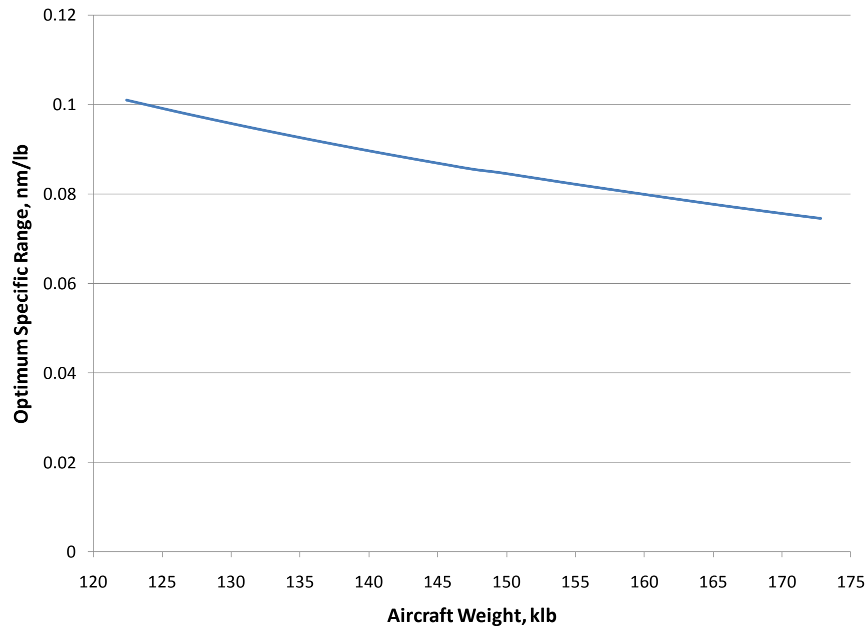
At off-nominal conditions, which are the main thrust of this study, the accuracy cannot be validated through the available public data. Therefore, it is not the intent of this report to provide accurate cruise performance estimates for the 737-800 and 777-200LR, nor should the results presented be interpreted as actual characteristics of these vehicles. The results provided are only meant to be representative of two classes of subsonic transports, not actual characteristics of any particular aircraft.

## 4.0 Analysis of Cruise Performance

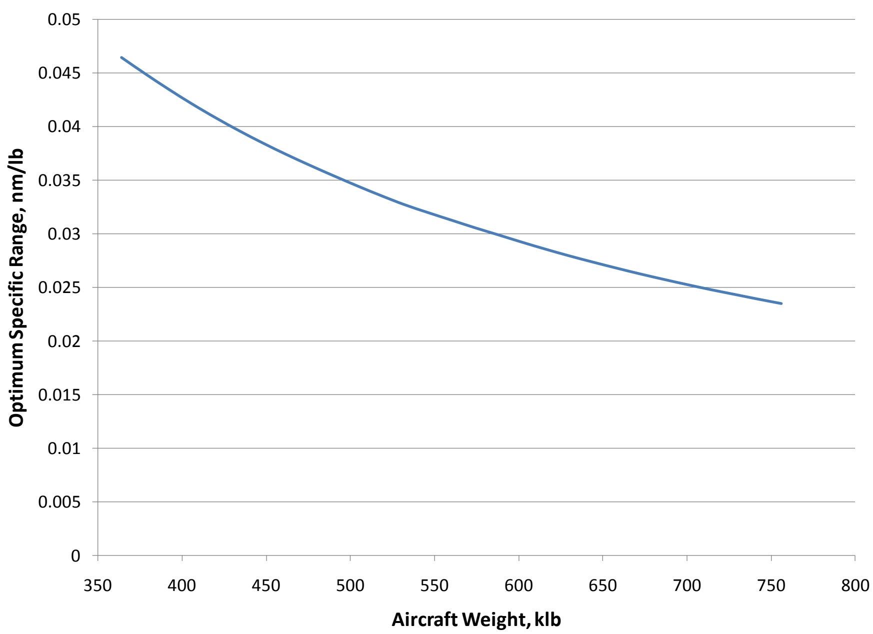
Once an analytical model of aerodynamic and propulsion performance is available in FLOPS, it is quite simple to perform analysis of cruise performance under various different scenarios. Because, as noted above, for a given aircraft and cruise profile definition (fixed altitude or optimum altitude, etc.) instantaneous specific range is only a function of weight, FLOPS calculates specific range versus weight for all the user specified cruise profiles (up to 15) prior to "flying" the mission. It is possible, therefore, to use FLOPS to assess both the instantaneous effects and integrated effects (cruise fuel consumption over a complete mission) of various cruise scenarios. Note that all performance analysis for this study was performed with zero wind speed.

### 4.1 Instantaneous Cruise Efficiency

The most efficient cruise scenario is flying at optimum speed and altitude for every point in the cruise. Figure 9 shows the variation of optimum specific range with aircraft weight for the single-aisle and twin-aisle models. Note that the specific range values for the twin-aisle vehicle are less than half those of the single-aisle vehicle due to the much higher weight. For the single-aisle vehicle, cruise altitude corresponding to these maximum values varies from 33,000 ft at the highest weight to over 40,000 ft at the lowest weight. The variation in altitude is even larger for the twin-aisle vehicle, varying from approximately 30,000 ft at the highest weight to the operational ceiling of 43,100 ft at the lowest weight. There is much less variation in optimum cruise velocity, however. Maximum specific range generally occurs around the Mach number at which the engines and airframe were designed to operate. Optimum Mach number is fairly constant around 0.775 for the single-aisle vehicle and 0.825 for the twin-aisle vehicle. Any variation in optimum velocity with weight is primarily the result of changes in the speed of sound associated with the altitude variation. These optimum Mach numbers would be considered the "Maximum Range Cruise" Mach numbers since they maximize the distance flown for a given amount of fuel. Because of economic considerations, however, it is typical to cruise at the "Long Range Cruise" Mach number, a slightly faster speed than that which provides maximum fuel efficiency. Typical cruise speeds at 35,000 ft are Mach 0.785 for the 737-800 and Mach 0.84 for the 777-200LR. (refs. 16 and 17)



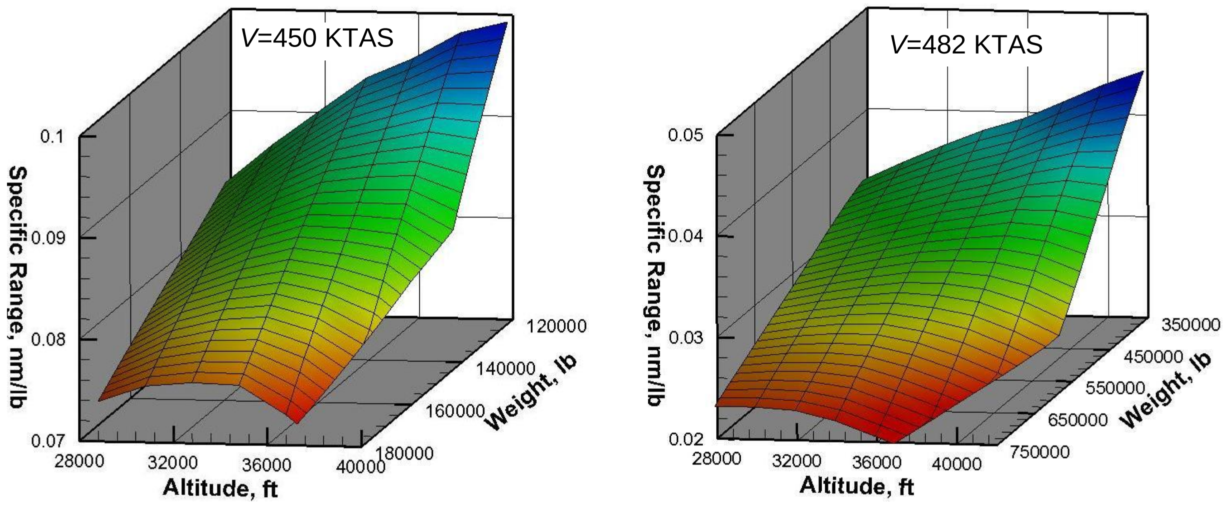

a.) Single-Aisle




b.) Twin-Aisle

Figure 9. Variation of optimum specific range with aircraft weight.

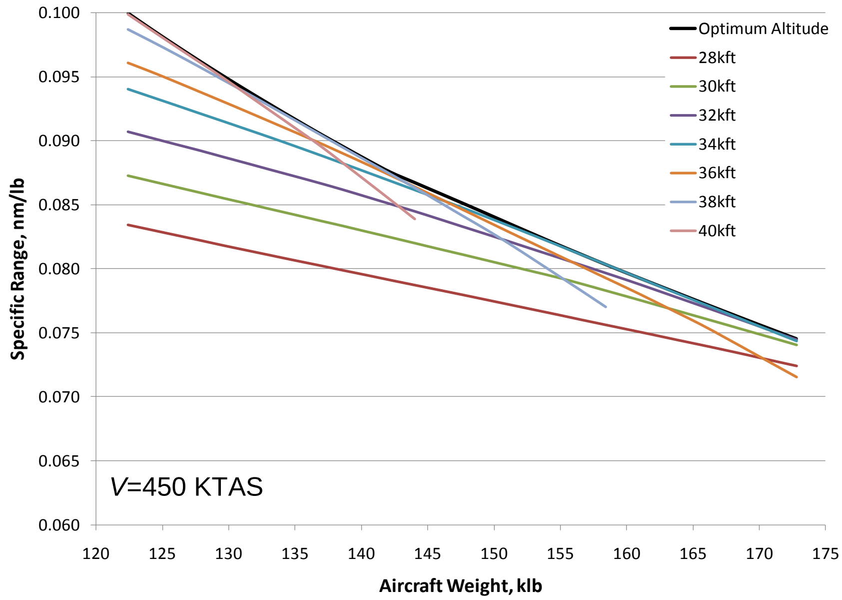
One way to assess the penalty of cruise altitude constraints, whether associated with ATM requirements or contrail mitigation, is to examine the variation of specific range with altitude. The variation of specific range with altitude and aircraft weight is shown in Figure 10. Unlike in Figure 9, for Figure 10 the velocity has been fixed to isolate the effects of altitude. The selected velocities of 450 knots true airspeed (KTAS) for the single-aisle and 482 KTAS for the twin-aisle are approximately equivalent to the respective typical cruise Mach numbers.



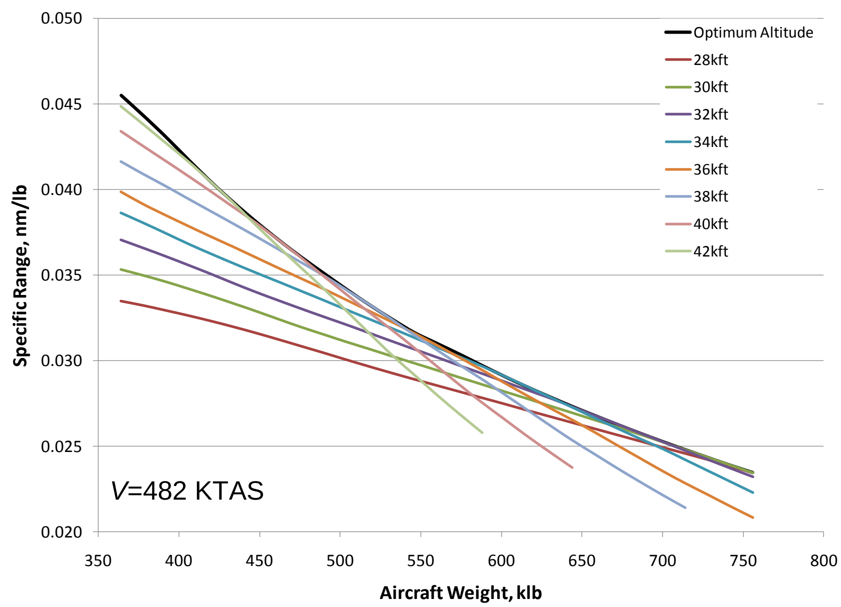

a.) Single-Aisle b.) Twin-Aisle

Figure 10. Variation of specific range with altitude and weight.

As can be observed by the curvature of the surfaces in Figure 10, there is an altitude that maximizes specific range which increases as the weight is reduced. This effect can be seen more clearly in the two dimensional plots in Figure 11, where the variation of specific range with weight is shown as a series of curves representing various cruise altitudes. Also shown is the specific range for the optimum altitude at each weight. As can be observed in Figure 11, each fixed altitude curve is close to the optimum curve over a certain range of weights (except for the low altitudes of 28,000 and 30,000 ft in the single-aisle case). Away from that range of weights, however, the penalty of continuing to fly at that altitude can be substantial. Also evident is that the sensitivity of specific range to altitude is non-linear. When flying close to the optimum altitude, the variation in specific range associated with flying slightly higher or lower is relatively small (the fixed altitude specific range curves are fairly close together). The sensitivities to altitude changes are much higher when the current altitude is off-optimum (moving away from the optimum curve, the specific range curves get farther apart).



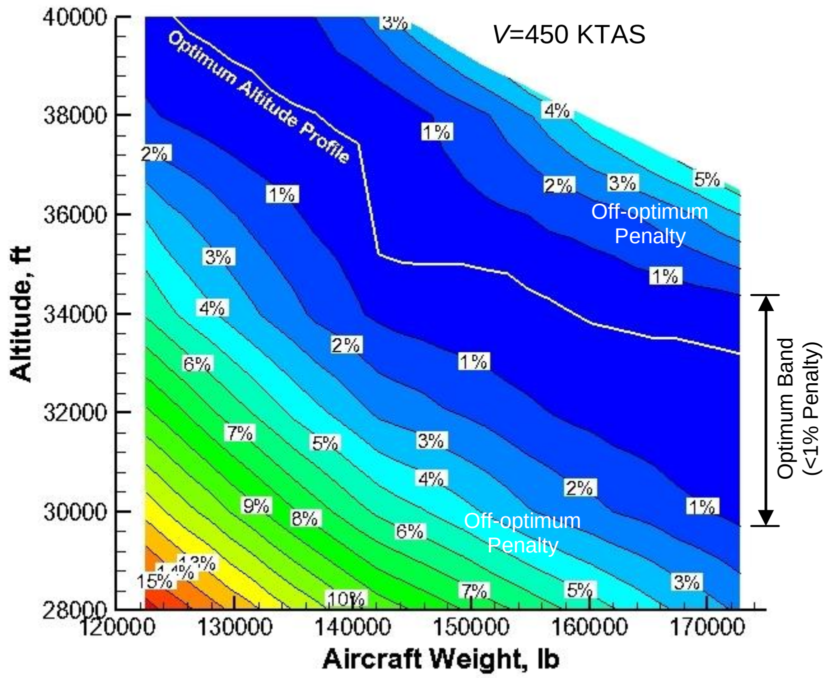

a.) Single-Aisle



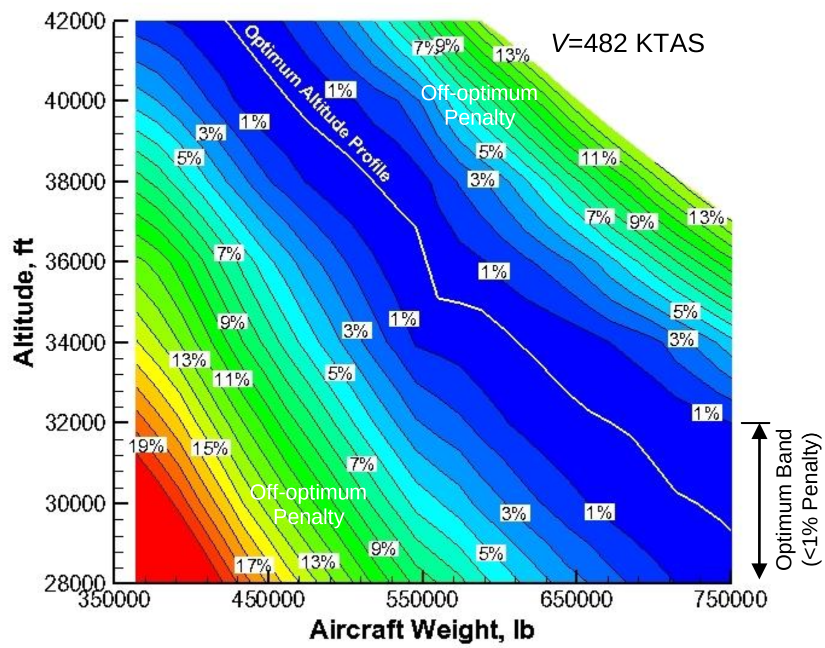

b.) Twin-Aisle

Figure 11. Variation of specific range with weight for fixed altitudes.

Although general trends can be observed in Figure 11, it is hard to clearly see the magnitude of the penalties associated with flying at off-optimum altitude conditions. The contour plots in Figure 12 provide a better illustration of these penalties. The contour values are the percentage reduction in specific range compared to the maximum possible at a given weight. (The upper right-hand corners of the plots are missing because at those conditions available thrust is insufficient to maintain the minimum rate-of-climb criteria of 300 fpm. Another potential limit to altitude at a given speed and weight is the maximum allowable cruise $C_L$. However, sufficient information on maximum cruise $C_L$ was not available for these vehicles to be able to apply a $C_L$ based altitude limit.)




a.) Single-Aisle




b.) Twin-Aisle

Figure 12. Off-optimum cruise efficiency (specific range) penalties.

An optimum altitude "band," is illustrated by the dark blue color in Figure 12. Within this band, the specific range penalty compared to the optimum is less than one percent. The height of the optimum band is fairly large, on the order of 4,000 ft or more in altitude for most weight conditions. This height is similar to the median thickness of "contrailing ice supersaturated" air layers according to the analysis of reference 3. Even in the worst case of a contrailing ice supersaturated air layer centered at the optimum cruise altitude, it generally should be possible to avoid the contrail layer with a cruise efficiency penalty on the order of 1%. The large optimum altitude band provides a lot of flexibility in selecting a near-optimum cruise altitude. Even so, efficiency drops off rapidly away from this optimum band and significant penalties can occur, especially if constrained to relatively low altitude at low weight conditions or high altitude at high weight conditions. Although seemingly small, a cruise efficiency penalty of 1% can be quite significant when extrapolated to the entire fleet. According to reference 18, the total fuel cost for U.S. carriers in 2010 was $36.4 billion. A 1% increase in fuel consumption would translate to $364 million in additional costs. However, it is not expected that a restriction such as contrail avoidance cruise would need to be executed on every flight. More importantly, one needs to recognize that the penalties shown in Figure 12 are relative to the optimum conditions. The penalty relative to where the aircraft would have been operating otherwise (not likely at exactly the optimum conditions) would usually be less.

The contour lines in Figure 12b are spaced closer together than those in Figure 12a, seeming to indicate a greater sensitivity to altitude for the twin-aisle case. This appearance is somewhat deceiving, however, because the twin-aisle plot covers a larger range of weight conditions due to the larger fraction of the maximum weight which is variable (fuel and payload). It is true, however, that the potential off-optimum penalties are much larger for the twin-aisle case. Because the optimum altitudes for the twin-aisle vehicle span a broader range, when the twin-aisle vehicle is flying at low weight and low altitude or high weight and high altitude, it is farther away from its corresponding optimum altitudes than in the case of the single-aisle vehicle and larger penalties result.

Also included in Figure 12 is a plot of the optimum altitude versus weight. The small wiggles in the optimum altitude profile simply reflect noise in the analysis and optimization process. However, there are two noticeable features of these curves which are significant results of the analytical models, a sharp drop in optimum altitude and a region of constant optimum altitude. For the single-aisle vehicle, the optimum altitude is constant at 35,000 ft in the weight range of approximately 144,000 to 150,000 lb. As discussed previously, the general expectation is an increase in optimum altitude as weight is reduced. This general expectation is based on aerodynamic considerations – increasing the altitude enables the aircraft to continue to fly at the most aerodynamically efficient conditions. But, optimum altitude is a function of not only aerodynamic characteristics but also propulsion characteristics. The TSFC of the CFM56-based engine model is at a minimum at 35,000 ft. In the weight range of 144,000 to 150,000 lb, a cruise altitude of 35,000 ft is close enough to the optimum aerodynamic altitude that the aerodynamic penalty of flying there is smaller than the propulsion benefit. At higher and lower weights, the benefits in propulsion efficiency of flying at 35,000 ft are smaller than the aerodynamic benefits of flying at a different altitude and the optimum altitude moves away from 35,000 ft. Optimum cruise altitude is always a balance between aerodynamic and propulsion considerations.

The second prominent feature of the optimum altitude curves is a sharp drop in optimum altitude that occurs around a weight of 140,000 lb for the single-aisle vehicle and 550,000 for the twin-aisle vehicle. This discontinuity in the optimum altitude can be traced to the atmospheric model used in the analysis. As is typical with most basic aircraft performance analyses, FLOPS uses a standard atmospheric model. FLOPS employs the 1962 U.S. Standard Atmosphere (which is equivalent to the 1976 U.S. Standard Atmosphere up to an altitude of 51 km). In this atmospheric model, the tropopause (the point at which temperature stops decreasing with altitude) begins at 11 km or approximately 36,100 ft and the atmospheric temperature is constant from this point to 20 km (65,600 ft). Because the speed of sound is a function of temperature, this is also the point at which the speed of sound becomes constant with increasing altitude. Below this altitude, holding velocity constant while altitude is increased translates to an increase in Mach number (speed of sound decreases with altitude). Above it, holding velocity constant as altitude is increased results in a constant Mach number. The change in the atmospheric model that begins at the tropopause influences the shape of the specific range versus altitude curves. Figure 13 shows the variation of specific range with altitude at four aircraft weights for the single-aisle vehicle. The inflection point in the curves around the tropopause is clearly evident. This results in a “double hump” shape with the potential for a local maximum in specific range both below and above the tropopause. Between 140,000 lb and 142,000 lb the global maximum switches from above the tropopause to below it, resulting in the sharp drop in optimum altitude seen in Figure 12. Of course the standard atmosphere model is an idealized model of the actual atmospheric conditions and in reality the tropopause is not such a well-defined point. The limitations of such idealizations need to be recognized when interpreting the results of analytical performance models.

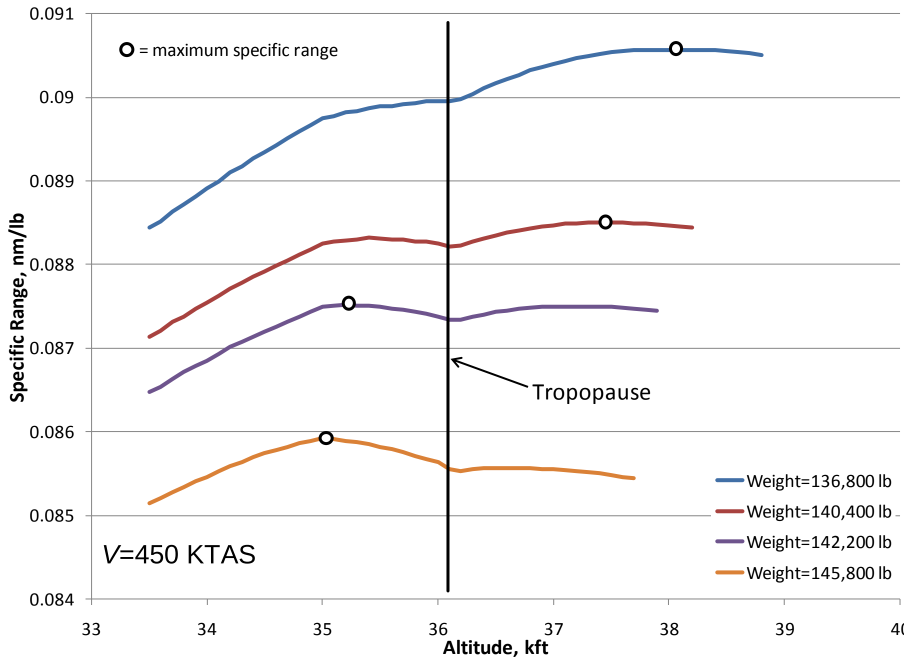



Figure 13. Variation of specific range with altitude for selected weights, single-aisle vehicle.

## 4.2 Overall Fuel Consumption Impacts

The analysis in Section 4.1 examined altitude effects on instantaneous cruise efficiency. The overall impact on total fuel consumption depends on the integration of these instantaneous characteristics (as well as any climbs or descents between them). Although it is possible to postulate a number of different flight profiles and calculate the resulting fuel consumption, it is difficult to generalize the potential overall impact of possible altitude restricted cruise profiles. Clearly the worst case scenario would be if the aircraft were forced to fly along one of the penalty contours in Figure 12; in other words, a “cruise-climb” type profile at off-optimum conditions. This seems to be an unlikely scenario, however. A more probable scenario would be a step cruise or fixed altitude cruise due to ATM, contrail avoidance, or other issues. The fuel consumption for various cruise scenarios is illustrated in Figure 14 for an example twin-aisle mission of 6000 nm with a zero fuel weight of 461,000 lb. The increase in fuel consumption associated with flying at the typical, long range cruise speed of Mach 0.84 instead of maximum range cruise speed is approximately 1%. The step cruise (with 2,000 ft intervals as permitted in Reduced Vertical Separation Minima airspace) results in only slightly more fuel consumption than the optimum altitude cruise profile (~0.5% increase). If at the right altitude (34,000 ft in this case), fixed altitude cruise is only a small additional penalty in fuel consumption compared to the step cruise. However, large increases in fuel consumption are possible if restricted to cruising at the wrong altitude. For example, fuel consumption for a 28,000 ft fixed altitude cruise is 7% higher than for the step cruise profile.

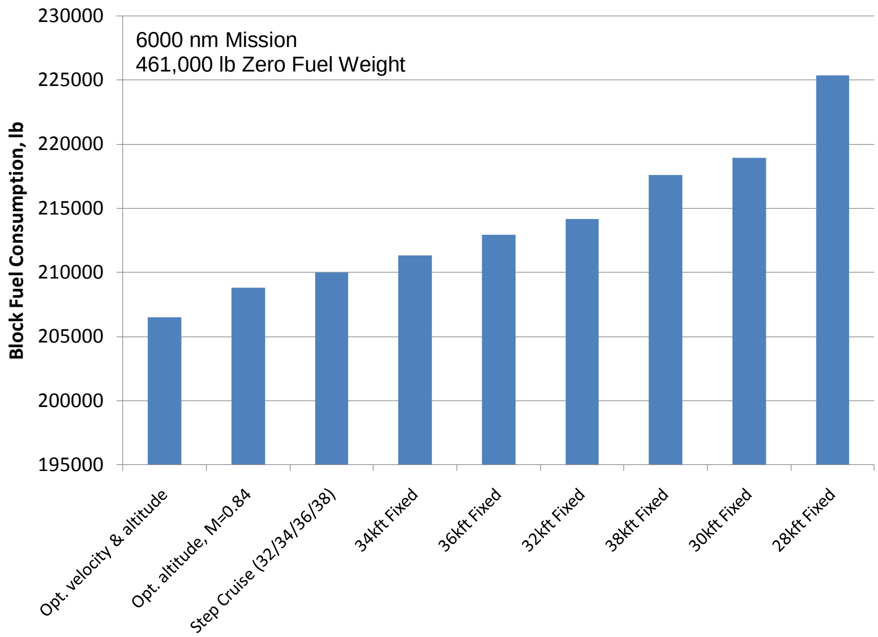



Figure 14. Twin-aisle block fuel consumption under various cruise scenarios, 6000 nm mission.

To investigate more fully the potential integrated fuel consumption penalty of fixed altitude cruise, a series of missions of various distances were analyzed for a range of cruise altitudes with fixed cruise velocity. Total block fuel consumption (gate-to-gate) was then compared to block fuel with an optimum altitude cruise profile. (Note: The baseline, optimum altitude case was flown at fixed Mach number rather than fixed velocity to align with FLOPS cruise profile options. This results in a higher velocity for the early cruise (high weight) portions of some missions.). The results of this analysis are illustrated in Figure 15 for the single-aisle vehicle. Zero fuel weight for these cases is 124,000 lb, corresponding nominally to a payload of 32,500 lb. Cruise velocity is fixed at 450 KTAS. Being constrained to fly at a constant altitude does not necessarily incur large block fuel penalties, as long as the altitude is not too low. For cruise altitudes of 34,000 ft and above the block fuel penalty is less than 2 percent. This is not surprising given the results in Figure 12 which show that the instantaneous penalty for flight at those altitudes is fairly small. (Note that the results for 40,000 ft and 38,000 ft do not extend for the full range of mission distances because the initial cruise weight becomes too high for flight at those altitudes.) At a mission distance of 1500 nm, a 2% increase in block fuel corresponds to approximately 57 gallons of additional fuel. Assuming a nominal fuel cost of \$3.00 per gallon, the increase in fuel consumption would correspond to \$170 in additional fuel expenses compared to a total fuel bill of ~\$8500 for the flight. Block fuel penalties for a constant altitude cruise at low altitude are significant, however. Contrail mitigation through simply restricting cruise altitude to be below a certain level would have a much greater negative impact on fuel consumption than providing the flexibility to fly above or below regions conducive to the formation of persistent contrails. Interestingly, the magnitude of the block fuel penalty does not necessarily grow as mission distance is increased. At longer mission distances the initial cruise weight is higher, and as can be seen in Figure 12, the efficiency penalty of low cruise altitude is lower for higher weight. In addition to mission distance, the initial cruise weight is also impacted by the payload weight. Changing the payload weight would, therefore, change the integrated fuel consumption penalties of the fixed altitude cruise profiles. One way to visualize the integrated impacts of constant altitude cruise is crossing the penalty contours in Figure 12 as the weight drops during cruise. The initial and final cruise weights dictate which contours are crossed during the mission, and therefore the magnitude of the overall penalty.

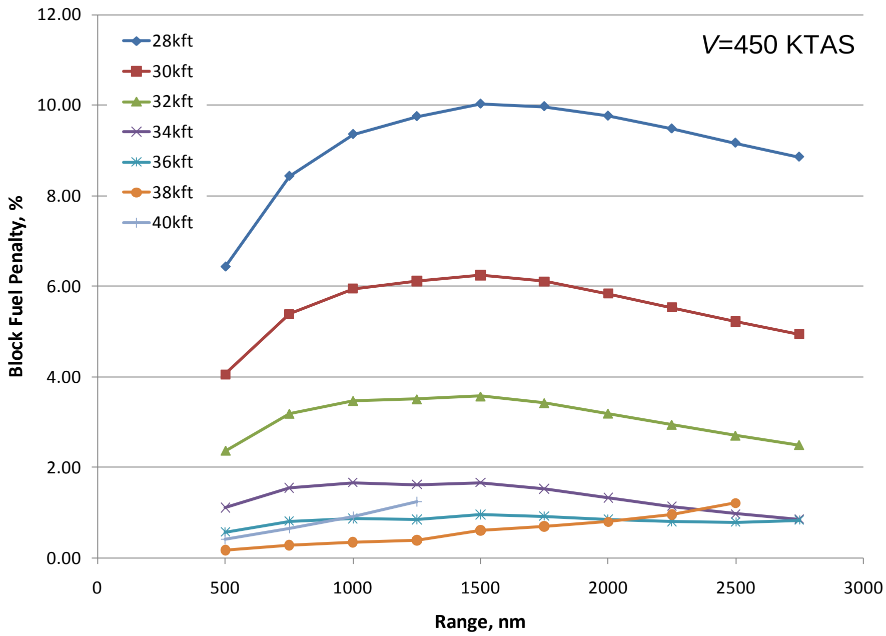



Figure 15. Single-aisle fuel consumption penalty for constant altitude cruise.

A similar analysis was conducted for the twin-aisle vehicle, with the results shown in Figure 16. Zero fuel weight for these missions is 461,000 lb. For the constant altitude cruise missions, the cruise velocity is fixed at 482 KTAS. The potential penalties are similar in magnitude to those in Figure 15, but the variation with mission distance is larger. For low altitudes (28 kft, 30 kft, 32 kft, 34 kft), the block fuel penalty decreases as range is increased, since the longer the range, the higher the initial cruise weight, the lower the initial optimum cruise altitude, and the closer these altitudes are to the optimum altitude for more of the cruise. At 38,000 ft and 40,000 ft the trend is reversed. These are good cruise altitudes for low cruise weight, but the longer the mission distance, the larger fraction of the cruise which is at high weight conditions. Of course the longer the mission, the less likely the cruise altitude would be restricted to a single altitude for the entire mission and the more unrealistic this simple scenario becomes. Although the relative penalties are similar to those of the single-aisle aircraft, the absolute penalties in terms of fuel consumption and cost are much larger for a heavier, longer range aircraft. A 2% increase in block fuel for the twin-aisle aircraft flying a 4000nm mission corresponds to approximately 400 gallons of additional fuel, or a $1200 increase in fuel expenses at a fuel cost of $3.00 per gallon.

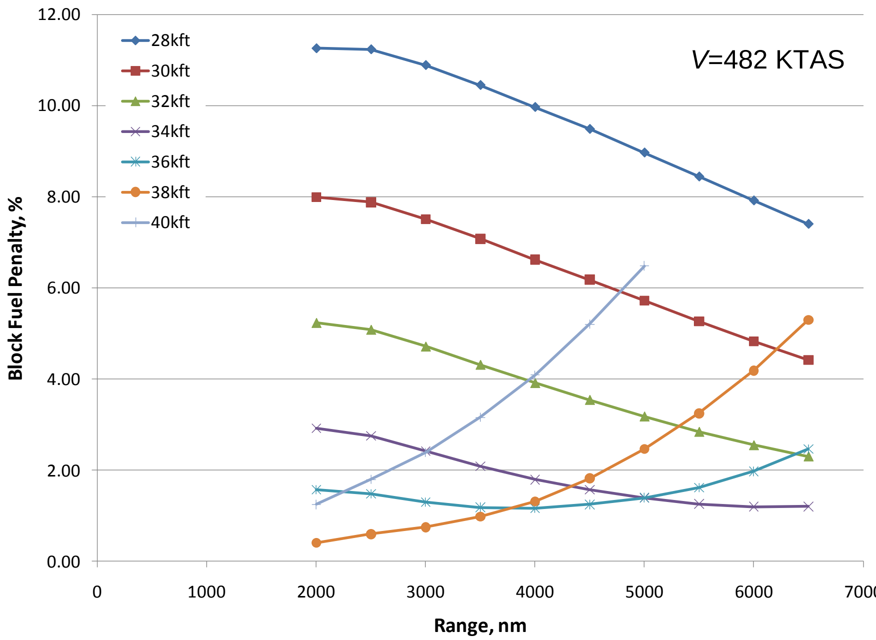



Figure 16. Twin-aisle fuel consumption penalty for constant altitude cruise.

# 5.0 Concluding Remarks

The effects of altitude on cruise efficiency have been examined for a Boeing 737-800 like aircraft and a 777-200LR like aircraft using analytical models to quantify the potential penalties of altitude restrictions (or conversely the potential benefits of relaxing cruise altitude restrictions). Both the instantaneous effects (specific range) and integrated effects (block fuel consumption) have been examined. The optimum cruise altitude band, in which the instantaneous specific range is less than 1% lower than its maximum possible value, was found to be relatively large, on the order of 4,000 ft in height. This provides significant flexibility to find a near-optimum altitude while avoiding "no-fly" regions which could be imposed for environmental or ATM reasons. Even in the case of a fixed altitude throughout the mission, the total fuel consumption penalty can be small (< 2%) as long as an appropriate cruise altitude is selected. Because optimum cruise altitude varies with weight, during a constant altitude cruise the altitude will generally be close to the optimum altitude at some point along the mission. Only when the constant cruise altitude is far from the optimum throughout the entire mission are large penalties in total fuel consumption (on the order of 10%) encountered. It is possible to construct cruise profiles that result in even larger efficiency penalties by flying a "cruise-climb" type profile that is offset from the optimum altitude profile. However, it seems unlikely that such a cruise profile would ever be necessary. Even seemingly small reductions in fuel efficiency can have significant impacts when extrapolated to fuel consumption across the entire fleet. With annual fuel costs in the tens of billions of dollars, even penalties as low as one percent could lead to hundreds of millions of dollars in increased fuel cost. Conversely, saving one percent in fuel consumption through a more flexible ATM system allowing near optimum altitude cruise would yield large savings in fuel costs. All of the analysis for this study was conducted in the absence of winds. Variations in wind speed and direction with altitude will also have an impact on cruise efficiency. Depending on the nature of these variations, the resulting penalties could be larger or smaller than those presented here.

In actual airline operations, there are many factors that determine the desired flight profile besides fuel consumption. For example, considerations such as passenger comfort and increasing engine life can lead to a shorter climb segment and lower cruise altitude than would be selected from purely a block fuel standpoint. Even in the case of a future, flexible ATM system with pilots able to fly at any desired altitude, it is unlikely that the most fuel efficient cruise profile would always be flown. Therefore, the penalties presented here may represent a worse case in the sense that the theoretically optimum profile used as the baseline is not today, nor likely in the future, the typical operational cruise profile.

This analysis was based on existing vehicles, designed to operate in the existing ATM system. If future vehicles are optimized to take advantage of a more flexible ATM system, it is possible that they could be more sensitive to altitude restrictions than current vehicles. Conversely, it would also be possible to design a vehicle that is more robust to altitude restrictions (giving up some in maximum efficiency while achieving near maximum efficiency across a broader range of altitudes). The limitations inherent in projecting analysis of existing designs to the potential impacts in the future need to be considered when using the results of this study.

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**14. ABSTRACT**
Aircraft fuel efficiency is a function of many different parameters, including characteristics of the engines, characteristics of the airframe, and the conditions under which the aircraft is operated. For a given vehicle, the airframe and engine characteristics are for the most part fixed quantities and efficiency is primarily a function of operational conditions. One important influence on cruise efficiency is cruise altitude. Various future scenarios have been postulated for cruise altitude, from the freedom to fly at optimum altitudes to altitude restrictions imposed for environmental reasons. This report provides background on the fundamental relationships determining aircraft cruise efficiency and examines the sensitivity of efficiency to cruise altitude. Analytical models of two current aircraft designs are used to derive quantitative results. Efficiency penalties are found to be generally less than 1% when within roughly ±2000 ft of the optimum cruise altitude. Even the restrictive scenario of constant altitude cruise is found to result in a modest fuel consumption penalty if the fixed altitude is in an appropriate range.

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