Reference Material for a Proposed Formation Flight System

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I. Formation Flight Aerodynamics and Performance

A. Naturally occurring examples

It is always striking to observe geese or other migratory birds fly in a regular V-shaped formation. There are several reasons why these birds fly in flocks: it makes the navigation or food searching easier, it provides them with a better protection, it permits them to stay in visual contact while avoiding collisions and they can profit from aerodynamic interference [1]. Experiments conducted by Henri Weimerskirch [2] on eight great white pelicans showed that these birds save a significant amount of energy by flying in formation. Figure I-1 shows how the wing-beat frequency and the heart rate change with the type of flight. A comparison of the last two cases– flight alone at one meter above the sea and formation flight at approximately one meter above the sea – shows a significant decrease of both the wing-beat rate and the heart rate. This is true especially for the followers; the leader gets only very small benefits.

Figure I-1: Wing-beat frequency and heart rate of pelicans engaged in various types of flight [2]

B. Aerodynamic background

Lissaman and Shollenberger [3] studied the formation flight benefits for birds by measuring flight power demand. They approximated each bird as a fixed wing aircraft. Figure I-2 shows the flow field behind the wing of a bird. It shows an upwash field beyond the wing. This field is very strong close to the wingtip.

Figure I-2: Flow field of a lifting wing [3]

This upwash is responsible for the decreased efforts of the followers. Flying in the upwash of another bird is equivalent to flying in an up-current, and each bird needs less power to generate lift.

This phenomenon can be further understood through a discussion of induced drag. As explained above, a lifting wing induces a downwash **w**. The effect of this downwash is to change the apparent free stream velocity $\mathbf{V}_\infty$ to $\mathbf{V}_{\mathbf{eff}} = \mathbf{V}_\infty + \mathbf{w}$ as shown in Figure I-3 (a). The amplitude of the apparent angle of attack is decreased: $\alpha_{\text{eff}} = \alpha - \alpha_i$. The lift now has a component in the direction of the free stream velocity $\mathbf{V}_\infty$; this component is the induced drag $\mathbf{D}_\mathbf{i}$.

Figure I-3: (a) Induced drag for a three dimensional wing [4]; (b) Influence of the upwash field

Figure I-3 (b) shows the influence of an upwash field on a wing situated behind another one. The upwash **w'** has the apparent effect of decreasing the self-induced downwash on the wing. Therefore, the induced angle α'_i is less than the original α_i and the induced drag is decreased. If the amplitude of the upwash is of the same order of magnitude as the amplitude of the downwash, the decrease in induced drag can be significant.

C. Performance benefits from formation flight

The range is usually calculated using the Breguet Range equation [5]:

$$R = \frac{V}{gc}\frac{C_L}{C_D}\ln\left(\frac{W_0}{W_1}\right)$$

V is the speed, g the acceleration of gravity, c the specific fuel consumption, C_L the lift coefficient, C_D the drag coefficient, W_0 the initial cruise weight and W_1 the empty weight.

C_D can be decomposed in two components: the profile drag C_{D0} and the induced drag C_{Di} (AR is the aspect ratio and e the efficiency coefficient of the wing):

$$C_D = C_{D_0} + C_{D_i}\text{, where } C_{D_i} = \frac{C_L{}^2}{\pi e\, AR}$$

The range is maximized by setting $C_{D_0} = C_{D_i}$.

Formation flight reduces induced drag so that $C_{D_i}' = \alpha\, C_{D_i}$, where $\alpha < 1$. Applying the above formula to this new problem, the maximum range is equal to:

$$R' = \frac{1}{\sqrt{\alpha}} R$$

The optimum lift coefficient has also changed: $C_L' = \frac{1}{\sqrt{\alpha}} C_L$.

This leads to a necessary change either in altitude (increase) or in speed (decrease) for the aircraft. The increase in altitude necessary to maximize the range of a formation in which the average benefit in induced drag is 40% (among the aircraft behind the leader is between 3500 and 7000 feet for formations of 10 aircraft or less. This is not negligible, and if an aircraft were to be designed especially for formation flight, this would have to be taken into account in choosing an engine.

Existing airplanes are designed to fly near their upper C_L limit. It would not be possible for them to increase their lift coefficient by the factor derived above.

The increase in range due to formation flight can also be calculated taking into account the constraint that C_L remain constant. In this case, the only benefit will come from a decreased drag coefficient:

$$C_D' = C_{D_0} + C_{D_i}' = C_{D_0} + \alpha C_{D_i} = (1+\alpha) C_{D_0} = \frac{1+\alpha}{2} C_D$$

The range while flying in formation will be:

$$R' = \frac{2}{1+\alpha} R$$

The increase in range obtained when keeping a constant C_L is less than in the first case, but there is no change in altitude or speed needed.

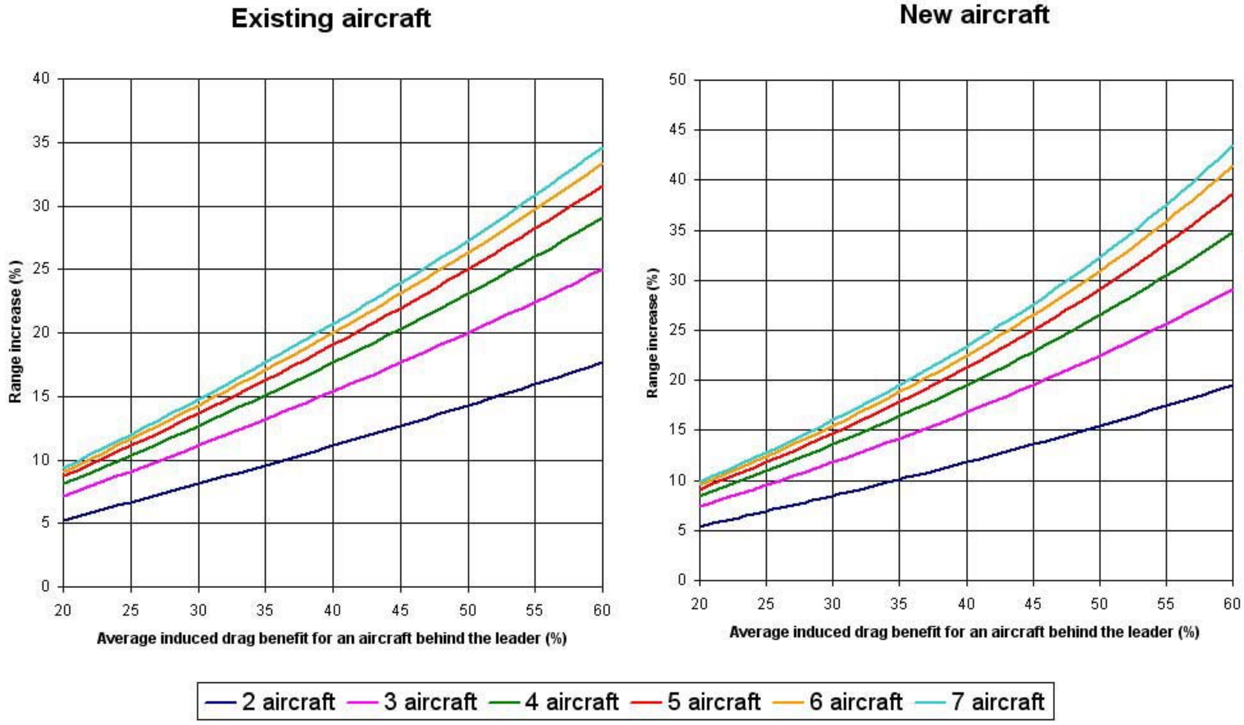


Figure I-4: Range increase when flying in formation compared to flying alone

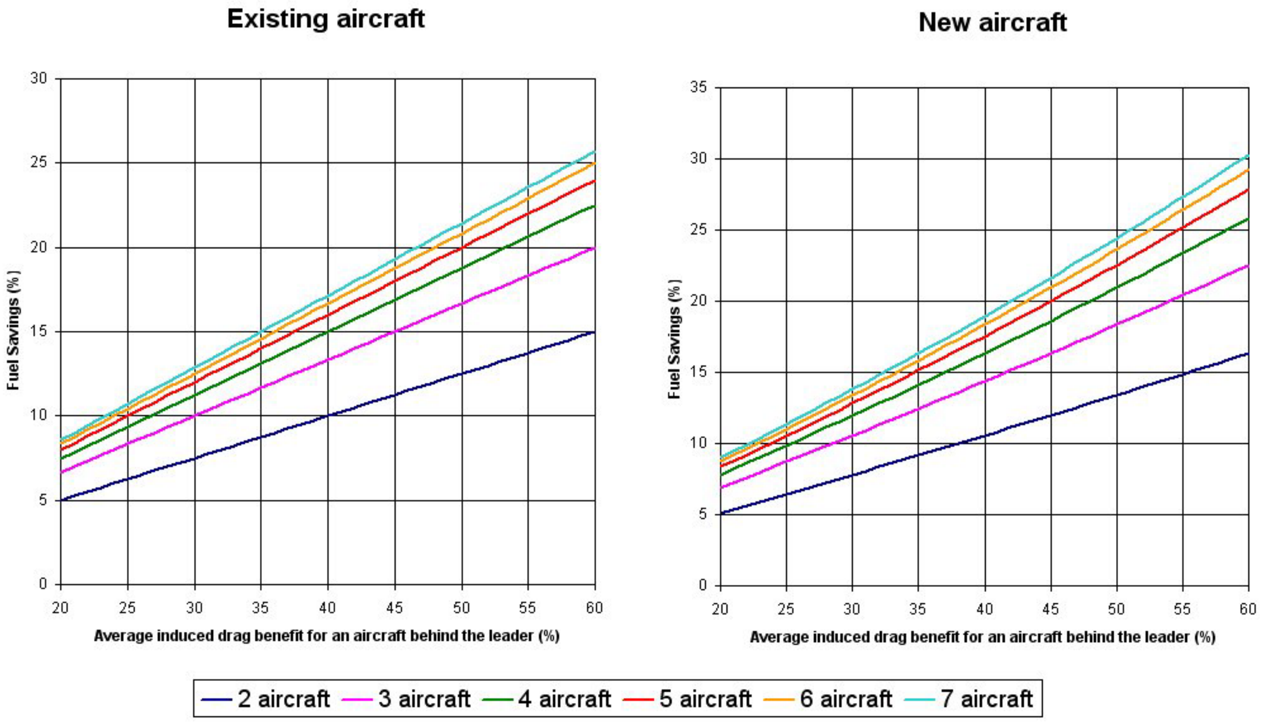


Figure I-5: Fuel Savings when flying in formation compared to flying alone

Figure I-4 and Figure I-5 show the range increase and fuel savings when flying in formation compared to when flying alone. These values depend on the average induced drag benefit for the aircraft behind the leader (on the abscissa) and on the number of aircraft in the formation (different curves). The fuel savings were calculated by taking the proportion of fuel remaining in the aircraft when it attains R (its range when flying alone). If ΔR is the percentage increase in range, then the percentage fuel saving is: $\Delta F = 100 \times \frac{\Delta R}{100 + \Delta R}$.

D. The theoretical “sweet spot”

As the flow field behind a lifting wing shows, there is a specific position behind the leader bird for a trailing bird to get the best benefits from formation flight. Blake and Multhopp [6] used a simple horseshoe vortex model to locate this position. The model uses Prandtl’s lifting-line theory, which postulates that a wing of finite span b can be replaced by a bound vortex of the length (π/4) b. The vortex is continued by two free vortices trailing downstream from the wing tips, because a vortex filament cannot end in the flow. Figure I-6 (a) shows two wings flying in formation and the horseshoe vortices representing them. This model is highly simplified but can account reasonably well for the phenomena due to an aircraft wake.

Figure I-6: (a) Formation Flight Geometry [6]; (b) Variation of Mutual Induced Drag with Aircraft Position, horseshoe vortex model [6]

Using this method, Blake and Multhopp mapped the benefits in induced drag for a wing following another. The results of their analysis are shown on Figure I-6 (b). This graph shows that the region where the benefits are the highest is very small. The “sweet spot” is situated at about 22% span overlap in the lateral direction and at the same altitude. The influence of the longitudinal distance does not appear because this model states that the vortex continues unchanged in the downstream direction (Munk’s theorem). In a circle of diameter about 0.1 span around this point, the benefits in induced drag for the follower should be above 50%, and in a circle of diameter approximately 0.25 span, they should be above 25%.

Blake and Multhopp compared these results with those given by a vortex lattice method. The results were very similar except near the tip of the leader's wing. The new sweet spot was situated at about 5% overlap for the wing considered and corresponded to maximum benefits of about 40% in induced drag. The gradients of the benefits were again very large around this point.

One drawback for formation flight at the sweet spot for the benefits is that the spot corresponds to the point at which the aerodynamic moments and the side force are the largest.

E. Transport Aircraft Wake

The wake of an aircraft is not as simple as the horseshoe vortex model implies. It is the result of the addition of several sources of vorticity: concentrated vortices coming from the flaps and the wing tips, an unstable vortex sheet starting along the trailing edge, and various disturbances coming from protruding parts and propulsive jets from the engines. Figure I-7 shows how these influences merge into a pair of concentrated vortices. Measurements made by DASA on an A321 showed that the merging between flap and tip vortices occurred rather abruptly at 2.5 spans behind the model [7]. Afterwards, the resulting vortex continued to trail vorticity downstream.

Figure I-7: Vortex Wake Roll-up and Factors affecting it [7]

The major parameter affecting of the strength of the vortex is the aircraft weight. However, other parameters also have an influence: the wing loading and the engine flow can be modified in order to reduce the strength of the vortex, at least in the near field [7]. This means that they can also be adapted in order to have the strongest vortex possible. This may not be a good idea in order to achieve drag benefits for an overall formation, as most changes that increase the vortex strength also increase drag on the vortex-generating aircraft.

Once the two trailing vortices are well formed, the evolution of their strength and position is very dependent on the environment. Atmospheric turbulence is the major factor involved in wake decay [8], but other parameters as ambient wind, stratification and heat flux (convection) can accelerate the dissipation of the trailing vortices [9]. After approximately 30 spans, it was observed that the vortex intensity and amplitude have decreased by 50%. Measurements also revealed a slow oscillatory motion of the vortices at six wing spans. This oscillation is damped as the intensity of the vortices decreases [8]. Figure I-8 shows the simplified evolution of the vortex intensity downstream of an aircraft of weight class "heavy".

Figure I-8: Wake decay characteristics [10]

More generally, a wake can be divided into four zones:

Location	Zone	Characteristics
Up to 1 span	Near-Field	Formation of the vortices and roll-up into a multiple pair system
1 to 20 spans	Extended Near-Field	Multiple vortices continue to roll-up and merge
20 to 50 spans	Far Field	Linear instabilities begin to appear
50 to 200 spans	Dispersion Field	Destruction of the vortices (due to turbulence and instabilities)

Table I-1: Description of an aircraft wake [11]

Therefore, it appears that the pair of trailing vortices is well formed between approximately 3 and 20 spans, and that it oscillates a little after 6 spans, making it harder to predict its exact position.

F. The real sweet spot and potential benefits

As we saw in the previous section, the real wake of a transport aircraft is very complex. The existing theoretical models are not able to accurately predict the location and strength of the pair of trailing vortices. Therefore, the location of the theoretical sweet spot and the predicted benefits cannot be taken as certain facts. Several wind tunnel measurements and flight tests were made that further explore the reality of formation flight.

The following is a brief summary of the results of these experiments:

- Blake and Gingras conducted wind tunnel measurements on two delta wings [12]: a maximum induced drag reduction of 25% was measured on the trailing aircraft with a wing tip overlap of 15-20% span. The discrepancy with the theory – which predicted a reduction of 40% in induced drag with 10% overlap – was attributed to flow separation at the tip caused by upwash. They also tested transport and fighter aircraft [13]. They observed a maximum increase of 30% in L/D for the trailing vehicle. They also reported sharp gradients laterally near the wing tips.
- Blake also conducted wind tunnel measurements on two model F-18 class aircraft [14]. He observed a significant decrease in drag when the wing tips of the aircraft were aligned. The amplitude of this decrease was very dependant on the lift coefficient of the aircraft.
- Flight tests were conducted using three T-38s [15]. The aircraft were not automated; tape markings were made on the fuselage of the leading aircraft so that the pilot of the trailing aircraft could maintain the proper position using visual clues. The flight tests for a two-aircraft formation showed with 80% confidence that the wingman saved fuel (8.8% ± 5%) in the predicted optimum position. For a three-aircraft formation, it appeared that none of the wingmen had statistically significant fuel savings. The explanation given for this result was the addition of the position errors when a third wingman joined the formation.
- More recent flight tests were made using two F/A-18s within the Autonomous Formation Flight (AFF) project at the NASA Dryden Flight Research Center in California [16]. The trailing aircraft was equipped with advanced station-keeping technology (developed by UCLA engineers) to be able to position the aircraft at precise locations. They measured maximum drag reductions of over 20% and maximum fuel flow reductions up to 18%. The recorded optimal position was in the following intervals: $-0.1b < Z < 0$, $-0.25b < Y < -0.1b$, $3b < X < 5b$, where b is the span of the aircraft, Z the vertical position, Y the horizontal position and X the longitudinal position.

In summary, most experiments show significant decreases in drag for the trailing aircraft, but the exact magnitude of this benefit and the position at which it can be attained are highly uncertain.

The experiments that are of most interest to this study are the flight tests conducted for the AFF project. They provide a good idea of the potential benefits of automated formation flight. NASA conducted experiments in two flight conditions: (1) at a Mach number of 0.56 and an altitude of 25,000 ft; (2) at the regime of commercial transports: at a Mach number of 0.86 and an altitude of 36,000 ft. They observed significant differences between these two flight conditions both in terms of performance benefits and vortex shape. Figure I-9 shows the contours for the drag reduction at a longitudinal distance of 4.4 spans (approximately the observed optimum longitudinal distance).

Figure I-9: Drag reduction contour plots as a function of Y-Z position at flight conditions 1 and 2 for a longitudinal distance X = 4.4 b [16]

These plots show that the benefits are much smaller for the second flight condition. The maximum decrease in drag is about 13% versus 22% for the first flight condition. This will have to be investigated further in the future as the conditions in which formation flight would be used for cargo aircraft are very close to the second flight conditions. Also, the shape of the real vortex is not as simple as the theoretical one, which was predictable. However, the “sweet spot” is very close to the predicted one, and the gradients are again very large around it, making the zone where the benefits are significant very small.

As for the longitudinal position, the measurements showed that the maximum benefits were obtained between 3 and 7 spans downstream of the leader aircraft.

G. Station-keeping precision

As shown above, a given position must be maintained very precisely to get the full benefits of formation flight.

An attempt was made quantify the influence of the precision of the station-keeping device on the induced drag benefits. It was assumed that the system has an access to the map of the potential benefits as a function of the position when flying in formation. Figure I-10 (a) shows a comparison of the results calculated based on the benefit maps given by two theoretical methods (a horseshoe vortex model using a vortex core size of 3% span and a vortex lattice method [6]) and two flight test measurements (AFF project for a longitudinal distance of 3 spans and flight conditions 1 and 2 [16]). The value of the benefit in induced drag shown on the graph corresponds to the maximum lower bound of the benefit for a given precision. That is, if a circle with radius equal to the given precision is superimposed on the map of the induced drag benefits, the value shown on the graph is the benefit at the edge of the circle when its center is at the optimum location. It is important to notice that this optimum location is very rarely centered on the point of maximum benefits, especially when the radius gets larger.

The results of the flight tests were originally presented as total drag reduction and were expressed as induced drag benefits using the assumption that the aircraft is flying at the maximum range conditions.

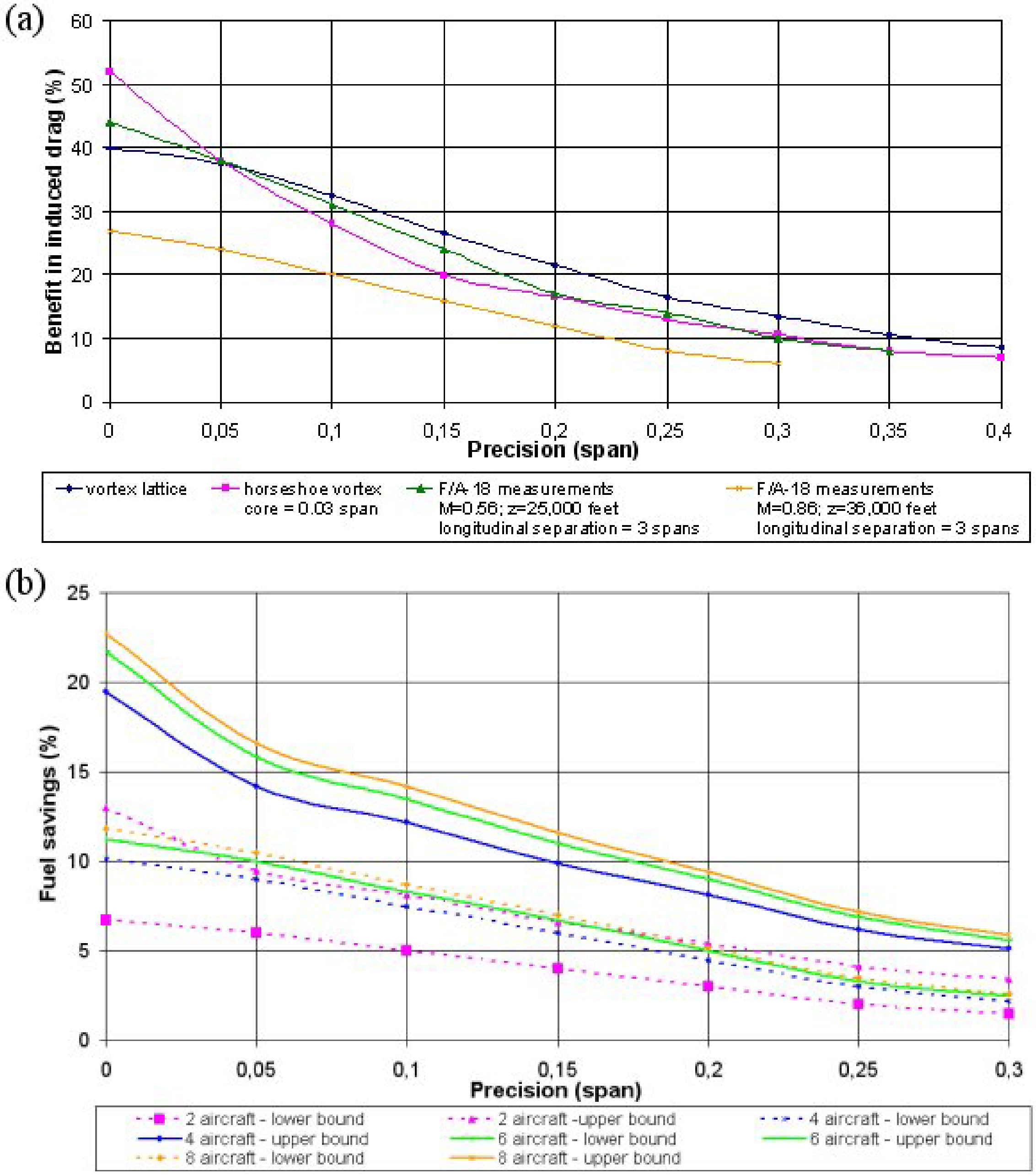


Figure I-10: (a) Potential induced drag benefit as a function of the precision of the station-keeping device; (b) Minimum fuel savings as a function of the precision of the station-keeping device.

As shown on the graph, the magnitude of the benefits is very dependent on the precision of the station-keeping. If the position cannot be maintained by less than 0.2 spans, the total drag benefits will be cut by half or more.

Fuel savings computed from these values are shown in Figure 10 (b) for formations of 2, 4, 6 and 8 aircraft. For the example of a 2-aircraft formation with a precision of 0.1

span for the station keeping, this graph shows that the fuel savings should be between 5% and 13%.

H. Shape of the formation

A number of formation configurations are possible. The obvious one is the one used by the birds: the V-formation, but others are possible. Figure I-11 presents the three most common shapes: the V-formation, the echelon formation and the chevron formation.

Figure I-11: Possible shapes of formation: (i) Echelon; (ii) Chevron; (iii) V-formation [17]

Several criteria are useful in evaluating each formation shape: safety, lift distribution, distribution of the benefits, etc…

Blake and Multhopp showed that the optimum lift distribution across the formation was an elliptical distribution [6]. It gives the best total induced drag benefits for the formation as a whole. It is interesting to note that streamwise spacing has no influence on the total benefits.

Figure I-12: Optimum lift distribution across the formation [6]

This distribution of lift means that the aircraft in the center should be the heaviest and those at the ends the lightest. To allow this distribution to occur from fuel use differences, the center aircraft should be getting the most benefits and those at the end the least benefits. In the case of a regular V-formation, the contrary happens, so that this configuration is far from being optimum. The chevron formation (reverse V-formation) is better, but it has the drawback that two aircraft are getting no benefits from the formation. As for the echelon formation, if the aircraft always stay at the same location, it is equivalent to half a V-formation, but if it rotates periodically, then a nearly elliptical lift distribution can be simulated [6].

Streamwise spacing is the decisive parameter affecting the distribution of benefits throughout the formation. If the leader and the follower are very close, the benefits are distributed among them, whereas if they are far, only the follower will get benefits. King and Gopalarathnam showed that the configuration that gave equal benefits in induced drag for each aircraft in the formation is a nearly elliptical V-formation: the aircraft are more spaced out at the ends and less so in the middle of the formation [18].

Figure I-13: V-formation giving equal benefits in induced drag in a formation of 25 aircraft [18]

This formation has two important drawbacks: it is not optimal in the sense of total benefits among the formation, and it is not feasible in practice for reasons of safety. The aircraft situated at the front of the formation are very close to each other, making the risk of collision unacceptably high. However, having equal benefits in induced drag is the only way to improve the range of the formation. If an aircraft has no benefits, then its range – and therefore the range of the formation – will be the same as when it flies on its own. The only benefits of the formation will be fuel savings. On the contrary, if every aircraft gets the same benefits in induced drag, then the formation will have benefits both in terms of fuel savings and in terms of range increase.

Among the configurations considered, the chevron formation doesn't permit an equal distribution of the benefits among the formation. The rotating echelon formation, however, can be adapted so that every aircraft has the same benefits. The time between the rotations has to be chosen so all the aircraft stay the same amount of time in a given position.

The V or echelon formations give less freedom of movement than the echelon formation. This can be a problem in case of emergency break-up of the formation. On the other hand, rotating the formation adds complexity to the system in terms of controls and operations. One thing that can be made in order to improve the chevron formation is to stagger the airplanes in the longitudinal direction so that there are never two aircraft at the same longitudinal position. This is illustrated on Figure I-14 (a).

Finally, if the only benefits which are needed are fuel savings, two configurations are optimum: a chevron formation, and a rotating echelon formation. If range benefits are needed, then only a rotating formation can give them, and in that case, the echelon formation is optimum.

Figure I-14: Optimal shapes for a formation. (a) Staggered chevron; (b) Rotating echelon [6]

The additional payoff obtained by adding an aircraft to the formation decreases with the number of aircraft. It is in particular very small beyond five or six aircraft [6]. Therefore, having a formation of more than 6 aircraft may not be worthwhile, since that the more aircraft the formation contains, the more safety hazards exist.

References

[1] Cutts C., Speakman J., “Energy Savings in Formation Flight of Pink-Footed Geese,” *Journal of Experimental Biology*, Vol. 189, pp. 251-261, Jan. 1994

[2] Weimerskirch H., Martin J., Clerquin Y., Alexandre P., Jiraskova S., “Energy Savings in Flight Formation,” Nature, Vol. 413, pp. 697-698, 2001

[3] P. Lissaman and C. Shollenberg, “Formation Flight of Birds,” *Science,* Vol. 168, 1003-1005, May 1970

[4] Dimock G., Selig M., “The Aerodynamic Benefits of Self-Organization in Bird Flocks,” AIAA 2003-0608, Jan. 2003

[5] Anderson J., *Introduction to Flight*, New York : McGraw-Hill, 1985

[6] Blake W., Multhopp D., “Design, Performance and Modeling Considerations for Close Formation Flight,” AIAA-98-4343, Aug. 1998

[7] Huenecke K., “Vortex Wake from Large Aircraft– A Challenge for Industrial Research,” AIAA 2000-2216, Jun. 2000

[8] Huenecke K., “From Formation to Decay – Extended-time Wake Vortex Characteristics of Transport-type Aircraft,” AIAA 2002-3265, Jun. 2002

[9] Kantha L., “Empirical Model of Transport and Decay of Aircraft Wake Vortices,” *Journal of Aircraft*, Vol. 35, No. 4, Jul.-Aug. 1998, pp. 649-653

[10] Huenecke K., “The Characterisation of Transport Aircraft Vortex Wake,” AIAA 2001-2427, Jun. 2001

[11] Journade J., “Numerical Wake Vortex Characterization,” AIAA 2003-3815, Jun. 2003

[12] Blake W., Gingras D., “Comparison of Predicted and Measured Formation Flight Interference Effects,” AIAA 2001-4136, Aug. 2001

[13] Gingras D., Player J., Blake W., "Static and Dynamic Wind Tunnel Testing of Air Vehicles in Close Proximity," AIAA-2001-4137, Aug. 2001

[14] Myatt J., Blake W., "Aerodynamic Database Issues for Modeling Close Formation Flight," AIAA 99-4194, Aug. 1999

[15] Wagner G., Jacques D., Blake W., Patcher M., "Flight Test Results of Close Formation Flight for Fuel Savings," AIAA 2002-4490, Aug. 2002

[16] Vachon M., Ray R., Walsh K., Ennix, K., "F/A-18 Aircraft Performance Benefits Measured During the Autonomous Formation Flight Project," AIAA 2002-4491, Aug. 2002

[17] Bangash Z., Sanchez R., Ahmed A., "Aerodynamics of Formation Flight," AIAA 2004-0725, Jan. 2003

[18] King R., Gopalarathnam A., "Ideal Aerodynamics of Ground-Effect and Formation Flight," AIAA 2004-0906, Jan. 2004

II. General study of the dynamics and stability of an aircraft in formation flight

A. Introduction

fig.1. Two F/A-18 flying in formation [1]

An understanding of the flight dynamics of formation flight requires a basic understanding of the aerodynamic effects. When trailing aircraft flies into the vortex of the leading aircraft as shown above, the wing in the upwash of the vortex undergoes an increase in lift and a decrease in induced drag, as sketched below:

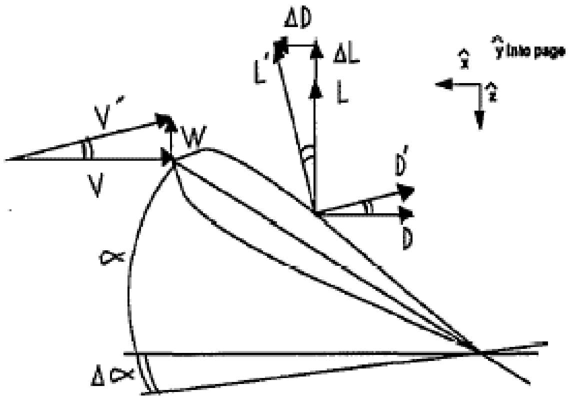


fig.2. Aerodynamic effects on a wing section in a vortex [2]

The other wing, in the downwash, undergoes the opposite effect. The aircraft is therefore subject to an asymmetrical effect resulting in a number of flight dynamic consequences.

fig.3. Resulting flight dynamics forces [3]

When flying in the optimal configuration, the asymmetrical drag reduction results in a yawing moment, which leads the nose of the aircraft to the right in Figure 3. The asymmetrical lift increase results in a rolling moment that makes the aircraft bank to the right. The aircraft also undergoes a side force due to the pressure of the vortex on the fuselage, which tends to move the aircraft to the right. Finally, the aircraft also undergoes a pitching moment due to the upwash of the vortex that lifts the nose of the aircraft. All these effects tend to break the formation, pushing the aircraft farther away from the leader.

The stability of the aircraft, both longitudinally and laterally, must be examined in the environment of these asymmetric forces.

There are two longitudinal natural modes: the short period mode and the phugoid mode.

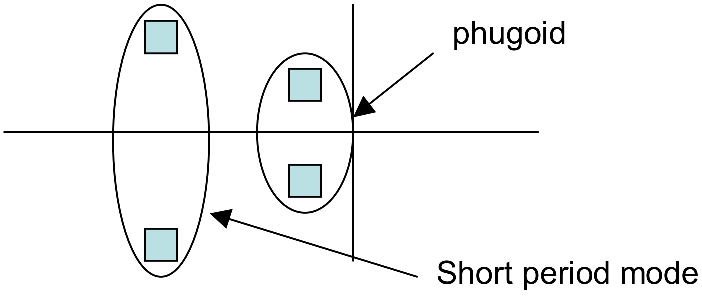


fig.4. Poles of the longitudinal modes

Only the phugoid risks becoming unstable. However, the phugoid is a slow motion that can easily be controlled by the pilot. The risks of instability in the longitudinal case are therefore low.

There are three lateral natural modes: the roll, Dutch roll and spiral modes.

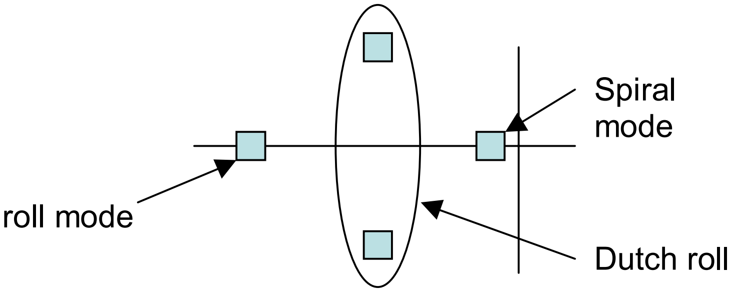


fig.5. Poles of the lateral modes

As it appears on the sketch above, the mode that is the closest to instability is the spiral mode. The spiral mode stability is determined from the following equation:

$$Cl\beta * Cnr > Clr * Cn\beta$$

Clβ is the rolling moment induced by a slip angle. It can be increased using a bigger dihedral.

Cnr is the yawing moment induced by a yaw rate. This coefficient corresponds to the route stability and can be increased by using a bigger vertical tail.

Clr is the rolling moment induced by a yaw rate. For example, when the aircraft is yawing to the right, the left wing's airspeed is higher than the right's, and therefore has a higher lift. This results in a rolling moment that can initiate a dangerous spin.

Cnβ is the yawing moment induced by a slip angle. While pointing the nose of the aircraft to the right, the airspeed comes from the right on the tail which then makes the aircraft yaw more to the right, an unstable response. Here the tail has an unbalancing effect.

As explained before, the trailing aircraft in the formation undergoes a rolling moment and yawing moment making the nose of the aircraft point down and to one side. This is exactly the movement that may initiate a spin, depending on the stability of the spiral mode. Therefore, it is important to ensure that this mode is stable for the aircraft in formation flight. The use of control loops in the autopilots may also have impacts on the stability of the spiral mode, as shown below:

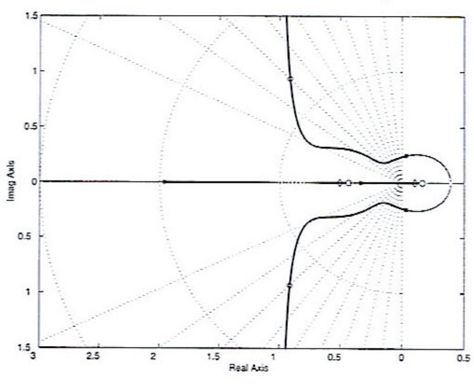


fig.6. Effects on stability of a loop of Φ on δa

It is therefore also important to check that the autopilot does not make the spiral mode unstable.

B. Experimental results of the formation flight dynamics

The data from the flight tests at NASA Dryden Flight Research Center using two F/A-18 aircraft **[1]** are helpful for analysis of the dynamics aircraft in formation flight. For this reason, some the graphs from the paper AIAA 2002-4489 are presented and discussed below.

- **55 ft nose-to-tail separation, M = 0.56, h = 25,000 ft**

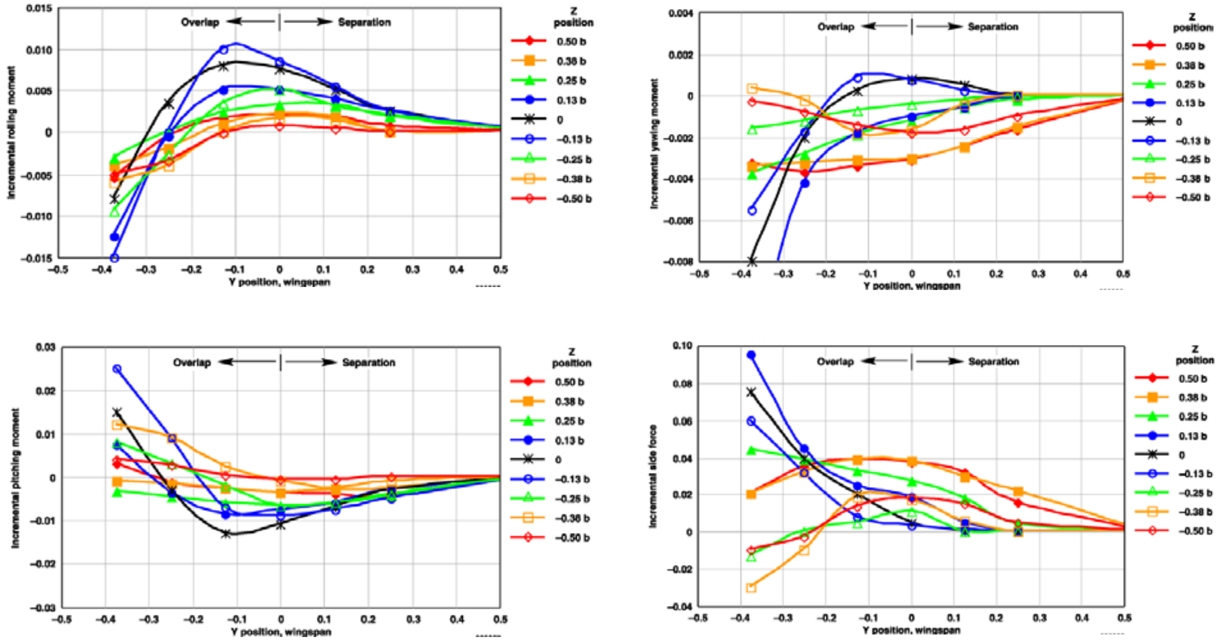


fig.7. Flight dynamics effects for a 55 ft separation, M = 0.56, and h = 25,000 ft

Figure 7 shows graphs of incremental rolling, yawing, pitching moment and side force, with respect to the lateral position *y*, plotted for a number vertical positions *z*. The main trends described above can be observed: when entering the vortex from the right, the aircraft first undergoes a positive rolling and yawing moment (left wing goes up and turns to the right), as well as a positive side force (in the sense of the vector y, along the right wing), that tends to break the formation. The sign of the pitching moment is easy to interpret and depends on the vertical position in the vortex.

However, these moments change signs and vary greatly around the point of maximum drag reduction, here at y = -0.13 b and z = -0.13 b. Once past the "optimal point" for formation flight, a dangerous behavior occurs: the rolling, yawing and even pitching moment change signs, thus changing drastically the behavior of the aircraft. This may lead to collision risks. The point of maximum drag reduction is therefore also the most challenging point from a control perspective.

- **110 ft nose-to-tail separation, M = 0.56, h = 25,000 ft**

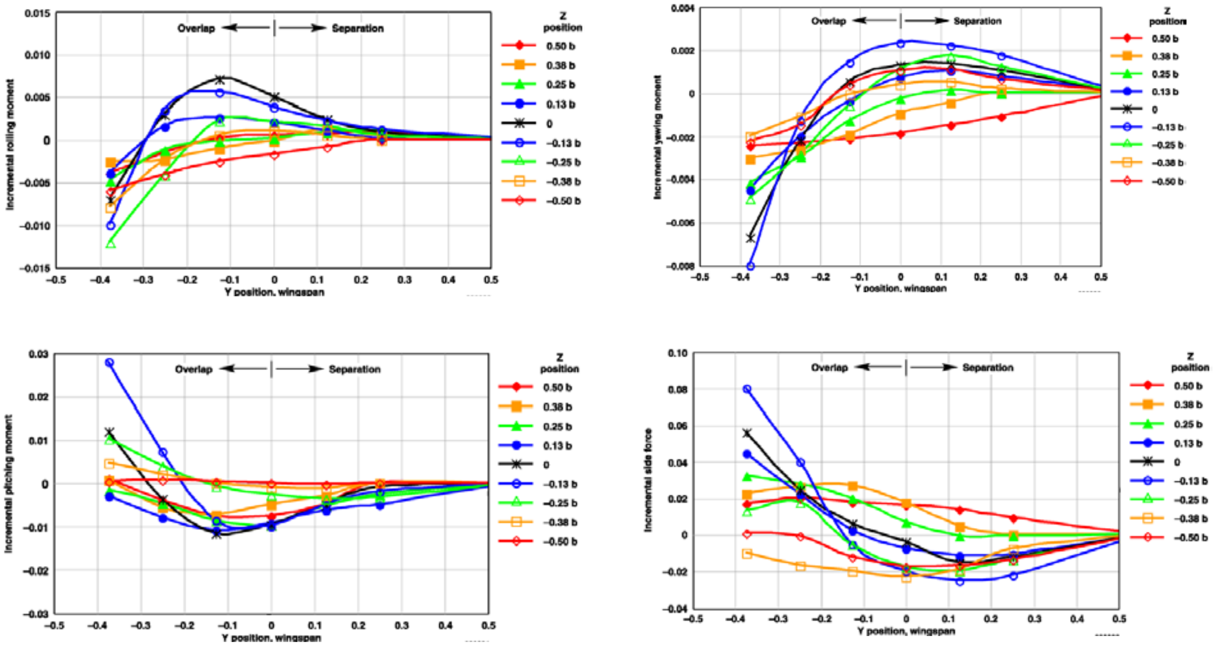


fig.8. Flight dynamics effects for a 110 ft separation, M = 0.56, and h = 25,000 ft

Similar trends appear in Figure 8. In this case, however, with the increase in longitudinal distance, the rolling and pitching moment decrease whereas the yawing moment and side force increase in magnitude.

- **55 ft nose-to-tail separation, M = 0.86, h = 36,000 ft**

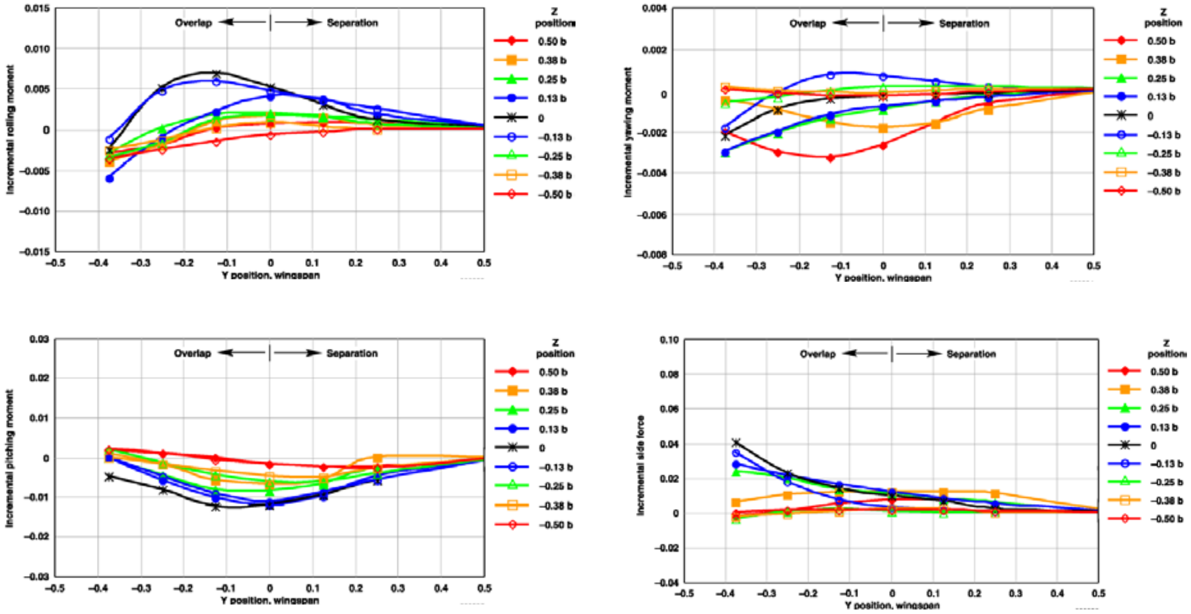


fig.9. Flight dynamics effects for a 55 ft separation, M = 0.86, and h = 36,000 ft

In figure 9 the most significant observation is that the vortex effects are weaker at transonic than at subsonic conditions.

- **110 ft nose-to-tail separation, M = 0.86, h = 36,000 ft**

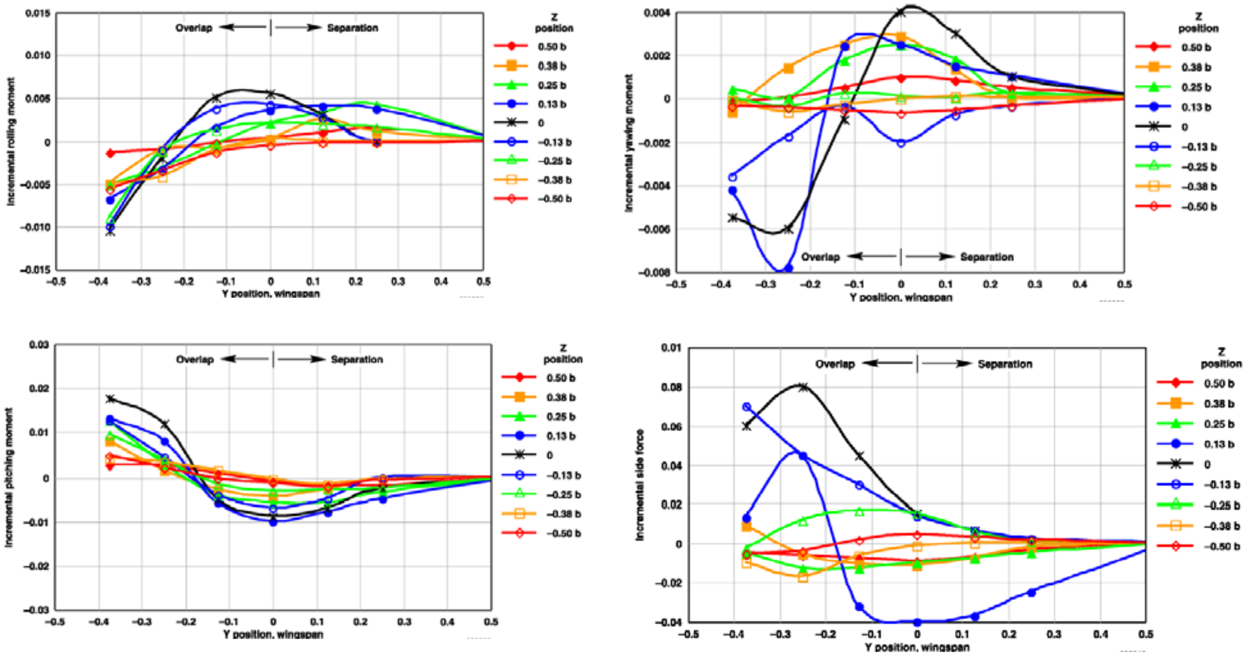


fig.10. Flight dynamics effects for a 110 ft separation, M = 0.86, and h = 36,000 ft

When compared with the subsonic case at same longitudinal separation, it appears that with the increase in Mach number, the pitching and rolling moment decrease whereas the yawing moment and side force increase.

The analysis of this flight dynamics, coupled with the previous study on the general stability makes it possible to consider a possible flight configuration for the trailing aircraft.

C. Configuration proposal

The flight regime of M = 0.86, h = 36,000 ft and 110 ft nose-to-tail separation seems to be the most interesting for several reasons. First, this choice of the Mach number and altitude corresponds to the regime of existing cargo aircraft. The longitudinal separation is large, so as to minimize the risks of collision, and using the fact that the benefits do not depend much of this distance, within a certain range. Also, vortex effects on the flight dynamics are weaker at transonic than at subsonic, which eases the controls and reduces the risks of instability. The choice of 110 ft nose-to-tail separation is also chosen because the rolling and pitching moments decrease while the yawing moment and side force increase. This is preferable for two reasons. First the rolling and pitching moment's amplitudes appear to be the largest. In addition, these dynamics are appropriate for the control strategy and aircraft architecture proposed below. Instead of trimming the aircraft with the ailerons, it could be trimmed with the rudder. The aircraft would then fly with a slip angle, resulting in a balancing rolling moment opposing the one coming from the vortex (the dihedral effect would tend to induce a negative rolling moment balancing the positive one described above). This would also induce a negative side force that would balance the positive force created by the vortex. However, the yawing moment may be worse if the aircraft's route stability is good (which is important for the spiral mode stability). In fact, the aircraft would tend to align with the airflow, adding to the positive yawing moment induced by the vortex. This could be countered by adequate yaw trim.

References

[1] Jennifer L. Hansen and Brent R. Cobleigh, "Induced Moment Effects of Formation Flight using two F/A-18 Aircraft", NASA Dryden Flight Research Center, *Flight Mechanics Conference and Exhibit*, Monterey, California, AIAA-2002-4489.

[2] Andrew W. Proud, Meir Pachter, and John J. D'Azzo, "Close Formation Flight Control", Air Force Institute of Technology, Wright Patterson AFB, Ohio, AIAA-99-4207.

[3] M. Jake Vachon, Ronald J. Ray, Kevin R. Walsh and Kimberly Ennix, "F/A-18 Aircraft Performance Benefits Measured During the Autonomous Formation Flight Project", NASA Dryden Flight Research Center, *Flight Mechanics Conference and Exhibit*, Monterey, California, AIAA-2002-4491.

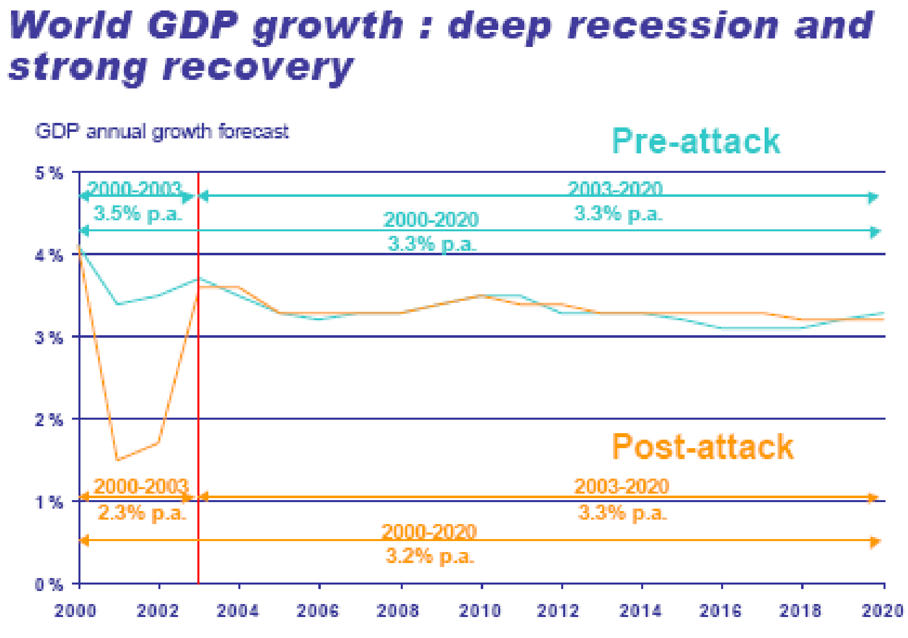
III. Commercial Cargo Market, Needs, and Metrics

A. Current State of the Market

Most economic models have shown an extremely high correlation between air cargo growth and economic growth, as measured by Gross Domestic Product (GDP). There are other drivers, such as globalization and lean inventory strategies, but the economic downturn is probably the biggest reason that the air cargo industry has been suffering through a huge recent crisis. This crisis was caused by multiple factors. Around the year 2000, the economic slowdown in the United States as well as in Europe preceded the terrorist attacks on Sept 11th, which then led to increased security costs. The reduction of information technology/high-tech equipment sales also put a small dent in air cargo. The recent outbreak of the SARS virus along with the plethora of conflicts that have plagued the 21st century so far were also key ingredients in forming the current crisis. In addition, falling yields, the expansion of integrated express carriers, and the consolidation of freight forwarders have all been recent trends in the air cargo industry.

B. Predicted Market Growth

However, most major market forecasters predict that world GDP will make a strong recovery (refer to Figure 1 below), which will then of course be the impetus for strong recovery in the air cargo market[1]. According to Airbus, the predictions for the next twenty years are for world GDP to grow on average 3.2% per year and for world air cargo traffic to grow on average 6.4% per year.



Source : DRI-WEFA

Figure 1: World GDP Growth

Below in Figure 2 is a chart of the top ten air freight markets in the next twenty years according to the Global Market Forecast produced by Airbus. As is evident, the fastest growing markets are those linking Asia to other regions as well as Intra Asia whereas the domestic US market and other maturing markets will grow much more slowly.

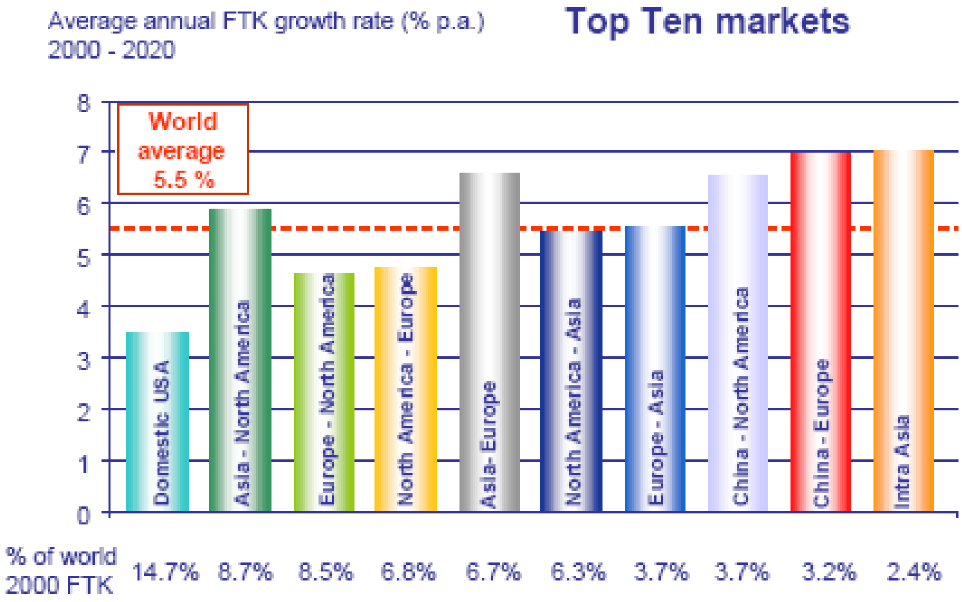


Figure 2: Market Growth

Specifically, the US share of the world market as measured by GDP is currently 30.4% and will decrease to 26.1% by 2021. Asia's share of world GDP will instead grow from 24.7% to 26.3%. Domestic China, one of the top future markets, will grow at 10.3% per year or possibly even 11.2% depending upon which source is used. The Intra-Asia market will grow at the fastest rate of all Asian markets, around 8.4%. The Asia-North America market will grow at 7.5%, and the Europe-Asia market will grow at 7.0%. The conclusion that can be reached from all of these numbers is that the fastest growing air freight markets are those connecting the Asia-Pacific region to Europe and North America. Seven out of the top ten markets serve this region, seen on the above chart, and together, they will represent 40% of the world air cargo market in 20 years and will be the basis for the demand for long range cargo airplanes[2].

C. Predicted Air Cargo Fleet Growth

In response, the world freighter fleet will more than double by the year 2020, according to most predictions, going from an estimated 1,540 in the year 2000 to 3,338 dedicated freighters in the year 2020[1]. Figure 3 below details specifics for the growth of the fleet.

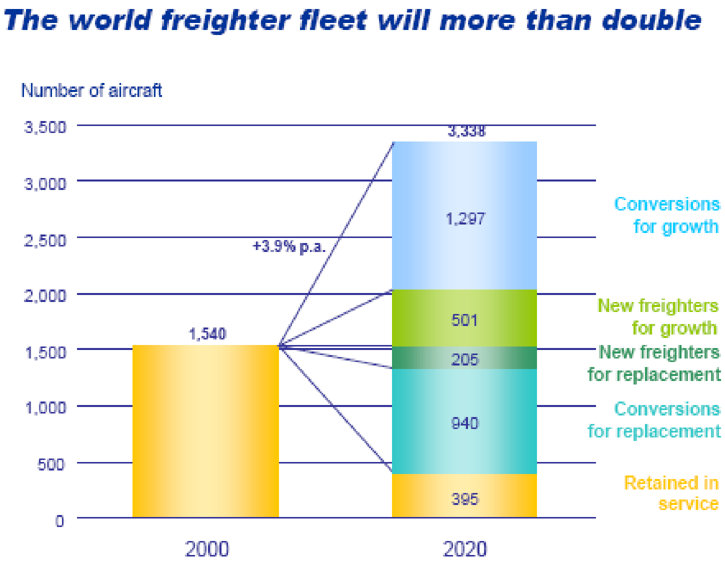


Figure 3: World Freighter Fleet Growth

About 395 of the fleet in 2020 will be aircraft retained in service throughout those 20 years. About 940 of those will be passenger airplanes converted to cargo aircraft to replace old or faulty planes. 205 will be new freighters for replacements, and 501 will be new freighters for growth. Finally, 1,297 will be conversions for growth of the industry to meet the increasing demand. Additionally, these numbers are all for dedicated cargo airplanes. This does not include the passenger aircraft system, which in the year 2000 carried 48% of the global airfreight traffic, and is projected to carry 43% of that traffic in 2020, as seen in Figure 4 below.

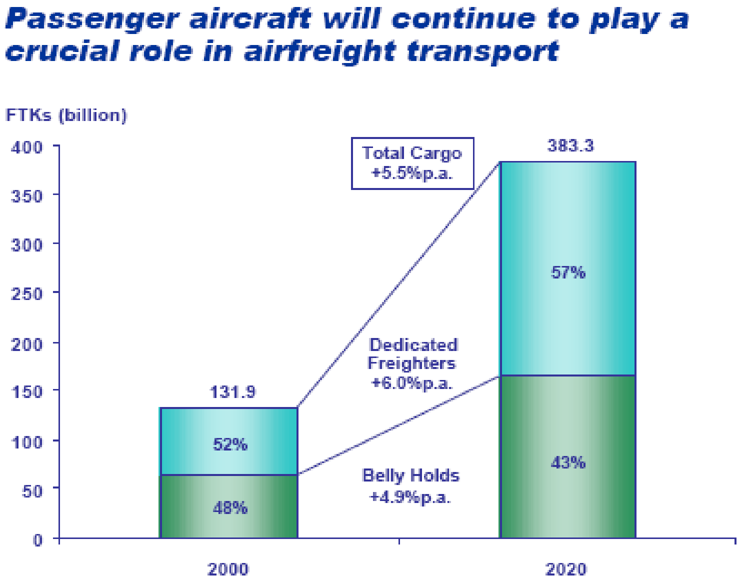
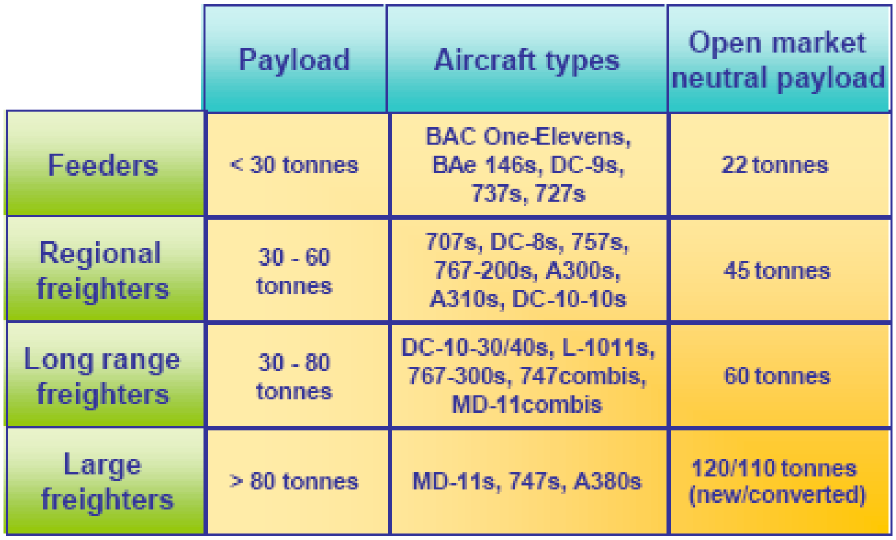


Figure 3: World Freighter Fleet Growth

To be able to support such a large increase in traffic, Airbus predicts that future freighters will need to be utilized much more often and that they will grow in size, increase capacity per aircraft, and thus achieve lower unit operating costs. The catch is that larger aircraft are beneficial only if you can fill them up completely. However, even though a majority of new production freighters will be large aircraft, the intermediate or regional size of aircraft will still comprise the majority of the actual market. In the following figure, the breakdown of cargo planes into 4 different segments is shown: the feeders, the regional freighters, the long range freighters, and the really large freighters[1].



	Payload	Aircraft types	Open market neutral payload
Feeders	< 30 tonnes	BAC One-Elevens, BAe 146s, DC-9s, 737s, 727s	22 tonnes
Regional freighters	30 - 60 tonnes	707s, DC-8s, 757s, 767-200s, A300s, A310s, DC-10-10s	45 tonnes
Long range freighters	30 - 80 tonnes	DC-10-30/40s, L-1011s, 767-300s, 747combis, MD-11combis	60 tonnes
Large freighters	> 80 tonnes	MD-11s, 747s, A380s	120/110 tonnes (new/converted)

Figure 4: Freighter Size

D. Current Transport System

It is also necessary to determine what airlines are currently serving the commercial market. The top five international carriers include Federal Express, Lufthansa Airlines, Singapore Airlines, Korean Air, and Air France. The top five domestic carriers are Federal Express, UPS Airlines, United Airlines, Northwest Airlines, and American Airlines. Whether it's designing an entirely new large freight transportation vehicle or using existing aircraft to fly formation to save on fuel costs, or possibly even some combination, no one has been unable to penetrate the long haul high-end trucking market or the high-end sea cargo market. From an overall market viewpoint, sea transport is currently responsible for 99% of the cargo market whereas air cargo takes only 1%. Conversely, those numbers are the exact opposite for passenger transport. Thus, the two markets, people and cargo, are significantly different, and so the systems that transport both are significantly different as well. If the benefits of formation flight would allow air cargo carriers to capture just one or two percent of the sea transport industry, then a large, profitable growth in the air freight market would result.

E. Existing Aircraft

Many existing aircraft are uniquely suited to serve as the backbone for future air cargo operations, especially formation flight. Some examples are listed below with their maximum payload, associated range, cruise speed, and the total of 8x9x13 standard FedEx containers that they can hold.

Aircraft Type	Max Payload (lbs)	Adjusted Range (nm)	Cruise Speed (Mach)	8x9x13 FedEx Containers
MD-11F	190,000	3,800	0.82	16
B747-400ER	248,600	4,970	0.845	20
A380-863F	330,517	5,700	0.85	22
***BWB**	525,000	4,000	0.85	68

Figure 5: Existing Aircraft[3,4, 5, 6]

From the chart above, it is clear that the A380 has a greater range, payload capacity, and cruise speed than any other aircraft in its class. However, the Blended Wing Body (BWB) and its substantial payload could prove to be a dominant force in the market.

F. Possible Route Comparisons

These aircraft have each been included in the calculation of long distance routes from Memphis, Tennessee, to Osaka, Hong Kong, Bangkok, Singapore, and Jakarta. The associated distance, number of each aircraft, payload per plane, total payload, and total time is shown is shown for each aircraft. The following charts[7] simply give a baseline performance estimate of the aircraft flying separately, not including the benefits of formation flight.

Memphis to:	Distance (nm)	# of MD-11	Payload per plane (lbs)	Total Payload (10^6 lbs)	Time (hrs)
Osaka	5,910	8	125,000	1.00	13.6
Hong Kong	7,119	13	75,000	0.98	16.3
Bangkok	7,817	28	35,000	0.98	18.0
Singapore	8,490	N/A	N/A	N/A	N/A
Jakarta	8,838	N/A	N/A	N/A	N/A

Figure 6: MD-11 Flying Solo

Memphis to:	Distance (nm)	# of B747-200F	Payload per plane (lbs)	Total Payload (10^6 lbs)	Time (hrs)
Osaka	5,910	7	140,000	0.98	13.6
Hong Kong	7,119	20	50,000	1.00	16.3
Bangkok	7,817	N/A	N/A	N/A	N/A
Singapore	8,490	N/A	N/A	N/A	N/A
Jakarta	8,838	N/A	N/A	N/A	N/A

Figure 7: B747 Flying Solo

Memphis to:	Distance (nm)	# of A380-863F	Payload per plane (lbs)	Total Payload (10^6 lbs)	Time (hrs)
Osaka	5,910	3	330,000	0.99	13.6
Hong Kong	7,119	4	260,000	1.04	16.3
Bangkok	7,817	4	230,000	0.92	18.0
Singapore	8,490	6	180,000	1.08	19.6
Jakarta	8,838	8	130,000	1.04	20.4

Figure 8: A380 Flying Solo

Memphis to:	Distance (nm)	# of BWB	Payload per plane (lbs)	Total Payload (10^6 lbs)	Time (hrs)
Osaka	5,910	2	415,000	0.83	13.6
Hong Kong	7,119	3	340,000	1.02	16.3
Bangkok	7,817	3	300,000	0.90	18.0
Singapore	8,490	4	270,000	1.08	19.6
Jakarta	8,838	4	250,000	1.00	20.4

Figure 9: BWB Flying Solo

Preliminary studies suggest that the benefit in induced drag for each aircraft flying behind the lead aircraft in a formation could be as high 40%. This corresponds to an increase in range of the aircraft, a decrease in the number of aircraft required to carry the same amount of cargo, an increase in the total possible payload of the aircraft, or a decrease in the amount of time to traverse each route. These factors are all tradeoffs that can be negotiated to bring about the greatest overall benefit or profit to the air cargo airlines. Below are charts similar to the ones displayed above, except with the benefit of formation flight added in. These are existing commercial aircraft that have not been modified in any way.

Figure 10: MD-11 Flying Formation

Memphis to:	Distance (nm)	# of B747-200F	Payload per plane (lbs)	Total Payload (10^6 lbs)	Adj. Time (hrs)
Osaka	5,910	7	140,000	0.98	13.6
	5,910	6	180,000	1.08	15.9
Hong Kong	7,119	20	50,000	1.00	16.3
	7,119	7	144,700	1.01	19.0
Bangkok	7,817	N/A	N/A	N/A	N/A
	7,817	8	121,000	0.97	21.0
Singapore	8,490	N/A	N/A	N/A	N/A
	8,490	13	73,700	0.96	23.1
Jakarta	8,838	N/A	N/A	N/A	N/A
	8,838	22	44,700	0.98	24.6

Figure 11: B747 Flying Formation

Memphis to:	Distance (nm)	# of A380-863F	Payload per plane (lbs)	Total Payload (10^6 lbs)	Adj. Time (hrs)
Osaka	5,910	3	330,000	0.99	13.6
	5,910	3	330,000	0.99	15.7
Hong Kong	7,119	4	260,000	1.04	16.3
	7,119	3	325,000	0.98	18.7
Bangkok	7,817	4	230,000	0.92	18.0
	7,817	4	284,600	1.14	20.7
Singapore	8,490	6	180,000	1.08	19.6
	8,490	4	250,000	1.00	22.5
Jakarta	8,838	8	130,000	1.04	20.4
	8,838	4	244,200	0.98	23.4

Figure 12: A380 Flying Formation

Memphis to:	Distance (nm)	# of BWB	Payload per plane (lbs)	Total Payload (10^6 lbs)	Adj. Time (hrs)
Osaka	5,910	2	415,000	0.83	13.6
	5,910	2	440,000	0.88	15.6
Hong Kong	7,119	3	340,000	1.02	16.3
	7,119	3	395,000	1.19	20.0
Bangkok	7,817	3	300,000	0.90	18.0
	7,817	3	361,300	1.08	20.7
Singapore	8,490	4	270,000	1.08	19.6
	8,490	3	325,800	0.98	22.5
Jakarta	8,838	4	250,000	1.00	20.4
	8,838	3	316,100	0.95	23.4

Figure 13: BWB Flying Formation

From these charts, it is clear that formation flight has the potential to make air cargo operations much more viable and profitable than it currently is right now.

References

[1] Airbus Global Market Forecast, Sept 2002, available at http://www.airbus.com/pdf/media/gmf2001.pdf•Barkowski, R. (2003). Future Concepts for Air Cargo Delivery, AIAA
[2] Boeing Current Market Outlook, June 2003, available at http://www.boeing.com/commercial/cmo•Clarke, J. P. (2004). Air Cargo Economics, Briefing Slides
[3] MD-11 Characteristics: >www.boeing.com/assocproducts/aircompat/acaps/md11.pdf
[4] B747 Characteristics: >http://www.boeing.com/commercial/747family/technical.html
[5] A380 Characteristics:
>http://www.aerospaceweb.org/aircraft/jetliner/a380/index.shtml
>http://www.airbus.com
[6] Expedited Transport Airlines, 16.899 Project Report, May 19, 2003

[7] Distances and paths between cities:
>http://www.indo.com/cgi-bin/dist/place1=@140832/place2=@174190
>http://www.macchiato.com/distance

IV. Military Cargo Market, Needs, and Metrics

A. Introduction

The market for a formation flight system for the U.S. military was analyzed. There is a huge variety of aircraft and uses of aircraft in the military, and so there is potential to apply formation flight to a much broader range of applications than commercial aircraft. Valuable benefits of in-wake formation flight include increased payload per aircraft, increased range, and reduced fuel costs. Fuel cost savings increase significantly when aerial refueling requirements are reduced. Obstacles to gaining any of these benefits include difficulties in increasing loads (load efficiency), the logistical complexity of timing flights to fly together, and ramp space limits on the number of aircraft that can be at one destination at a time. Despite the obstacles to gaining significant benefits, the military system has advantages for developing formation flight. The military already flies in formation, has its own certification process, already flies many autonomous systems, has test airplanes available,

In the analysis that follows it is proposed that military aircraft can obtain fuel cost savings similar to commercial aircraft but with less frequency, that there may be a case for a formation flight system in aerial refueling aircraft, and that there is not a substantial benefit from formation flight for Army expeditionary mission goals. An example mission of flying 6 F-15C's in formation on a 3,500 nm deployment requires 4 refueling aircraft with formation flight, instead of 5 without. There are many questions and potential obstacles in meeting the expeditionary force deployment time objective. If load efficiency and airport throughputs are not limiters, then formation flight capability could reduce a medium-weight brigade deployment time by about 0.8 days, from 7.4 to 6.6 days. This is still 2.6 days longer than the 96-hour objective. The methods used in this analysis are very rough. Military planning and simulation software such as JFAST exist and could give a more accurate idea of what actually benefits are obtainable.

To analyze the market for military applications we must first look at how value is defined in military terms. The basic definition of valuable is anything that enhances military capability towards meeting goals, or reduces costs without sacrificing capability. There are several missions where formation flight may have value such as expeditionary force airlift, general and strategic airlift long-range bombing, ferry flights, aerial refueling, and UAV missions. The expeditionary airlift mission was analyzed in detail for the Army's near-future "Objective Force" concept [1].

B. Value

Value has always been difficult to define in the military. That is in part why there are so many controversial or cancelled Department of Defense projects. Robert S. McNamara, as Secretary of Defense in the 1960s, defined value as cost-effectiveness: fulfilling required capabilities at minimal costs. It is still true today that the DoD's goal is to have the readiness and capability required, now and in the future, within the allotted budget. Anything that can help achieve that goal has value. There is no standard document in use that defines value, however documents such as the Quadrennial Defense Review (QDR) [2] and the National Security Strategy (NSS) [3] create readiness and capability goals that can show goal-fulfillment side of the value equation. Military strategy and management decisions are based on these documents. The best way to analyze the value that could be created with formation flight is to analyze the missions where it could be used. If a mission objective cannot be met with the current system, then there is a need. An improvement to the system that fulfills that need is valuable. A reduction of costs without sacrificing capability is also valuable. In-wake formation flight has potential to reduce fuel costs, and improve mission capability with current equipment. Exceptionally valuable is the potential of formation flight to improve capability to the extent that new acquisitions are not needed, resulting in a huge cost benefit.

Military strategy has recently changed with the end of the cold war and the beginning of a new type of conflict. The military is no longer required to be able to fight a full-scale war on two fronts[1]. The Quadrennial Defense Review is the overall strategic planning document of the Department of Defense and defines principle changes in U.S. defense strategy [2]. Secretary Rumsfeld outlines these changes in the excerpts from the forward below [2].

Changing enemy:

> The attack on the United States and the war that has been visited upon us highlights a fundamental condition of our circumstances: we cannot and will not know precisely where and when America's interests will be threatened, when America will come under attack, or when Americans might die as the result of aggression…We can identify threats, but cannot know when or where America or its friends will be attacked… Adapting to surprise - adapting quickly and decisively - must therefore be a condition of planning.

Capabilities-based approach:

> A central objective of the review was to shift the basis of defense planning from a "threat-based" model that has dominated thinking in the past to a "capabilities-based" model for the future. This capabilities-based model focuses more on how an adversary might fight rather than specifically who the adversary might be or where a war might occur. It recognizes that it is not enough to plan for large conventional wars in distant theaters. Instead, the United States must identify the capabilities required to deter and defeat adversaries who will rely on surprise, deception, and asymmetric warfare to achieve their objectives.

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[1] Military strategy actually began to gradually change towards what it is today in the 1960's with President Kennedy and McNamara. Before Kennedy, military strategy focused on nuclear deterrence to the point the only options were to not fight or to wage full-scale nuclear war. Kennedy and McNamara recognized the need to be able to use the military with a limited response and began to rebuild conventional forces. McNamara also recognized benefit (mostly in terms of money) of having joint programs between the branches of the military. Joint forces is a central concept in today's military, even though it was not accepted in the 1960s.

A key capability is fast, precise strikes including the expeditionary mission analyzed in this paper. QDR states that the implementation of the Army's Objective Force will be accelerated in accordance with this strategy shift. The Objective Force white paper states the Army's deployment goals [1]. These goals are to be able to deploy a brigade any where in the world in 96 hours from liftoff, a division in 120 hours, and five divisions in 30 days [1]. These goals are very ambitious and currently unattainable [4]. Capability improvements to achieve these goals are sought and would be highly valued. The capability, and thus the value, enabled by formation flight for this mission is analyzed below.

C. Existing Airlift Fleet and Structure

A description of the structure and size of the airlift fleet follows. Although there are missions where non-airlift airplanes can be used for formation flight benefits, only the airlift fleet is described. The airlift mission is the most similar to the commercial cargo mission analyzed in the accompanying conference paper, and is the mission analyzed in detail below.

Military airlift services, with the exception of some special forces type units, are provided by the U.S. Transportation Command (USTRANSCOM). USTRANSCOM is one of the DoD's unified commands, a joint service. Its primary components are the Air Force's Air Mobility Command (AMC), the Navy's Military Sealift Command, and the Army's Military Traffic Management Command. AMC is responsible for peace and wartime airlift deployment, aerial ports, and aerial refueling among other missions. The AMC also procures airlift services from the commercial fleet and manages the Civil Reserve Air Fleet [5].

The number of aircraft existing now and in the future is important for any analysis of a formation flight retrofit kit for existing aircraft. For airlift only, and excluding the civil reserve, there are four types of aircraft primarily used. These are the C-5, C-17, C-141, and C-130. The C-141 is being retired and will be completely gone in 2006 [6], so it is not considered in the analysis below. The C-130 is the tactical level workhorse for the military; its function is described as intra-theatre airlift. C-130 primary role in a conflict is to move troops and equipment to the front lines, and repositioning. The radius of operations for a C-130 is around 1500 nm, but it is typically used in deployments on the order of 500 to 1000 nm. Because it operates on the front lines of a conflict, it is at high risk and needs maximum operation flexibility and minimal visibility. A formation is easier for the enemy to see than a single airplane, and the logistics of planning formation flight could reduce operational flexibility. Increased vulnerability and reduced flexibility in a combat environment, and at ranges where the benefits of formation flight are minimal are reasons why the C-130 could not be a likely candidate for a formation flight system. C-5s are the largest aircraft in the U.S. fleet and can carry almost anything the Army owns [6]. They can carry more weight than any other aircraft. C-17s are the next in size. C-17's and C-130J's are the only transport aircraft currently still being produced [6]. Although C-17's cannot carry as much as a C-5, they are actually more efficient in the expeditionary mission analyzed below [4]. This is due to an increased readiness rate, reduced ground-time, and reduced footprint (parking space taken) compared to the C-5.

Payload range curves for the current cargo fleet are shown below. Also shown are key metrics on operating costs, cargo bay dimensions, and planned numbers of transports until 2009.

Figure 1: Payload-Range Curves for Current Fleet [6]

	C-17	C-5	C-141	C-130J-30
$/ flying hr (FY97 $)	4,992	6,324	3,103	1,343
Fuel $/hr	2,394	2,724	1,745	601
Cargo bay HxWxL	12.3x18 x88	13.5 x 19x143	9x10.25x 93.3	9x9.9x55

Table 1: Costs and Cargo Bay Sizes [6]

	FY02	**FY05**	FY09
C-17	84	**116**	153
C-5	104	**92**	92

Table 2: Planned Inter-theatre Transports [4]

All of transport aircraft discussed can operate from austere environments with rougher and shorter runways than commercial aircraft can handle. Another key factor is floor strength. Commercial aircraft would need major modifications to handle the point loads of medium-weight armor. Airlift requirements in the new age of conflict and the war on terror are not going to decrease. Operation Enduring Freedom in Afghanistan in

2002 had the 3rd largest airlift in history according to the USTRANSCOM annual report [5].

Airlift Support	
Missions	9,564
Sorties	35,088
Passengers	238,466
Cargo (short tons)	318,283
Aerial Refueling Missions	3,199

Table 3: Statistics of USTRANSCOM Involvement in Operation Enduring Freedom [5]

In the table above, missions are a combination of sorties (one or more aircraft) with a single objective. Sorties are flights of one aircraft from takeoff at a departure location to landing at a destination.

C-17 and C-5 payload-range curves from above were recalculated to show the potential benefits of formation flight. Range increases or payload increases can be estimated from these curves. For a 120,000 lb or 60 short-ton (s.t.) load, the C-17 has a range of around 3,600 nm. Drawing a horizontal line from the 120,000 lb point, the formation flying range is about 4,500 nm, for a total range benefit of 900 nm, or 25%. For a 3,500 nm range the C-17 carries about 125,000 lb. For the same range, a formation flying C-17 carries 150,000 lb, an increase of 12.5 s.t. or 20%. In this case the C-17 trades fuel weight saved from formation flight for cargo weight. An optimistic 10 s.t. increase was used in the analysis below. The approximate range curves below were created using a 15% assumed fuel savings from formation flight.

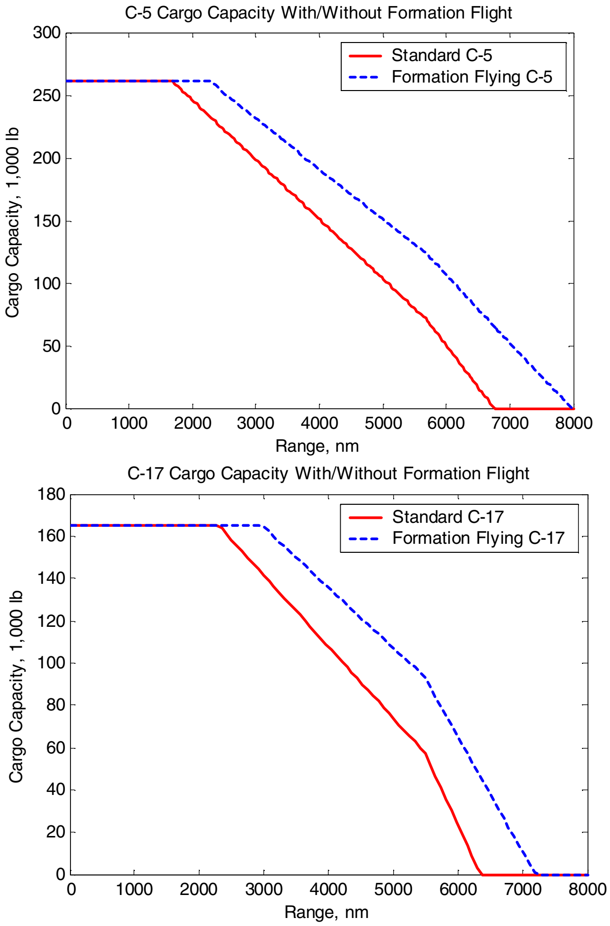

Figure 2: C-17 and C-5 Payload Range Curves Standard, and with 15% Fuel Savings

D. Missions

To determine the market for a formation flight capability in the military, missions where formation flight could be used had to be researched first. Second, it had to be determined if there would be value in its use. Missions where formation flight could be used are described below.

General and strategic airlift are missions very similar to the commercial cargo mission. For the purposes of this paper, general and strategic airlift is defined as any airlift outside of special operations airlift and expeditionary airlift (which is described below). General airlift covers the peacetime airlift needs of the military. Strategic airlift covers the airlift required to build-up for and sustain military operations. One third of strategic airlift including all personnel deployments are done with civil carriers contracted out as a reserve fleet. These missions were not analyzed. The requirements for analysis are details on usage and scheduling of general and strategic airlift. As the military scheduling system is not as structured as the commercial system, it would likely require significant logistical system changes to allow the opportunity for formation flight.

Assuming that airplanes can be scheduled to fly together, then the operational cost savings would be similar to commercial fuel cost savings.

Long-range bombing, long-range ferries, aerial refueling, and UAVs are other missions that were investigated but not analyzed in detail. Long-range ferries refer to when fighter, attack, and other aircraft deploy to an overseas base. Bombers could fly together, fighters could fly together, or all could fly in formation with their tankers. UAVs could fly longer range and the technology that allows formation flight could allow for aerial refueling of autonomous vehicles.

The expeditionary mission is a quick deployment of large forces conflict somewhere in the world. Expeditionary forces are the first to arrive at a conflict. The destination is assumed to have minimal support and the location is often austere, requiring troops to be carried on military transport[2]. Higher mobility and faster force response required by the QDR are especially important in the expeditionary forces. In the initial stages of a conflict, the Army, Air Force, and Navy/Marines will deploy expeditionary forces. Although the equipment is different, the Airlift missions are similar in nature, similar in timing requirements, and in competition over airlift resources. The Army typically receives about 30% of joint forces airlift capability at the start of a conflict [4].

a) Army Expeditionary Force Deployment Mission

The plan for the future expeditionary force of the Army is called "Objective Force." The mobility goals of Objective Force are to be able to deploy a continental U.S. (CONUS) based combat capable brigade in 4 days, anywhere in the world; a combat capable division in 5 days; and 5 divisions in 30 days [1]. Research shows that the Army cannot currently meet these goals, and that the expected deployment time is closer to one to two weeks [7]. The primary unit of the future combat system is a medium-weight fighting vehicle. The system will be fully operational in 2012 [4]. In the interim, the Army is acquiring Stryker vehicles to go into Stryker Brigade Combat Teams (SBCTs). An analysis of the impacts of formation flight on meeting Objective Force deployment goals with SBCTs was performed for this study, based on the study in *Speed and Power: Toward an Expeditionary Army* by RAND.

Speed and Power, analyzed the deployment capability of a single SBCT brigade. The studied looked at deploying an SBCT from the continental United States, to a representative destination in Macedonia, with a round trip distance of around 13,000 nm. The study concluded it would take 7.4 days to deploy for this mission using an optimistic 38% of the airlift fleet. The mission goal is 4 days.

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[2] "Afghanistan highlighted that our base of operations can be increasingly austere, and we do not always have assured access to operational bases." - General John Handy, USTRANSCOM Commander [5].

There would be great value in a formation flight system if it could close the gap in time to deploy. The key drivers where formation flight could reduce deployment time are in the round-trip time, and number of missions required. Round-trip time could be reduced only if, for a specific mission, the range increase from formation flight could eliminate a refueling stop from the trip. The number of missions required could only be reduced if a payload weight increase could be obtained from formation flight for the same flight plan. The limiter for a payload weight increase is when aircraft are already filled up on volume, or "cubed out." Efficient loadings that do not cube-out take logistical planning and optimization. The analysis must keep in mind that any added restrictions on logistical planning reduce necessary flexibility in military operations. Another limiting factor is MOG, the number of aircraft that can be on the ground at an airport at any given time. Research shows that an MOG of 3 is typical [4]. For any deployment mission where cargo aircraft are destined to the same airport, the formation would be limited to no more than the MOG of the destination airport, or any refueling stops.

The mission used for the analysis is shown below. Using different airports on the way in and out frees up MOG on the route. The analysis assumes that only C-17's are used because they are more efficient, giving a more optimistic and conservative estimate [4]. The figure shows the flight segment times, and the time on the ground during stops.

Figure 3: Mission Route [4]

Formation flight can improve range or weight. The ability of the range increase to improve mission performance depends highly on the mission and number of stops. For this mission, removing one of the stops would improve round trip time by 2.25 hours. However, considering the segment ranges and an overall range increase of less than 1,000 nm, and a minimum segment length of 2,082 nm (considering no refueling in Skopje), no segment could be cut out of the mission. So there would be no benefit from formation flight due to range increase for this mission.

Load efficiency is an important factor in determining the potential benefit from formation flight. *Speed and Power* indicated that for this study, 71 loads would cube out at 45 s.t., leaving 199 missions where payload weight increases would be possible. For this analysis, it was assumed full advantage could be taken of a payload weight increase from formation flight without cubing out. Many factors influence loading efficiency. A combination of analysis and testing would be required to get a more accurate prediction of the expected loading efficiency. An example of an optimized load for a Stryker Brigade deployment is shown below. The figure shows that 3 vehicles and 36 troops with combat loads can raise the payload weight to 64.5 s.t.

Figure 4: An Optimized SBCT Deployment Load [4]

The impact of increasing loads on 199 out of 270 missions was analyzed[3]. The maximum segment length from figure XX is 3,400 nm. Using figure XX at 3,400 nm range, the load increase from formation flight is around 10 s.t., increasing the load from 60 to 70 s.t. The number of total missions required after the load increase is applied to 199 missions is 199 × (60/70) + 71 = 241.

Mission time is the greater of:

$$\left[\frac{\#Missions \times RTtime}{\#A/C \times \mathrm{Re}\,adyRate}\right] - \frac{1}{2}RTtime \quad \text{or} \quad \left[\frac{\#Missions}{(24/GroundTime)MOG}\right] + \frac{1}{2}RTtime$$

The second equation checks to see if the number of missions per day is limited by the throughput capacity of the destination airfield. The study apparently used a ground time in Skopje of 1.75 hours, based on planning factors that were noted elsewhere in the report to be conservative. The results of a 1.0 hour ground time are included below. This is ignoring en route stops where the ground time is higher. This would likely be another significant obstacle to improving capability for this mission with formation flight.

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[3] The deployment weight of a Stryker Brigade is estimated to be near 15,000 s.t. in this study.

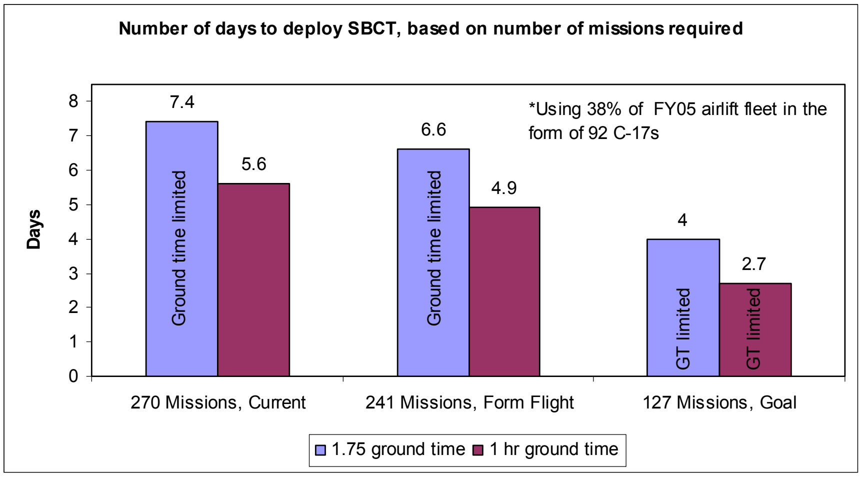


Figure 5: Number of Days to Deploy as a Function Missions Required and Ground Time

b) Refueling Mission Example

Air Mobility Planning Factors, an Air Force pamphlet, was used for a rough estimated effect of formation flight fuel savings on an example mission. Section 18 of the pamphlet includes an example showing how to calculate the number of KC-135R tankers would be required to fly 6 F-15C's 3,500 nm from Langley, VA to Spangdahlem, Germany [8]. The example calculation is repeated here [8]:

On-load required per F-15 = (dist / TAS × fuel flow) – total fuel + destination res.
= (3500 / 480 × 10,822) – 23,000 + 7500
= 63,410 lbs (per receiver) × 6 = **380,462 lbs total fuel**
Off-load per tanker = total fuel – (dist / TAS × fuel flow) – destination res.
= 180,000 – (3500 / 480 × 10,718) – 30,000
= **71,848 lbs per tanker**
Tankers required = 380,462 / 71,848 = **5 KC-135R's required**
dist = total distance from takeoff to landing
TAS = average airspeed of receiver leg
fuel flow = fuel burn rate in lbs/hr
total fuel = total fuel on board at takeoff
destination res. = required fuel reserves at destination

The pamphlet reports 5 KC-135R's required, when the number calculated is 5.3. Applying a straight percent reduction to fuel flow in this rough estimate, the number of KC-135R's required for this example mission is recalculated for a range of fuel flows below. The fuel flow reduction is applied to the refueling aircraft and the F-15C's.

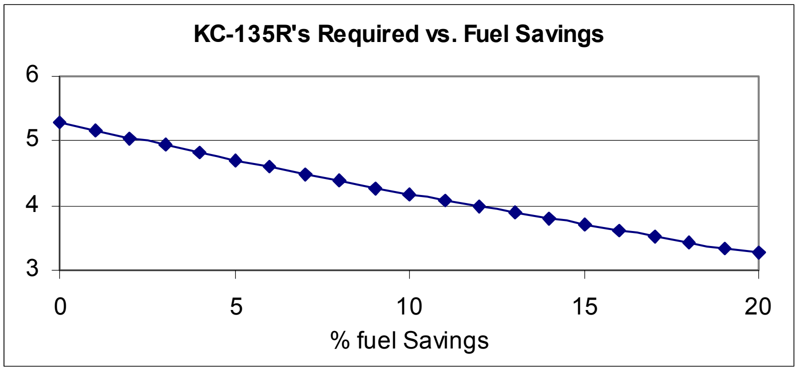


Figure 6: Example of Advantages of Formation Flight for Aerial Refueling

The results show that the number of refueling aircraft required for this mission is reduced from 5 to 4 for a 10% fuel savings, and to 3 for a 20% savings. For 9 to 11 aircraft in formation (fighters and tankers), a 10% fuel savings on a 3,500 nm mission may be somewhat conservative.

The pamphlet notes that simulation should really be used for this type of planning. No investigation was made into whether or not this is a representative mission. Mission planning software, statistics on actual missions flown, and mission costs would be useful in a detailed analysis.

References

[1] United States Army. "Concepts for the Objective Force."

[2] Henry H. Shelton (Chairman of the Joint Chiefs), "Quadrennial Defense Review Report."
September 30, 2001. Forward by Secretary of Defense, Donald Rumsfeld.

[3] "The National Security Strategy of the United States of America." September, 2002. Available at www.whitehouse.gov/nss/.

[4] Eric Peltz, J. Halliday, A. Bower. *Speed and Power: Toward an Expeditionary Army.* RAND Document MR-1755. 2003.

[5] United States Transportation Command Annual Report, 2002.

[6] Federation of American Scientists: www.fas.org.

[7] Alan Vick, D. Orletsky, B. Pirnie, S. Jones, *The Stryker Brigade Combat Team: Rethinking Strategic Responsiveness and Assessing Deployment Options.* RAND Document MR-1606. 2002.

[8] Air Force Pamphlet 10-1403. *Air Mobility Planning Factors.* December 18, 2003. Available at www.e-publishing.af.mil.

V. UAV’s Market, Needs, and Metrics

A. The market

The market for UAVs is expected to be worth $**10.6 billion in the next 10 years**, according to Forecast Internationals' "The market for UAVs systems".
UAVs have been used in military actions in Afghanistan, the Philippines, Yemen and more recently Iraq.
Northrop Grumman, with the Global Hawk, and General Atomics, with the Predator, control 50% of this market's total value.

Fig.2. The Predator [2]

Fig.1. The Global Hawk [1]

The Pentagon has a growing demand for UAVs ($5.4 billion worth of contracts expected in the next 10 years).

B. Mission profiles

- **Attack**

In an attack mission, a group of UAV bombers, for example, seek to destroy an objective (Unmanned combat aerial vehicles – UCAVs).

- **Reconnaissance**

In a reconnaissance mission, UAVs fly in formation above an unknown area to discover the situation. (High Altitude Long Endurance – HALE).

- **Surveillance**

In the surveillance mission, a group of UAVs fly in formation inside an area to monitor events.

- **Testing the technology**

UAV formation flight can also be considered as a first step towards cargo or passenger transport formation flight since the development and testing costs are much lower.

C. The advantages

- **Increase in range or payload**

This advantage is significant since many small UAVs have very limited range.

- **More information shared** (visualization, coordination)

Flying in a group allows better viewing and launching angles.
It can also increase the survivability of the group.

- **Simpler and less costly tests, design and development**

Tests with small UAVs, compared with those for full-scale aircraft, would encounter less practical problems, fewer constraints and would be much less expensive, making potential crashes less catastrophic.
Design and development would be easier, quicker and cheaper because of the small scale.
The human resources would be cheaper as well since there would be no need for pilots.

D. The disadvantages

- **Market is smaller than cargo**

The market is mostly military although there are also a growing number of **civil applications**, such as maritime surveillance to monitor coastlines for security and environmental protection, wildlife monitoring, illegal fishery monitoring, and swifter oil spill discovery. However, the military is willing to pay for performance and has a strong interest in UAVs.

- **The benefits of formation flight on small UAVs are unknown**

There will still be benefits in flying in the vortex of a leader aircraft, but these benefits may be different for smaller Reynolds numbers.

E. Conclusion

The UAV market is an attractive market for formation flight, with many potential applications, especially for the military.
In addition, it could be the first step towards the development of cargo and/or passenger aircraft formation flight.

References

[1] http://www.is.northropgrumman.com/products/usaf_products/global_hawk/pic-1.html

[2] http://www.airforce-technology.com/projects/predator/predator6.html

VI. Competing Systems / Vehicles

With global demand for freight transport growing, opportunities for developing new systems have arisen. The purpose here is to list the systems that are likely to be competitors of any formation-flight based system, to find which markets they are targeting, and to determine how interesting they would be for potential customers.

A. Systems overview

c) Freighter ships

Ships are the most widely used system for freight transportation, especially on transoceanic routes where they account for 99% of the weight transported. Ships are of course of different types and sizes. In particular, we can distinguish between the ships dedicated to the transport of raw material (crude oil, natural gas, iron ...) and those transporting standardized containers. The first type of ships targets a market highly unfavorable to air cargo, where the volume of the goods is more important than the weight; we will therefore concentrate on the second class of ships.

Modern containers ships are huge and, above all, optimized for cost reduction. They are highly automated, with a crew of only 13 people for a 6000 TEU (twenty-foot equivalent unit). Such a ship is shown below:

Fig. 1. Container ship [1]

They are diesel powered and are able to reach 23 knots. While their ton-mile cost is the lowest of all transportation systems, they are also very slow and unreliable as goods are subject to salt corrosion and theft.

d) Railroad

Trains are the continental counterpart to container ships. They are slow but inexpensive. Like container ships, they are highly automated to reduce the cost of transportation. The loading/unloading time has been drastically reduced by using intermodal containers and double-deck systems (see picture) have been developed to increase the payload.

Fig. 2. Double Deck System [2]

e) Cargo aircraft

Existing cargo airplanes

Current cargo airplanes are all derived from airliners to avoid having to pay extra development costs. The focus here will be on the wide-body aircraft since they are expected to account for 90% of air freight capacity by 2021. The current wide-body long-range cargo aircraft fleet is composed mainly of 747s and MD-11s. The A-380, whose cargo derivative is expected to be operational in 2008, will also be looked at. The following table gives the characteristics of each aircraft:

	payload (lbs)	range (full payload) (Nm)	speed (mph)
747-200F	248,600	4,000	560
A-380F	335,000	5,780	560
MD-11	200,000	3,800	560

These aircraft will still be found in air cargo fleets in 20 years, since air cargo companies usually prefer retrofitting old airliners into cargo aircraft than buying brand new airplanes: this option is by far cheaper in terms of capital costs.

Advanced systems

With the growing demand for air-cargo, the development of a genuine cargo aircraft (which would not be derived from an airliner) may now be a profitable option. We will review three advanced all-cargo systems which are currently being studied to both satisfy this demand and take market share from air-cargo competitors (ships and trains).

The **Boeing Blended Wing Body** (BWB) (see picture below) is a new aircraft concept that has the potential to substantially reduce the operating costs of air transportation.

Figure 3 Boeing BWB [3]

The projected decrease in direct operating costs is 30% for a gross payload of 500,000 lbs, a range of roughly 5,000 Nm and a speed of Mach 0.85. According to its designers, the BWB would not raise any operational issues since it stays in the 80-meter box required to operate in current modern airports.

Boeing is also working on the **Pelican**; this huge aircraft would take advantage of the ground effect to carry a 1,500,000 lbs payload composed of standardized containers at 300 mph across either the Pacific or the Atlantic oceans.

Figure 4 - Boeing Pelican [3]

When flying in ground effect, it is expected that the Pelican burns 50% less fuel than it would have burnt flying "conventionally". However, many technological and operational difficulties still have to be solved to come up with an operational system.

The **Hybrid Ultra Large Aircraft** (HULA) is another concept that consists of having an aircraft that uses a non-rigid shape to generate 60% of its lift using buoyant aerostatic lift and 40% of its lift using powered aerodynamic lift while in motion.

The resulting aircraft would carry 2,000,000 lbs at a speed of 80-100 knots.

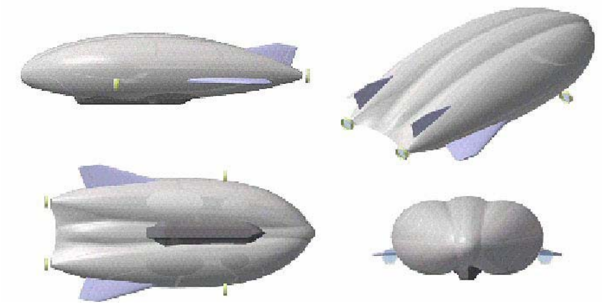


Figure 5 AeroVehicles, Inc. "Aerocat" [4]

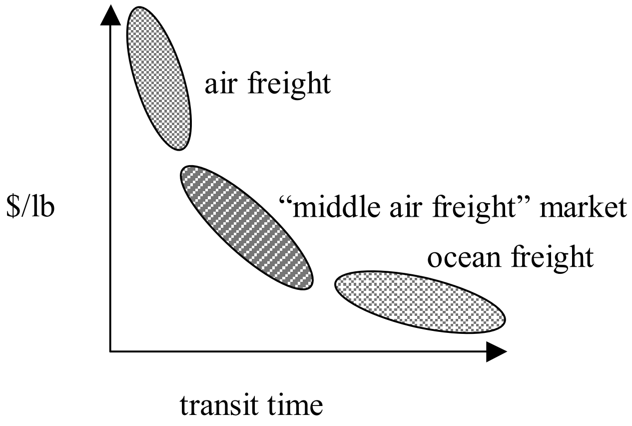
No estimates of the expected decrease in operating costs have been published yet.

B. Market overview

a) The idea of a "middle-air" market

Today, customers have two options for their transoceanic freight: they can choose air freight, which is fast and reliable but expensive or they can choose sea freight which is much less expensive but also unreliable and very slow. One can then assume that air is the best way to move high value freight while ocean shipping is good for low value freight.

For many goods, speed is not so critical. Therefore, there exists a real market for a system which would be faster then ocean shipping but less expensive than current cargo aircraft. This middle air freight market is expected to have an enormous potential. The Pelican and the HULA are systems that are targeting this market since they are trading speed for lower operating costs. They are expected to have such low operating costs that it is likely that no other air cargo system can compete with them in terms of operating costs.



These systems have however, major weaknesses:

· they both have risky technical challenges to overcome before actually building the aircraft. This can lead to high development costs that would induce high capital costs for the customers.

· they both have little in common with current cargo aircraft. It can be a problem for customers that are already operating fleets of "classical" cargo aircraft and want to optimize their recurring costs such as maintenance. Will the low operating costs balance the cost of opening new maintenance facilities?

· from an operational point of view, strong challenges are likely to arise: these aircraft will require new airport facilities. Who will pay for them? How can we incorporate these aircraft into the existing air traffic control system without penalizing them?

And above all, these systems may not be competitive in markets where time is critical.

b) Express air freight: a promising market for formation flight

The intercontinental air freight market can be divided in two sub-markets: express air freight and non-express air freight. The express air freight market currently accounts for 0% of the international air freight market and is growing fast since it is expected to reach 20% of the international air freight market by 2020.

Figure 6 International Air Freight Market growth [5]

Systems that trade speed for savings in operating costs cannot compete in this market, so that the systems that are competing with our formation flight concept in this market reduce to the BWB and existing cargo airplanes.

Now, buying two 747-200 and make them flying in formation gives a system that has the payload and the range of a BWB. The operating costs of the BWB will be 30% less than those of the formation, but the ownership costs of the formation will be much lower than those of the BWB so that the two systems are ultimately equivalent.

This is definitely the market where formation flight based systems can be a commercial success.

c) Taking market shares from ocean shipping

We saw that for markets where time is critical formation flight based systems were at least equivalent to their main competitor (the BWB). The next question to ask is whether they will be able to take a share of the middle air market or not. This is equivalent to asking if they will be able to take any market share from the ocean freight market since we can assume that the middle air freight market will come from a larger reduction of the ocean freight than of the air freight market.

Blaine K. Rawdon, from the Boeing Phantom Works has compared the Total Distribution Cost (TDC) for three systems (ship, existing cargo airplane, Pelican), depending on the value per pound of the goods times the inventory carrying cost:

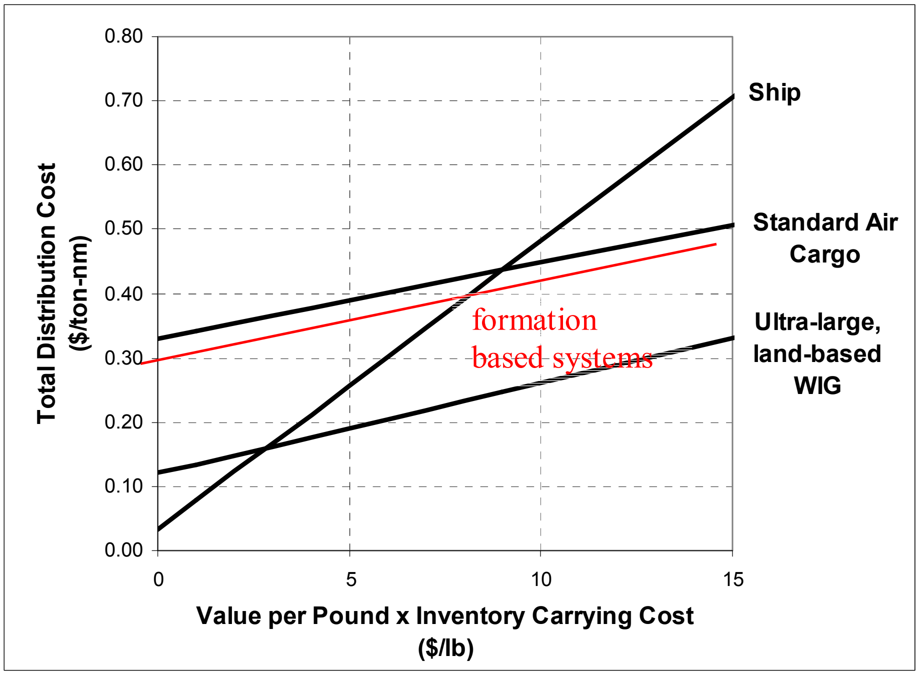


Figure 7 Total Distribution Cost vs Value per pound × Inventory Cost

In terms of value per pound times inventory carry cost, the point above which an air cargo system is cheaper than a shipping system is 9 $/lb. The Pelican would be able to take market share from the ocean freight market by lowering this threshold. A formation flight based system would have a Cargo Rate (Y-intercept of the straight lines) a bit lower than existing cargo airplanes. It would, therefore, lower the threshold between air freight and ocean freight, but not as much as a system like the Pelican or the HULA would.

Formation flight based systems have the potential to take market share from ocean shipping. However, Pelicans and HULAs are strong competitors in this middle-air market and are likely to quickly capture most of the market as soon as they are operational.

C. Customers

a) different types of customers

The following graph shows the major freight airlines in 2000, by weight:

Figure 8 Major Freight Airlines in 2000 [6]

One can notice that the 2 largest freight airlines are FedEx and UPS, two express air freight companies. They operate large fleets of all-cargo aircraft. As we mentioned before, these companies will probably not be interested in HULA or WIG (wing in ground effect) systems since their business is time-critical.

The other air freight companies are actually combination airlines that carry freight in passenger aircraft bellies or have a dedicated cargo fleet.

These customers have specific requirements:

· the aircraft must operate from existing airports, sometimes under severe noise regulations.

· they will want to take advantage of the possible synergies between their passenger and cargo aircraft in terms of maintenance and airport operations.

These two requirements could be more easily satisfied with BWB or conventional aircraft than with HULAs or Pelicans, although the cost per ton-mile could be lower for these advanced systems.

Therefore, even for the freight airlines that do not operate in the express air freight market, the Pelican and the HULA, may not be the best options.

b) BWB and formation flight based system operating costs

Since the major competitor of a formation flight based system seems to be the BWB, in this section is a comparison of the operating cost per ton-mile of each system. The following operating cost model is used:

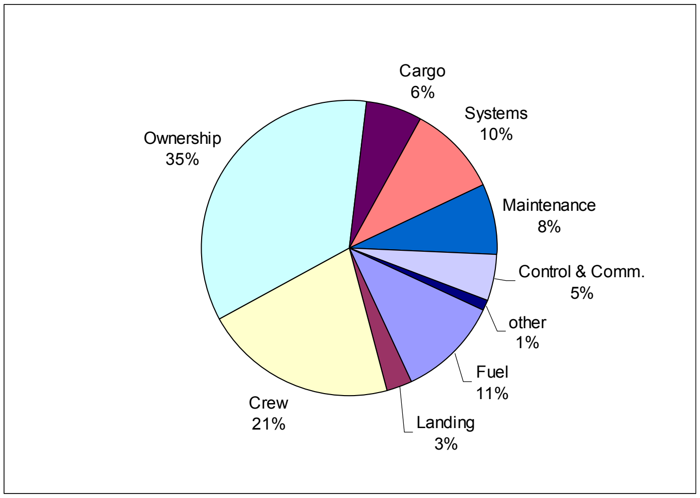


Figure 9 operating costs model

with the assumption that only crew, landing and fuel shares may vary between the systems we are looking at.

Taking the Boeing 747 Freighter as a reference, we find the following operating costs for the A380F, the BWB, a formation of B747F's and a formation of A380F's (a 10% decrease in fuel consumption is assumed due to the formation):

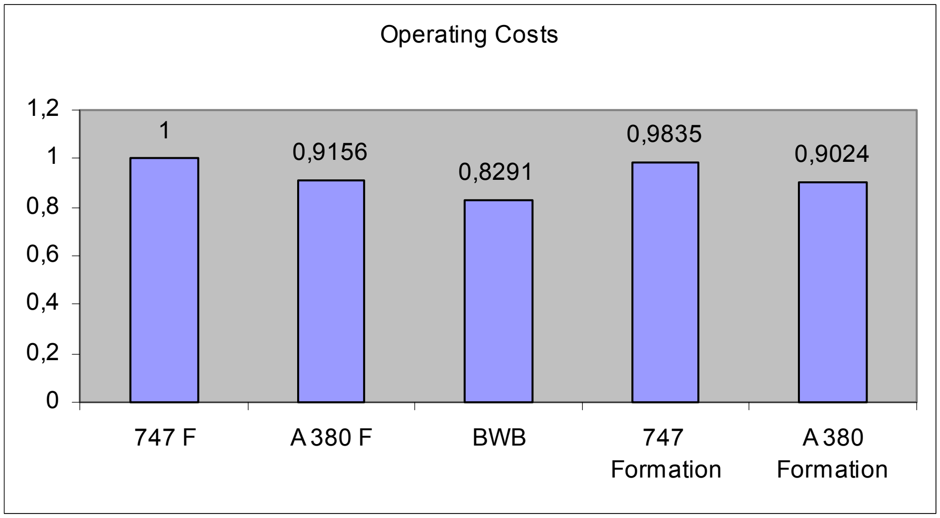


Figure 10 Operating Costs Comparison

These results show that the operating costs of a formation-based system will always be much higher than those of a BWB. However, our model is very simple and does not take into account the fact that the ownership cost of a brand new BWB will probably be high. It will probably be higher than the ownership cost of several "old" B747's retrofitted to fly in formation. Therefore, it is much likely that the difference in cash airplane related operating costs will be balanced by the difference in ownership costs.

Moreover, formation flight can be used to increase the range of existing airplanes. As we mentioned before, two 747-200F's flying in formation carry the same payload and have the same range as a BWB. Provided the retrofitting operation is not too expensive, this system would be perfectly adapted to air freight companies that have always preferred converting old airliners into cargo airplanes than buying brand new aircraft, in order to reduce the ownership costs.

D. Conclusion

The growing demand in both international and national air freight may now allow the development of an all-cargo airplane that would not be the freighter version of a passenger airliner. Several concepts are currently being developed.

The more advanced ones (Pelicans and HULAs) aim at revealing a middle air market and at taking market share from the ocean freight market by using new aircraft concepts that enable them to drastically reduce their operating costs.

Although they look promising, they are not the most dangerous competitors to our formation flight based system since they have not yet matured and do not target the whole air freight market.

In order to compete with more reasonable systems like the BWB, which combine high payload, long range and low operating costs, formation flight systems must achieve very low ownership costs. This can be done by retrofitting cargo aircraft to make them fly in formation instead of trying to apply formation flight to brand new aircraft.

References

[1] http://www.simplonpc.co.uk/Aurora_MaidenCruiseBreak
[2] http://www.speakeasy.org/~peterc/.../containr/shipng04.htm
[3] Boeing
[4] AeroVehicles, Inc.
[5] International Air Freight and Express Industry Study – Air Cargo Management Group (2003)
[6] AIAA 2000
[7] Air Cargo Operation Costs Database – Logistics Management Institute
[8] FedEx 2003 Annual Report
[9] IATA Freight Forecast 2002-2006