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9. Manual Control Theory Applied to Air Traffic Controller-Pilot Cooperation

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Reduced runway separation standards are among the means which have been proposed for increasing airport capacity. The probability of a blunder will dominate the calculation of safe separation standards. Then the determinant of safe system performance will be the system reaction time comprised of the air traffic controller's detection, decision and communication delays, and the response times of the pilot and aircraft in executing a collision avoidance manuever. Estimates of these times, based on existing data, show that the delays ascribable to the human portions of the man-machine system are comparatively unimportant. New developments in radar, computers, and data links will be required to provide any substantial improvement of the existing system, and the goal of 2500 ft of separation may not be achievable.

INTRODUCTION

By the summer of **1969,** in the United States, the growth of air carrier traffic and of operations by elements of the general aviation fleet had led to readily apparent distress and to certain dislocations with respect to the capacity of major airports and the functioning of the air traffic control system. Very lengthly departure delays were frequently encountered. In the eyes of some travellers, the matter seemed to approach the quality of a civil disaster when some members of the organized air traffic controllers staged a "sick out" in the middle of the summer. The peak travel period in the summer of **1970,** however, did not seem quite as bad. At the present time, the air carriers have cut back their schedules, the Boeing **747** aircraft (capable of carrying many more passengers per departure or arrival) have come into service in substantial numbers, and in some cases, such as at JFK International Airport, the imposition of high landing fees has discouraged air taxi operators and commuter airlines from using the airport. This has led, at least by comparison, to a breathing spell during which new solutions to the problems may be sought.

The problems, of course, are by no means entirely technological. The proposed solutions are increasingly subject to economic and particularly to political constraints. In the vicinity of New York City, for example, *every* proposed location for the "fourth" jetport has been opposed by some groups, and two of the locations considered promising by the Port of New York Authority have been defeated in voter referendums.

While clearly recognizing the often conflicting interests of airport developers and the airport's neighbors, the report of the Department of Transportation Air Traffic Control Advisory Committee (the Alexander Committee) (ref. **1)** says flatly:

> Air traffic is in crisis . . . major improvements in current airport capacity must be achieved. (Emphasis added)

In another place, the same report says:

> The conclusions reached on air traffic control for the **1980's** and **1990's** *assume* that runway capacity in the dense traffic areas will be provided. This is our present severe bottleneck, and the improvements to the ATC system discussed in this report will not *be* significant unless the airport (runway) problems are also resolved. (Emphasis added)

Further on, the report says, in part:

> . . . additional capacity can be provided by utilizing airport acreage more efficiently by decreasing the 5,000-foot separation between independent IFR runways. The Committee believes it will be possible to safely reduce

this separation between runways to **2,500** feet and the final spacing on approach to two mites. This will require **an** improved landing aid, such as the scanning beam microwave **ILS, as** *well as provisions for precise monitoring and data linked commands* in case **of** blunders.

At the present time, and for the forseeable future, the enforcement of safe separation standards will require the joint efforts of human air traffic controllers and pilots and will involve a geographically vast and technologically complex array of "machines" including radars, beacons, digital computers, displays, and communications, **as** well as aircraft with their primary and secondary flight control and propulsion subsystems. In short, the augmentation of runway capacity by means of reduced separation standards will demand the utmost performance of a truly named man-machine system. Faithful adherents of the '(Annual Manual," over a comparatively short period of time, have witnessed explosive development of a theory of manual control for at least certain problems in man-machine systems. We take it that manual control theory is understood to involve an abstraction of the performance of human operators in such a way as to allow an analysis of the relationship between the controller(s) and the "object of control." In particular, in our view, the abstraction and the analysis are mathematical. Can manual control theory contribute to the determination of safe separation standards for terminal area air traffic control? We propose in this paper to demonstrate that it can. It will, however, eventuate that the performance of the system with respect to separation standards is not critically sensitive to the performance of the air traffic controller and the pilot.

Determination of safe separation standards for operations on independent IFR runways may be influenced by consideration of an inordinately large number of *combinations* of system parameters and subsystem performances. Among these are

- Runway configurations
- Aircraft types (e.g., CTOL and STOL aircraft)
- Airborne equipment complement (e.g., flight director or automatic coupled approach)
- Gust, wind, and wind shear environment
- Data acquisition system capabilities (e.g., airport surveillance radar)
- The type of operation (e.g., front course or back course approach with or without simultaneous departures, etc.)
- The frequency of occurrence of blunders
- Controller intervention rules
- Controller response
- Pilot response

as well as, possibly, still other factors. We are unprepared to deal with all these factors in anything like an exhaustive fashion. Instead, we shall assume a prototype problem which will serve the primary purpose of providing a setting or background for considering the influence of controller and pilot responses on the performance of the system.

THE PROTOTYPE PROBLEM

Consider two conventional aircraft approaching an airport along parallel paths. These paths are separated laterally by a distance which is currently set at 5000 ft for 'independent" IFR operations. (Independent here means that no account is taken of any possible separation of the aircraft in a direction parallel to their tracks.) Because of gusts and wind shears, radio beam anomalies, spurious control actions, etc., the motion of each airplane is a random function of time which can be presumed to take place with respect to some mean or average motion which carried each aircraft toward its landing runway.

In the absence of better information, we can assume that the distributions of the three cartesian displacements and the corresponding velocities of each aircraft with respect to their mean paths are Gaussianly distributed and independent. This appears to be reasonable for small displacements and velocities, but it is generally conceded that the assumption will seriously underestimate the frequency of large deviations. This is because of the possibility of "blunders."

A blunder is a random process in the sense that its occurrence is probabilistic, but, for our purposes at least, where it occurs it is a single deterministic function of time. An example of a dangerous blunder would be a manuever which would place one of the approaching aircraft on a collision course with another.

A typical case of parallel approaches has the aircraft on extended runway centerlines **762** m (2500 ft) apart. Without air traffic controller intervention, in order for the variances of the time functions representing the random motions of each aircraft with respect to its mean motion to contribute as much as **1** percent to the overall probability of a collision, we have calculated that it would be necessary that any blunder occur less frequently than once in $\mathbf{7.787 \times 10^{17}}$ approaches. (This has been done by a method similar to the one given in references **2** and **3.** The exposition of the method is worth a paper in itself.) Another representation of this fact is that at the mean level of instrument approaches in the United States in the years **1964–1966** inclusive (6.16×10^5 instrument approaches per year), if blunders occurred more often than approximately once in a million years, the statistics with respect to blunders would completely dominate the determination of safe separation standards. We may easily believe and act on the belief that this is the case.

Given that blunders can and do occur, we wish to inquire as to the effect of air traffic controller intervention in maintaining the safety of operations.

In our prototype problem, we, therefore, assume that the progress of both of the airplanes on parallel approach paths is being monitored by a final controller using a display of secondary surveillance radar data. (This is currently the case at major airports). Where, on the basis of the information available to him, the final controller detects a violation of one aircraft's collision threat space by the other, he will issue a warning to one or both pilots. (We shall neglect, for simplicity, the probability that the controller does not detect the threat.) One or both pilots will then execute a collision avoidance maneuver. This will allow the system to be "safe" provided only that the parallel approach paths are sufficiently separated so that there is ***time*** for the controller to detect the threat, to communicate a warning, and for the pilot(s) to complete an avoidance maneuver. This time may be very considerable. The total time is called the system reaction time T_R. It has the following components:

- Data acquisition delays
- Data processing delays and uncertainty
- Controller decision delays
- Controller/Pilot communication delays
- Pilot effective reaction time delays
- Aircraft response delays as determined by its
  - Speed
  - Maximum rate of climb
  - Maximum bank angle.

In order to be able to place the controller's and the pilot's performances in perspective, we choose a particular example blunder scenario. This is illustrated in figure **1.** The numbers associated with the graph are choosen for convenience, but they are approximately representative. The aircraft are on "independent" parallel approach paths at the same altitude and separated by **1250** m **(4100** ft) laterally. (This latter is a little less than the current minimum separation, but it is rather more than what it is hoped can be achieved.) Each aircraft is proceeding at **61** m/sec **(200** ft/sec). At time $t=0$, aircraft ***A*** preceeds aircraft *B* by **488** m **(1600** ft). At that point in time, aircraft ***A*** initiates a postulated blunder, banking to an average bank angle of 35° for approximately **7** sec and then

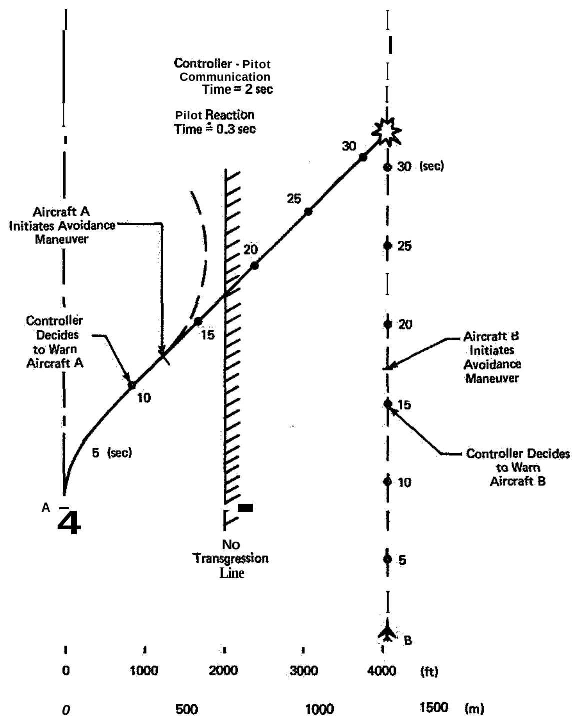

FIGURE 1.—A blunder scenario.

recovering to straight flight. The surveillance radar beam sweeps over the positions of both aircraft once every **5** sec. (The airport surveillance radar at JFK International Airport rotates **13** times per min.) Assuming that the beam has just passed both aircraft at $t=0$, the positions of both aircraft at 5 sec intervals, as they might appear to the air traffic controller, are indicated by the heavy dots in figure **1.** In the absence of controller intervention there will be a collision between the two aircraft at $t=$ **32** sec. Is there time in which to detect the threat, issue a warning, and have the innocent pilot and aircraft respond?

ESTIMATE OF THE SYSTEM REACTION TIME

In principle, without rate weighting, the average effective time delay in radar data, sampled once every **5** sec, is half the sampling period. We may, however, take a more pessimistic view with respect to the geometry of figure **1.** At $t=5$ sec the blunderer, aircraft ***A*****,** is only a little more than **76.2** m **(250** ft) off course. The data are somewhat noisy in any case and on the scale of the display this error would be nearly imperceptible to the controller. When the radar next determines the position of aircraft ***A*****,** it might be clear to the traffic controller that he should intervene. Conventionally (ref. 4), this is done so as to command aircraft ***A*** to turn away from the "no transgression line" perhaps established half-way between the approach paths. We shall shortly justify in more detail a figure of **2.3** sec for the time required for the controller to communicate a warning to the pilot and for the pilot to respond. Beginning at $t=12.3$ sec we have shown (dotted) in figure **1,** a compensating left turn by aircraft ***A*** which is similar but opposite to the turn which initiated the blunder. This, it may be observed, carries aircraft ***A*** well clear of the no transgression line.

But suppose that the pilot of aircraft ***A*** does not receive the warning, or for some reason fails to heed it. Because **of** the small displacement between the uncorrected and corrected tracks, this may or may not be evident to the air traffic controller at $t=15$ sec. We will presume, however, that he at least suspects the danger, and that he practically instantaneously decides to command a collision avoidance manuever for aircraft **3.**

What is a reasonable estimate for the controller decision and communication time as well as for the reaction time of the pilot of aircraft ***B?***

Data on which to base such an estimate are not abundantly available.

A lower bound for the estimate, however, might be discovered by reconsidering the two-operator tracking tests conducted by Russell (ref. 5). In these experiments a "director" observed a compensatory display of tracking error and gave verbal instructions to a "tracker" who then operated a handwheel control so as to null the error perceived by the director. The controlled element was a pure gain. The course or forcing function was a sum of four sine waves. Figure **2** is a replot of a sample of Russell's two operator data and the corresponding single operator data for the same tracker. The effective time delay, τ_e, for the single tracker is estimated, from a fit to the phase lag data, to be **0.2** sec. The two operators together seem to be characterized by a lag-lead describing function which includes a larger delay. If the phase angle contribution of the lag-lead characteristic is subtracted from the total phase Iag of the two-operator describing function, the residual phase lag corresponds to a time delay of 0.8 sec. This leads us to conclude that (exclusive of the tracker's delay) the *average* time delay ascribable to the director's decision and communication delays is:

$$\Delta\tau_{e_c} = \mathbf{0.6} \text{ sec.}$$

This estimate is rather neatly supported by the observation that, on the average, instructions from the director to the tracker were communicated 48 times per minute, or equivalently with an intersample interval of **1.25** sec. The effective *average* time delay is almost exactly half the sample interval. The nature of the instructions from the director in this case, however, was extremely simple, comprising a series of commands such as "left, left, right, right, right, left . . ." to each of which the tracker responded with standardized increments of control deflection. Furthermore, it may be that this continuous tracking experiment is not representative of what might be expected in the case of discrete events. Nevertheless, considering the necessity

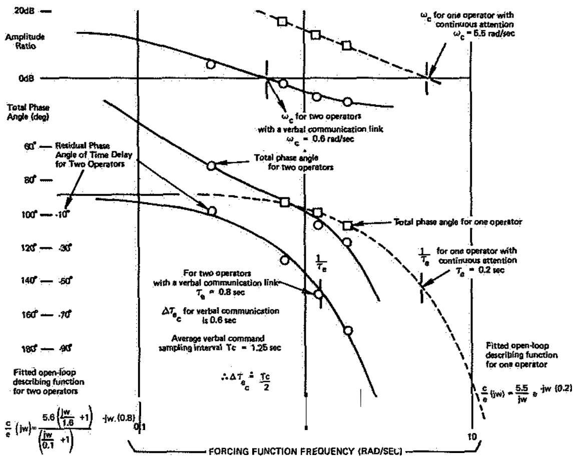

FIGURE 2.—Comparison of Russell's (ref. 5) measured open-loop describing functions for one- and two-operator tracking.

for more complicated messages and the fact that the message is not necessarily expected by, in the second case, the pilot, we might guess that in the case of air traffic control, the controller's decision and communications delay might be as little as two to three times the average decision and communications delay from the two-operator tracking tests.

One source of data on actual two-way transmissions between air traffic controllers and pilots is reference *6* which discusses several examples of two-way transmissions of nonurgent messages in which the time difference between the initiation of the message and the reply or acknowledgment is as little as **4** to *5* sec.

From this we conclude that the controller's decision and communication time, as it enters into our problem, is unlikely to be much less than **2** sec, nor more than **4.** We shall take **2** sec as representative. It would be interesting to measure controller's decision and communication times in simulator experiments if this has not already been done.

Assuming that the pilot of aircraft B is alert and that he knows that at approach altitudes, for an intrusion from the side, a pull-up and climb is the preferred avoidance maneuver; we ask: What are the response times of the pilot and the aircraft?

Figure **3** (taken from reference **7)** shows step reaction times for visual stimuli. It shows that

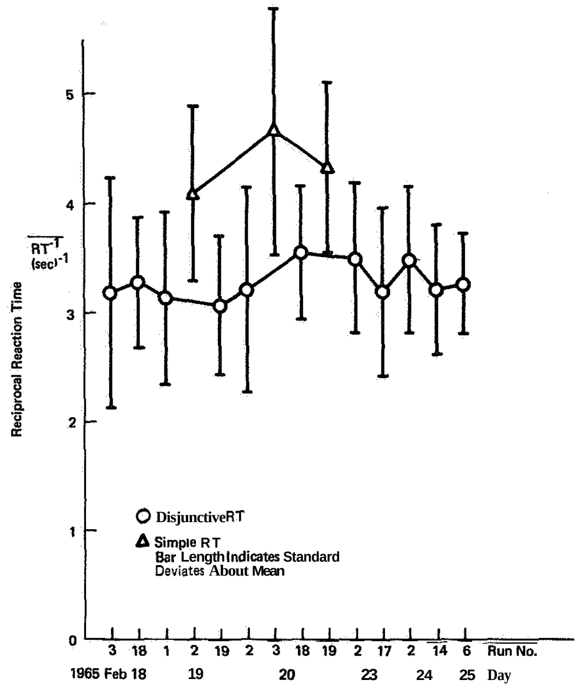

FIGURE 3.—Run-to-Run variability of the 20-trial step reaction time samples.

if the direction of the response is not known beforehand (disjunctive reaction time) the mean reciprocal reaction time is approximately 3^{-1} sec. In the absence of better information on step responses to aural stimuli we take as representative of the step response of the pilot of aircraft B to the warning of the controller a time delay of **0.33** sec.

The response of the aircraft to pilot control may be represented by a flight path response to pitch attitude commands. In transfer functions form this is

$$\frac{\gamma(s)}{\theta_c(s)} \doteq \frac{\exp(-\tau_\theta' s)}{T_{\theta_2}' s+1} \qquad (1)$$

where

τ_θ' = is the closed-loop system delay (a fraction of a second)

$T_{\theta_2}' \doteq \dfrac{2(W/S)}{g\rho U_0 C_{L\alpha}}$

$\dfrac{W}{S}$ = wing loading

g = acceleration of gravity

ρ = air density

U_0 = trimmed airspeed

$C_{L\alpha}$ = aircraft's lift curve slope.

The quantity T_{θ_2}' is often termed the flight path response time constant. Note how it depends on the aircraft's performance, notably on the wing loading and approach speed. Small time constants are, of course, desirable. For the DC-8, T_{θ_2}' is approximately *1.56* sec in approach. It is only about *0.5* sec for the Navion.

The minimum pull-up maneuvering time, following receipt of the climb command by the pilot, can be computed as the sum of the effective closed loop time delay, τ_θ' plus the time to establish the flight path acceleration $3T_{\theta_2}'$ plus the time to terminate the flight path acceleration $\tau_\theta'+3T_{\theta_2}'$ plus an interval of steady acceleration $(\dot{h}_c-\dot{h}_0)gn_{z_{max}}$. Here $n_{z_{max}}$ is the maximum normal acceleration in g units. It is limited in the case of interest here by the approach to a stall. In the form of a sum, the minimum pull-up maneuvering time T_m then becomes

$$T_m=2\tau_\theta'+6T_{\theta_2}'+\frac{\dot{h}_c-\dot{h}_0}{gn_{z_{max}}} \tag{2}$$

where

$\dot{h}_c$ = the rate of climb command

$\dot{h}_0$ = the initial rate of climb or descent.

The displacement *d* which can be achieved at time *t* after command of the pull-up maneuver and steady climb can be calculated with good approximation by assuming constant velocity U_0 and using the equation

$$d(t)=\dot{h}_c[u(t-T_m)]t+U_0\int_0^{T_m}\gamma(t)\,dt \tag{3}$$

where $\gamma(t)$, the aircraft's flight path angle, is the inverse Laplace transform of the product of equation *(1)* multiplied by the transform of the pitch attitude command θ_c, viz.,

$$\theta_c(s)=\dot{\gamma}_{z_{max}}\frac{1-e^{-T_s}}{s} \tag{4}$$

Here

$\dot{\gamma}_{c_{max}}=gn_{z_{max}}/U_0$

$T=\tau_\theta'+3T_{\theta_2}'+\dfrac{\dot{h}_c-\dot{h}_0}{gn_{z_{max}}}$

$u(\cdot)$ = unit step function applied at time (°)

$\tau_\theta'=\tau_\theta+\dfrac{2\zeta_{sp}'}{'}$

τ_θ = pilot's reaction time delay for a deterministic input ≐ 0.33 sec

ζ_{sp}' = modified aircraft short period damping ratio (modified by the pitch attitude feedback)

ω_{sp}' = modified aircraft short period natural frequency (rad^{-1}) (modified by the pitch attitude feedback).

For the case of a D G 8 going from an initial glide path sink of rate *−3.05* m/sec (*−10* ft/sec) to a steady rate of climb at +3.05 m/sec (*600* ft/min) (low, but convenient), substitution in equation (2) yields T_m = *10.35* sec.

A more elaborate calculation, which is capable of showing the effect of the steady climb after the T_m sec have elapsed, yields the results shown in figure **4.** Plotted there is the time required to reach a given displacement above an initially descending path. Note that the effect of the incremental load factor in the pull-up is comparatively small. The biggest effects are, of course, to be found in the steady rate of climb which may be achieved. This depends primarily on the thrust to weight ratio. The actual formula is

$$(R/C)=\frac{(T-D)U_0}{W} \tag{5}$$

where

(R/C) = rate of climb

T = thrust

D = drag

U_0 = aircraft velocity

W = aircraft weight.

In a missed approach pull-up, the drag is small compared to the thrust, and the climbout velocity is likely to be nearly the same for a variety of aircraft. The big differences between aircraft will

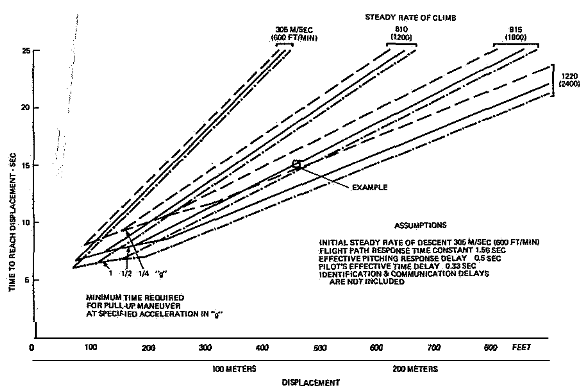

FIGURE 4.—Theoretical minimum time to reach a given displacement above the glideslope by a pull-up avoidance maneuver and steady climb.

then reside in their different thrust to weight ratios. This, of course, is one of the most important determinants of performance in many different respects, but we are not likely to see any spectacular improvements here because high thrust to weight ratios tend to make airplanes uneconomic.

Figure **4** may be used to estimate a lower bound on the elapsed time interval required to achieve, say, **140** m **(460** ft) of displacement above the glideslope, for example; if the maximum incremental acceleration is limited to one-half g and the final steady rate of climb is **1800** ft/min. By entering on the abscissa of figure **4** at **140** m **(460** ft), the time ordinate corresponds to the solid line for **9.15** m/sec **(1800** ft/min) (denoted by the square symbol). It may be read as **15** sec elapsed time. To this time interval following receipt of the climb command by the pilot must be added the ATC surveillance, identification, intervention, and communication delay. Thus, a typical overall latent period between the initiation of a lateral threat to an aircraft of the approach and achievement of **140** m **(460** ft) separation ***above*** the intruder is on the order of one-half minute or about one-quarter of the time required to fly from the outer marker to the middle marker.

The results are similar if we consider intrusions from above in which the most correct response is a lateral avoidance maneuver. Such a maneuver is the familiar side-step whereby lateral displacement is achieved by a double sinusoidal aileron command which recovers the original direction of flight. After achieving a safe lateral standoff, the pilot of the evading aircraft can then execute a missed approach.

Figure **5** (fig. 28 of ref. 8) shows the time required to achieve a given lateral separation by a double banking maneuver (X-turn). (Ref. **9** has shown that the approximate theory is confirmed by experiments with **14** aircraft flown by airline and professional test pilots.)

In Figure **5,** the maximum bank angle, φ_{max}, and the maximum roll rate, p_{max}, might possibly be somewhat altered and the results recomputed. The values assumed are typical, however.

We may use figure **5** to estimate a lower bound on the elapsed time interval required to achieve, say, **152** m (500 ft) of lateral separation if the

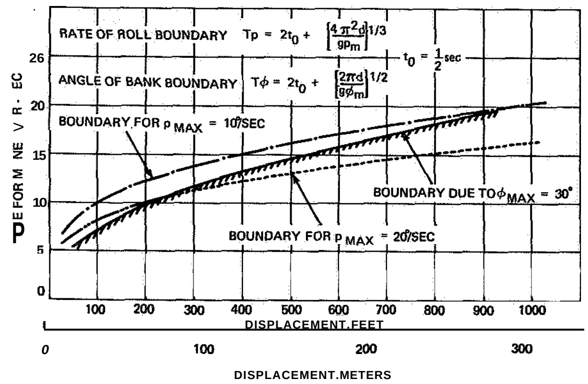

FIGURE 5.—Theoretical minimum times for sinusoidal maneuvers limited **by** rate **of** roll **(fig.** 28 of ref. 8).

maximum roll rate (p_{max}) is limited to 10 deg/sec. By entering the abscissa of figure **5** at **152** m **(500** ft), the time ordinate corresponding to the boundary for $p_{max} = 10$ deg/sec (denoted by the circular symbol) can be interpolated between **16** and **17** sec elapsed time for the maneuver. This value is seen to be similar to the one for the pull-up maneuver.

If the evasive maneuver were considered to be a turn away from the course and then flight in a straight line, the same separation distances would be achieved in somewhat shorter times. The improvement would not, however, be astounding. It appears that the pilot aircraft combination will typically require about **15** sec to achieve **152** m (500 ft) of lateral separation with aircraft as we have known them to be configured. Can anything else be done? Very large thrust to weight ratios, the availability of large amounts of direct lift control, and anything that would induce the pilots to use larger bank angles would help. No dramatic improvement in these factors, however, is likely to be brought about.

We have now seen that, at least for the choice of a miss distance of **140** to **152** m **(460** to **500** ft), either the side-step or the pull-up takes approximately **15** sec for typical values of the parameters for transport aircraft. Since we have also seen further above, that in connection with the prototype problem the effective controller's delay (including data acquisition (three scans = **15** sec) and communication delays **(2** sec)) is currently, perhaps, of the order of **17** sec, the total system response time T_R is likely to be approximately 32 sec. Thus, in our prototype problem, the system is "safe" at a runway separation of 1250 m (4100 ft), if a miss distance of 140 m (460 ft) is considered acceptable.

CONCLUSION

For a typical case of independent approaches to parallel runways, there is an appreciable probability of a blunder. The safe spacing of runways depends on making the system reaction time T_R sufficiently small so that adequate miss distances can be achieved between aircraft on collision courses when the air traffic controller must intervene.

The dominant effects are comprised within the times required to predict the impending collision and for the aircraft to respond to a collision avoidance maneuver command. Of the 32 sec system response time calculated in connection with the prototype problem, only 2 sec are ascribable to the controller's decision and communication delays, and only 0.33 sec to the pilot's response time. No effective improvement is to be expected from attempts to improve the performance of the human operators. The response time of the aircraft is likewise not readily amenable to improvement. The installation of track-while-scan (phased array) radars, and computer prediction of conflicts possibly based on down-link transmission of airborne sensor data could reduce the system reaction time by perhaps 5 sec. This would allow the runways to be safely spaced at 1036 m (3400 ft) in the prototype problem. The data linking of collision avoidance maneuver commands could possibly obviate the necessity for the 2 sec communication time we have allowed. This would then allow the runways to be separated by only 945 m (3100 ft). Further reduction in the spacing to the 762 m (2500 ft) called for in reference 1 would then be at the expense of miss distance in the event of a critical blunder.

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