JOURNAL OF AIRCRAFT
Vol. 37, No. 1, January–February 2000

Transportation Requirements for the Fast Freight Market

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The need to expand the space transportation market is identified, and the express package delivery market (fast freight) is presented as a potential application for space transportation technology. The fast freight market is characterized in terms of potential revenue, pricing, elasticity, cargo, and operational issues. The generic fast freight transportation mission is analyzed with respect to operational, range, speed, and turnaround time requirements. The analysis indicates that supersonic (Mach ~ 2) aircraft could be a practical fast freight system, whereas space transportation-based vehicles must meet stringent operational requirements to be competitive.

Nomenclature

A = parcel sender, originating terminal
B = parcel recipient, destination terminal
c_S = speed of sound, 573.5 kn
E_c = expected number of casualties resulting from a single vehicle flight
f_z = fraction of time zones that can be serviced by a fast freight system
g = standard unit of terrestrial gravitation, 32.174 ft/s^2 or 68,625.44 n mile/h^2
M = mean Mach number of fast freight vehicle
n_{AD} = normalized flight acceleration/deceleration, 0.15 g
n_F = fast freight vehicle flights per day
n_V = number of fast freight vehicles supporting a service route
R = flight range between fast freight terminals, 5,200 n mile
t_A = flight time to accelerate to cruise speed
t_C = flight time at cruise speed
t_D = flight time to decelerate from cruise speed
t_1 = time to convey parcel from customer's door to fast freight counter
t_2 = parcel waiting time for next available flight
t_3 = time to process parcel into payload container, 1 h
t_4 = time to load payload container into fast freight vehicle, 0.25 h
t_5 = time for vehicle to leave origin terminal A and execute takeoff, 0.475 h
t_6 = time for vehicle to travel distance between terminals A and B
t_7 = time for vehicle to descend, land, and park at destination terminal B, 0.475 h
t_8 = time to unload payload container from fast freight vehicle, 0.25 h
t_9 = time to segregate parcel from payload container, 1 h
t_{10} = time to deliver parcel from fast freight counter to recipient's door
t_{11} = time to fuel and maintain fast freight vehicle for next flight
Δt_C = counter-to-counter time
Δt_D = door-to-door time
Δt_T = terminal-to-terminal time
$\Sigma\ t_S$ = accumulated fixed timeline segments of fast freight service cycle, 3.45 h
$\Sigma\ t_T$ = accumulated fixed timeline segments of fast freight turnaround cycle, 1.45 h

Introduction

OVER the past decade, the aerospace community has become aware that continued growth of space exploration and of space commercial exploitation is faced with the following dilemma:

1) Expanded exploration and commercial development of outer space requires significant reduction in the cost of space transportation.

2) Such reduction is possible only with fully reusable space transportation systems.

3) These systems are inordinately expensive to develop.

4) To amortize the development of these systems, revenue from space transportation must increase.

In other words, a needed decrease in the recurring cost of space transportation is jeopardized by increased nonrecurring (amortization) cost.

Arising from an appreciation of this dilemma is the understanding that the available market for space transportation technology must be greatly expanded to provide a much larger financial base over which to amortize system development, hopefully to a degree that can realize net reductions in space transportation cost. Therefore, it is crucial to identify additional markets (beyond conventional space transportation), to which space transportation systems may be applied and from which revenue might be obtained, as a strategy that would permit the financing of advanced, fully reusable, space transportation systems.

One such possibility is express package delivery, or what we are calling here fast freight: the transportation of high-priority parcels over intercontinental distances in a few hours of time. As a point of comparison, current commercial services (e.g., Federal Express, United Parcel Service, DHL) may take 12 h or more to fly between Japan and the United States, resulting in delivery times ranging from 24 to 48 h (for example, a 7000-n mile flight from Osaka, Japan, to Memphis, Tennessee, will take 12 h, nonstop). As will be described, there may exist a large market for fast package delivery if these times can be reduced significantly. It is possible that high-speed vehicles incorporating technologies in common with reusable space transportation systems may be candidates to serve this market. It is, therefore, necessary to identify the criteria and requirements pertaining to this market to assess candidate vehicles.

This paper undertakes 1) to identify and characterize the fast freight market, as we understand it from our conversations with current delivery service vendors, 2) to analyze the requirements for efficient market service, with an emphasis on clarifying the value of speed in satisfying these requirements, and 3) to draw conclusions with respect to a preferred method for satisfying the fast freight market.

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Fast Freight Market Description

This section considers results of initial market research and an interview with a current vendor of express package delivery services.

Initial Research

Our initial research into the fast freight market focused on the following topics: market potential, market pricing, market elasticity, potential cargo, and operational issues.

Market Potential

Early insight into the potential of the fast freight market came from information provided by the Boeing Commercial Airplane Group (BCAG). In its 1998/1999 World Air Cargo Forecast, BCAG predicted a yearly growth rate of 18% in the international express segment of the international market.[1] This is shown in Fig. 1. As the total international cargo market more than triples over the next 20 years, the international express market will grow to six times its current size. By 2017, international express will represent approximately 36% of the total international market (~ 139 revenue tonne-kilometers/year). Note that the international express market is not synonymous with the potential fast freight market. Many international routes, such as London to Paris, are too short to justify a very-high-velocity vehicle such as the ones being discussed in this paper. It is, however, logical to assume that these encouraging international express growth rates would apply to the longer routes that are candidates for the fast freight market.

Market Pricing

The next step in understanding the market was a literature review followed by telephone contacts with international express carriers (including Federal Express and DHL). A key objective of this activity was to better understand the pricing of international express services. Though data does not exist to produce a curve of demand vs price, several points resulted from this line of investigation (circa 1996):

1) Express delivery from the United States to Tokyo takes two days and is priced at $70 for the first pound and $10 for each additional pound.

2) Overnight delivery to the United States from Europe costs $220 a package.

3) Same day delivery from Los Angeles to Tokyo (taking advantage of time zones) is priced at $365 for packages up to 10 lb.

4) BCAG sends urgently needed airplane parts worldwide, on the next available commercial flight, often for $300/lb.

The implication of the preceding statements is the following: If by 2017 the annual international express package delivery market is on the order of 139 revenue tonne-kilometer (RTK), i.e., 1.655×10^{14} lb-n mile/year, and a representative route distance is 5200 n mile (see the following requirements discussion), and a fast freight service could charge $10/lb, then the estimated annual market for this service could be on the order of $\$318 \times 10^9$.

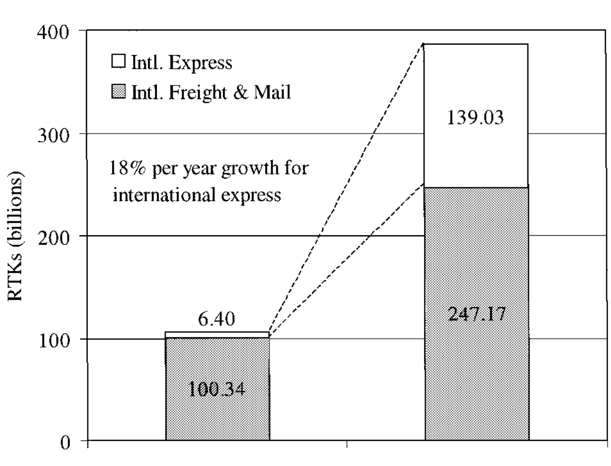

Fig. 1 Express delivery as part of international parcel market.[1]

Market Elasticity

Another key question was how much more customers would pay for improvements in delivery time. This is key to understanding how much more a carrier could charge for a fast freight service:

1) One express carrier stated that in markets where both one-day and two-day international delivery are available, customers pay 60% more for the one-day service.

2) One carrier offers express delivery service between New York and London on the Concorde. Customers transport their packages (often these are negotiable financial instruments) by helicopter to the airport, to be loaded into the Concorde minutes before take-off. These customers save approximately 4 h in delivery time, and are charged a 20% premium.

3) In cases of extreme urgency, customers may buy a round-trip ticket for a courier to transport a critical package on the next available (subsonic) commercial flight. Tickets such as these, purchased at the last minute, can cost $2000.

These examples indicate the potential utility of a fast freight service that could save a customer many hours on an intercontinental route.

Potential Cargo

Discussions with express carriers (including Federal Express and DHL) and express customers (such as BCAG) included the subject of what types of cargo would be most able to take the advantage of a fast freight service:

1) Delivery of replacement parts for out-of-service equipment was thought to be one of the most obvious potential markets. Sometimes a small part can put an entire assembly line out of commission, resulting in large losses in revenue. Obviously, several hundred dollars in fast freight costs would be well worth the expenditure if it could get a part to its destination several hours earlier than conventional methods. (For example, according to BCAG, canceling a scheduled commercial airline flight, while waiting for a part, can cost an airline on the order of $40,000.)

2) Financial securities for banks were felt to be another potential cargo category. Loss of a single day's interest due to delivery time can mean huge dollar losses. A fast freight service could make the difference.

Some of the industry sources were skeptical that there could be a large potential market for fast freight service. Others thought that such a capability would stimulate the creation of totally new markets. Examples they gave for future markets were delivery of transplant organs or of short-half-life radioactive materials, as yet uncharacterized markets that could not tolerate today's delivery speeds but that could take advantage of fast freight.

Operational Issues

As well as the opportunities that fast freight would present, several challenges were also identified:

1) If the time in air is drastically reduced by a fast freight vehicle, other delays may prevent full realization of these time savings (e.g., ground transportation or customs).

2) Frequency of departure must be high enough that the delay in waiting for the next flight does not negate the gains of high air speeds.

3) The fast freight network (number of cities served) must be extensive if a significant business base is desired.

Interview Research

After this round of data gathering, we analyzed a conceptual design of a fast freight system. This effort raised additional questions and motivated a visit to one of the major international express delivery companies for discussions with some of their senior management. What follows are the questions we asked and the answers they provided. Our interlineations are given in brackets.

Question: What would you estimate the demand for fast freight would be (in pounds per day) as a function of price (in dollars per pound)?

Answer: It is very difficult to predict the nature of the express mail market 10–15 years in the future, though it would seem that the push for faster delivery times would continue, making the issue of fast freight a question of when, not if.

The price the authors assumed for this analysis ($300/lb and 5500 lb/flight) is reasonable. Today, our highest quality international service commands a price of $150 per package for same day service (given time-zone effects).

Electronic media will continue to make documents a smaller and smaller percentage of the business. Two examples follow:

> [E.g., "A small U.S. company plans to inaugurate a new satellite-based delivery service in July in an effort to snatch business away from Federal Express, DHL, and other overnight carriers. Executives at A/E/C Express, a 30-person company in Scottsdale, Arizona, will use satellites to beam architectural blueprints around the United States. Company officials plan to expand their service to the Pacific Rim in late 1997 or early 1998. Their long-range goal is to grab up to 30% of the estimated $1.5 billion global market for overnight deliveries.[2]
>
> ... The new service will charge about the same as air-express services such as FedEx, typically $30 to $40 a package. But rather than overnight, A/E/C will complete its deliveries within four hours of copies being dropped off at local printers."[3]]

Companies with centralized inventories of high-value items would be prime customers for fast freight.

Addressing two markets with a "combi" vehicle that could carry cargo and people simultaneously might be a better way to introduce this service into operation. People have always been the "cargo" most interested in reducing transit times.

Question: What would be the day-to-day variation in demand? (The highest demand would be what percent more than the average? The lowest, what percent less?)

Answer: The maximum traffic day would have a demand of 20–25% more than the minimum demand day. (This relatively small variation in demand is good news in terms of vehicle oversizing. A vehicle sized to meet peak demand would still be quite full on minimum demand days.)

Question: Do we need to accommodate the maximum demand, or can we turn business away?

Answer: One might consider differential pricing and service (i.e., the more you pay, the greater likelihood it would go out on a fast freight shipment), as long as a customer understands this. What is not acceptable is to promise a certain time of delivery and not meet it.

Question: What would be the demand vs time-of-day profile? (Are two departures per day twice as good as one per day?)

Answer: The distribution of demand as a function of time of day is not known. However, increasing the number of flights per day would decrease the average wait until the next flight, which could not hurt.

Question: How would you make the best use of fast freight if it were characterized by 1) a limited number of hubs, 2) a limited number of daily departures (not designed for unscheduled emergency deliveries), and 3) did not deal with rest of the delivery timeline (customs delay, etc.)?

Answer: The best use of fast freight would be to integrate it into the existing network, using it as a premium service on the legs that it serves. It is probably unrealistic to assume that only businesses near a hub city would be customers.

A small number of departures per day would significantly limit its value to those who cannot schedule their demand to coincide with the departure schedule.

The increasing globalization of the economy might yield streamlining of customs processing.

Question: What would be the tolerance to flight delays or cancellations? (What is the case with current conventional aircraft?)

Answer: Customers are not at all understanding about delays in delivery.

Question: What would be the criteria for hub location?

Answer: Compatibility with current network.

Question: Would the hub need to be at a major commercial airport?

Answer: Not necessarily, though, if it were not, some way of getting packages to and from its location at reasonable speed and cost would have to be developed.

Question: Would wet lease be the preferred mode of operation? (Wet leasing is an arrangement whereby the aircraft lease includes maintenance services and, occasionally, operational services, as contrasted with dry leasing, which is limited only to the physical aircraft itself, with the lessee providing all required maintenance and operational services.)

Answer: Probably. We would not be interested in owning and operating these vehicles.

Fast Freight Transportation Requirements

This section considers the operational requirements imposed by commercial fast freight service, the likely range requirements for a fast freight vehicle, the influence of block speed on service time, and the requirements for vehicle turnaround time.

Fast Freight Operational Requirements

Operational requirements comprise all functional characteristics (other than flight range and cruise speed) required for vehicle compatibility with commercial fast freight service, as identified by current service vendors and as informed by our experience as a manufacturer of air transportation systems, that is, compatibility with existing commercial airports and airline operations, nonhazardous exoatmospheric operations, reliability, maintainability, operating environments, and payload accommodations.

Compatibility with Existing Commercial Airports and Airline Operations

Delivery service vendors have made it very clear that any fast freight vehicle must be compatible with commercial airline operations at existing commercial airports, that is, compliant with Federal Aviation Regulations (FAR) Part 135 (see Ref. 4). Their concern focuses on 1) minimization of capital investment required to integrate such vehicles into their operations, such as servicing infrastructure and personnel training and 2) obviation of any regulatory issues attendant on vehicle operation, particularly concerning operational certification and air traffic control. A summary of detailed requirements would include the following:

1) No element of the system, operating from a commercial airport, shall be loaded with propellants that constitute a potentially explosive combination. The air vehicle element shall not be loaded airborne with such propellants at altitudes below 10,000 ft.

2) The air vehicle shall operate at subsonic speeds when over populated territory.

3) The system shall comply with regulatory limits on emitted noise, for example, compliant with FAR Part 36, Subpart C, Section 36.201 "Noise Limits" (see Ref. 5).

4) Aerodynamic flight over populated territory (specifically during takeoff and landing at commercial airfields) shall be powered and piloted, and the pilot shall be equipped to communicate with applicable air traffic control environments.

5) The air vehicle shall possess 45 min of reserve powered flight capability at its scheduled destination.

6) The balanced field length for the air vehicle element shall be $\leq$10,000 ft.

7) With the exception of any required push-back movement from the cargo or passenger loading areas, the system shall be capable of providing its own motive power for taxiing onto the designated takeoff runway (or launch position) and for taxiing from its final position after landing to its required parking position at its destination. (Movement between loading areas and any servicing areas need not be self-propelled.)

8) Fuels or propellants shall be selected such that any spills or released vapors do not constitute an exceptional flammability, toxicity, or corrosion hazard.

Nonhazardous Exoatmospheric Operations

If the fast freight vehicle operates above the atmosphere (exoatmospheric), it must not constitute an unacceptable ballistic hazard to civilians in the event of propulsion or crew-support failures, and it must be susceptible to positive control of its trajectory at all times.

1) For planned or unplanned ballistic operation, the collective risk from a vehicle impact shall not exceed 30 casualties in 1×10^6 launches ($E_c \leq 30 \times 10^{-6}$). This criterion conforms to current practice with respect to space launch vehicles.[6]

2) The overall fast freight system shall have the capability to operate the air vehicle element remotely, at any time throughout its flight.

Reliability

High reliability of vehicle operation is indispensable to economic fast freight operations, not only because it is economically undesirable to experience the loss of a vehicle (and the prospective collateral damage and/or casualties), but also because any uncertainty in mission performance will undermine the perceived benefit of faster delivery. Accordingly, we would like to see the following:

1) The system probability of mission success, that the payload is delivered on schedule for a given flight, shall be no less than 0.999950, where "on schedule" may be defined as a delivery that is delayed by no more than 10% of the actual flight time. (For fast freight service to be credible to commercial users, we conservatively estimate that vehicle reliability must be sufficient to limit airframe losses to less than once in 10,000 flights, for example, corresponding to a year of system service at one round trip per day among 13 city pairs. This implies a mission success probability of at least 0.999900. However, to provide 90% confidence that this level will be achieved, the design requirement would have to be 0.999947. Failure to provide such a confidence level would leave the system vulnerable to early casualties, which could drastically erode user confidence. In any case, this is a significant concession to the immaturity of any fast freight vehicle based on space transportation technology; contemporary commercial aircraft typically are designed to a reliability goal of 0.999999999.)

2) The system dispatch reliability, that a given air vehicle will successfully initiate a scheduled flight, shall be no less than 0.985. (This is conservatively representative of current commercial airline dispatch reliabilities.)

3) All critical systems of the air vehicle, and any ancillary system elements required for airborne operation, shall be fault tolerant in the sense of a) fail operational for the first subsystem failure and b) fail-safe for the second subsystem failure.

Maintainability

This bears directly on the issue of recurring costs that presumably must be no greater for a fast freight vehicle than for the systems it would be replacing. This leads to the following maintainability requirements:

1) On average, the fast freight system shall require no more than 20 maintenance work hours per flight cycle.

2) The air vehicle shall not require scheduled overhaul more frequently than once per 25 flight cycles.

Operating Environments

Any fast freight system must be capable of operating in environments as severe as those experienced by contemporary air transportation (e.g., adverse weather, pressure and temperature extremes, precipitation, and gusts), to which must be added the environments unique to exoatmospheric flight if the vehicle operates exoatmospherically, for example, solar radiation, micrometeoroids, and cosmic rays.

Payload Accommodations

Provisional requirements would include the following:

1) The air vehicle shall carry $\geq$3000 lb (mass) of payload and shall provide a rectangular volumetric capacity of $\geq$300 ft^3 with a weight distribution not to exceed 750 psi at any location (this pressure limit primarily applies to point loads). The payload may be containerized. (The payload design value ordinarily would be the result of a detailed study of market traffic volume, load factor, and system flight rate.)

2) The payload shall be maintained in accordance with environments typical of contemporary airliner cargo holds.

Crew and Passenger Accommodations

A crew is required for reasons of operational safety in proximity to commercial airports, as already discussed. Accommodation of passengers is desired to partially exploit the high-priority travel market.

1) The air vehicle shall accommodate a) a pilot and a copilot and b) at least two passengers. Accommodations shall be provided for the range of bodily dimensions and weights between the 95th-percentile adult male and the 5th-percentile adult female.

2) Such accommodations shall be consistent with medical requirements pertaining to tolerable limits on vibration, acceleration, personal volumetric space, temperature, humidity, air pressure and composition, ionizing radiation, ambient illumination, and noise. (For example, if the air vehicle operates above approximately 60,000-ft altitude for the majority of its flight, both crew and passengers may be required to wear protective suits for survival of a cabin depressurization event.)

Fast Freight Range Requirement

To estimate the appropriate range requirements for a fast freight vehicle, we referred to the 1991 air traffic data appearing in Ref. 7 final report, summarized in Table 1, under the assumption that the fast freight market would be proportional to the aggregate air freight market. The cumulative mail tonnage distribution as a function of intercity distance is plotted for the top 25 city pairs in Fig. 2.

Table 1 1991 Air freight data from Ref. 7

Air freight city pairs	Distance, n mile[a]	Tons,[b] 1991	Cumulative tonnage[c]
London–Sydney	9,191	1,576	66,065
New York–Tokyo	5,867	3,662	64,489
Tokyo–London	5,169	2,039	60,827
London–Johannesburg	4,896	1,344	58,788
Tokyo–Frankfurt	4,802	1,483	57,444
Frankfurt–Hong Kong	4,751	2,225	55,961
Tokyo–San Francisco	4,470	3,366	53,736
Seattle–Tokyo	4,160	2,039	50,370
Frankfurt–Chicago	3,871	3,152	48,331
New York–Rome	3,730	3,477	45,179
Frankfurt–Washington, DC	3,671	2,828	41,702
New York–Frankfurt	3,494	6,675	38,874
New York–Madrid	3,421	1,762	32,199
Tokyo–Honolulu	3,354	2,132	30,437
New York–Brussels	3,183	1,576	28,305
New York–London	3,012	6,351	26,729
New York–Paris	2,982	3,894	20,378
Frankfurt–Teheran	1,853	1,483	16,484
Tokyo–Manila	1,626	1,298	15,001
Tokyo–Hong Kong	1,542	2,735	13,703
Tokyo–Guam	1,318	2,039	10,968
Tokyo–Seoul	622	2,272	8,929
Frankfurt–London	544	2,596	6,657
Hong Kong–Taipei	415	2,086	4,061
Chicago–Toronto	380	1,975	1,975

[a] Great circle distance between city pairs, based on published geographic coordinates.[8]
[b] Values are scale interpolated from the reference data.
[c] Tonnage is accumulated from shortest- to largest-distance pair.

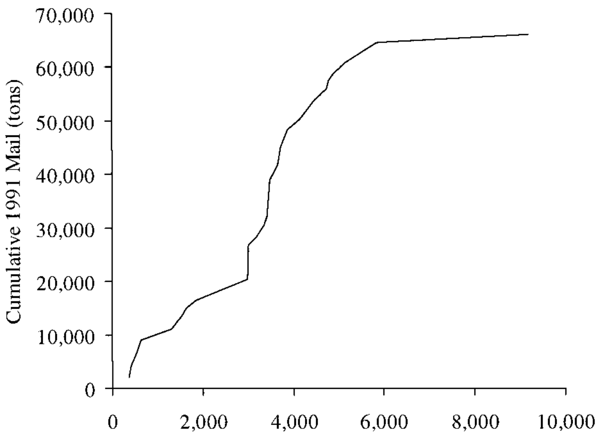

Fig. 2 Cumulative 1991 tonnage vs city pair distance.

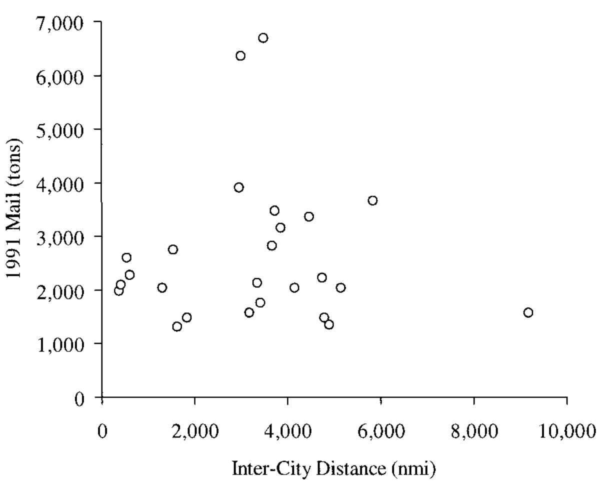

Fig. 3 Tonnage for 1991 vs city pair distance.

From inspection, clear breaks in this market sample occur at approximately 3000 and 5000 n mile with 64.0% of the sample being captured between these ranges. This includes city pairs from London–Johannesburg (4896 n mile) to New York–Paris (2982 n mile). If Tokyo–London (5169 n mile) is included, the market capture would increase to 67.1%. We, therefore, propose a nonstop range capability of 3000–5200 n mile as being an appropriate requirement for a contemporary fast freight service. (We have made the assumption that intercity distances of less than 3000 n mile are not large enough to merit fast freight service. If this assumption is relaxed to 1000 n mile the sample capture can increase to 78.6%.)

The validity of this requirement is reinforced by discrete examination of city pair traffic tonnage vs intercity distance, as shown in Fig. 3. Few city pairs lie beyond the 5200 n mile range limit, and those that do constitute only a small portion of the market sample. Increasing the maximum range requirement to 6000 n mile would improve the sample capture by only 5.5% (inclusion of New York–Tokyo). The extreme long-distance city pair (London–Sydney, at 9191 n mile) represents only 2.4% of the sample.

It is possible that more recent data may show growth in existing air freight routes, or the introduction of new routes as leading high-volume routes (most likely trans-Pacific). However, we do not expect that such new data would significantly alter fast freight range requirements. In the first case (growth in existing routes), growth would occur in routes already captured by the 3000–5200 n mile requirement. In the second case (prominence of new, trans-Pacific routes), ranges would vary from 4000 to 5000 n mile, which also are captured by the proposed requirement. (The arc from Tokyo to Los Angeles, for example, is 4764 n mile.)

Fast Freight Block Speed Requirement

To understand the parametric sensitivities of a simple example of fast freight service, we modeled a direct-route service concept, in which both the sending customer and the parcel recipient were located in proximity to the terminals of a two-way fast freight service. Two varieties of service were examined: overnight delivery, in which the parcel arrival is synchronized with the recipient's workday, and as soon as possible (ASAP) delivery, in which the parcel must reach the recipient ASAP in response to an unscheduled need. For each service, the modeled timeline is the recipient's estimated wait from parcel submittal to parcel delivery. This discussion will develop the basic equation for fast freight service delay, then will apply the equation to develop requirements for overnight and ASAP deliveries.

Basic Service Delay Equation

The delivery process was analyzed in the timestep sequence t_1–t_{10}.

(Note that the waiting time t_2 is not considered part of the timeline for the overnight-delivery market, where it is assumed that customers deliberately synchronize their parcel submittals to the departure schedule of the fast freight service.)

We distinguish among three measures of transit time, terminal-to-terminal time Δt_T, counter-to-counter time Δt_C, and door-to-door time Δt_D, defined as follows:

$$\Delta t_T \equiv t_5 + t_6 + t_7 \tag{1}$$

$$\Delta t_C \equiv t_2 + t_3 + t_4 + \Delta t_T + t_8 + t_9 \tag{2}$$

$$\Delta t_D \equiv t_1 + \Delta t_C + t_{10} \tag{3}$$

For purposes of obtaining insight into the value of speed for fast freight service, we judged the counter-to-counter time Δt_C to be the most relevant metric, for the following reasons.

Terminal-to-terminal time Δt_T, despite being most sensitive to the raw speed potential of a fast freight air vehicle, does not include the fixed time elements of the service ground operations that customers correctly perceive to be as important as flight time. We, therefore, conclude that Δt_T is an incomplete measure of fast freight performance.

Door-to-door time Δt_D, despite being the most complete representation of service time, is only Δt_C to which has been added a variable delay time that is 1) independent of fast freight vehicle selection and 2) dominated by user-specific details, for example, distance from user to terminal, mean speed of street traffic, and occurrence of random delays. We, therefore, conclude that Δt_D is an uncertain measure of fast freight performance. (This uncertainty is particularly relevant to the problem of customs delay that can range from hours to days depending on the destination point. Because an adverse customs processing environment is inherently inimical to the fast freight concept, we have assumed that a practical accommodation must occur for the concept to be realized and that the associated time interval should be reflected in Δt_D.)

Consequently, selection of Δt_C includes all delays relevant to the performance of the fast freight service proper and disregards delays over which a fast freight service either has no control, or that cannot be modeled accurately for all customers. Accordingly, we can summarize Δt_C by

$$\Delta t_C = t_2 + \sum t_S + (R/c_S M) + (c_S M/n_{\mathrm{AD}} g) \tag{4}$$

in which the first term is the customer's average waiting time ($t_2 = 0$ h for the overnight-delivery market and $t_2 = 12/n_F$ h for the ASAP delivery market, where n_F is the daily flight departure rate from a fast freight terminal).

The second term accumulates all of the fixed time segments in the service cycle, for example, $\Sigma\ t_S = t_3 + t_4 + t_5 + t_7 + t_8 + t_9 = 3.45$ h. This value is a rough estimate, based on plausible assessments of the timeline components, 1 h to process parcels into and out of a payload container (t_3, t_9), 15 min to load the payload container into and out of a fast freight vehicle (t_4, t_8), and a mean time of 28.5 min to leave from or arrive at a route terminal (t_5, t_7). This latter time is composed of the following estimated segments, based on personal observation of contemporary airline operations: 6–12 min for pushback from terminal, 12–18 min for taxi to runway position, and 3–6 min hold for clearance. The arrival timeline is assumed to be symmetrical. The precise value of $\Sigma\ t_S$ is not crucial to the development of the results of this analysis because it serves only to adjust the value of Δt_C upward or downward without affecting its dependence on block speed Mach number.

The third term represents the cruise portion of the flight time. The speed of sound is approximately constant at 573.5 kn between the altitudes of 36,000 and 83,000 ft that we assume here to be typical of fast freight vehicles operating over a wide range of supersonic Mach numbers.[9]

The fourth term represents the acceleration–deceleration portion of the flight time, as developed in the Appendix. Current subsonic transport aircraft typically perform with $n_{AD} = 0.05\ g$. Analysis of high-speed supersonic fighter aircraft suggests that advanced high-speed aircraft might achieve $n_{AD} = 0.15\ g$. This latter value will be used in the results developed later.

Overnight Delivery Market Requirement

The overnight-delivery scenario consists of a customer at location A, who has prepared a parcel at the end of the working day and desires to deliver it to a recipient at location B, who is to receive it at the beginning of the next working day. The question becomes: What is the time interval that satisfies the requirement for overnight delivery? The answer to the question depends on how strictly we wish to interpret the delivery requirement.

Strict rule. We interpret the requirement to mean that delivery must occur precisely at 0800 hrs local time. Let us assume that the local working day, worldwide, is from 0800 hrs to 1700 hrs. It therefore follows that if customer A and recipient B are in the same time zone, overnight delivery requires ≤15 h. If recipient B is located one time zone eastward, this will decrease to 14 h. Eventually, if recipient B is located 15 h eastward, the overnight delivery would have to be instantaneous, which, of course, is impossible. At this point, one must wait 24 h for the next opportunity to deliver at the beginning of recipient B's working day. Thus, as we consider all possible recipients, it follows that the overnight requirement can range from 0 to 24 h, depending on the time zone separation between A and B. (Time zone separation does not always correlate with distance: polar routes can cover an arbitrary number of time zones over distances of only a few thousand nautical miles.) This requirement is illustrated in Fig. 4. We can then define the fraction of time zones, f_z, that can be served by a fast freight system as $f_z = 1 - \Delta t_C/24$, which is plotted in Fig. 5.

Relaxed rule. We interpret the requirement to mean that delivery may occur at any time during the local working day. We revisit

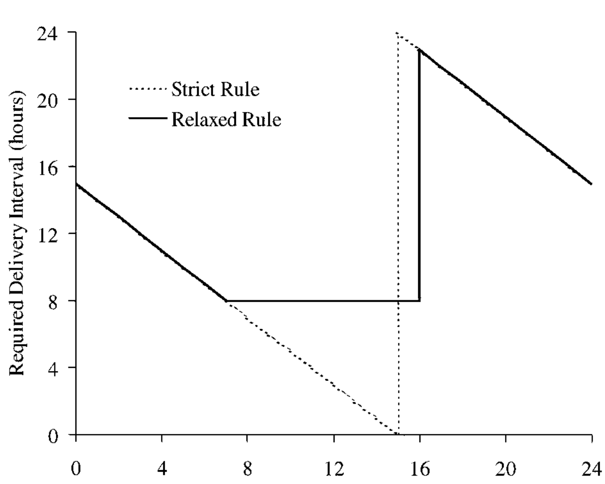

Fig. 4 Overnight delivery requirement.

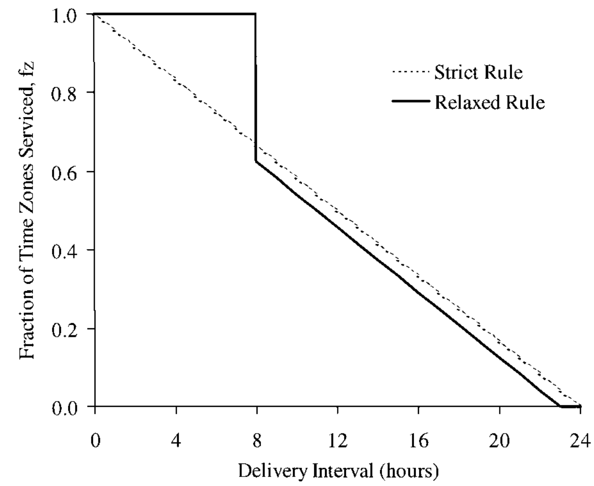

Fig. 5 Effect of overnight delivery rules.

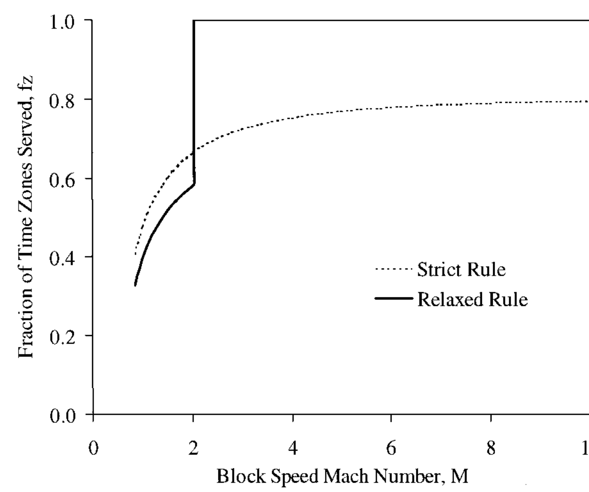

Fig. 6 Overnight delivery performance (*R* = 5200 n mile).

the preceding analysis, to note that if recipient B is seven time zones eastward, the delivery time is 8 h. However, if recipient B is located eight time zones eastward, we can still deliver in 8 h. but will arrive 1 h late at 0900 hrs local time. In all likelihood, this would be acceptable, compared to the alternative of waiting until the following morning. Similarly, if we progress eastward 16 time zones (the equivalent of progressing westward eight time zones), we will arrive at the end of the recipient's working day, but this working day is very nearly the same day that the package was sent (a real-time delivery delay of only 8 h), and so it is likely to be an acceptable performance compared to an extra day's wait. This means that 10 of 24 time zones (7–16 h east) can be satisfied with 8-h minimum delivery times (see Fig. 4), leading to a discontinuous function for f_z, as $\Delta t_C \leq 8$ h, $f_z = 1$; 8 h $\leq \Delta t_C \leq 23$ h, $f_z = (23 - \Delta t_C)/24$; and 23 h $< \Delta t_C$, $f_z = 0$. This is graphed in Fig. 5 as a function of Δt_C. Clearly, the relaxed rule shows a decisive benefit for low values of Δt_C ($\lesssim$8 h).

Using the basic delay equation for Δt_C, we can plot similar results for f_z as a function of M, shown in Fig. 6 (where the initial point on each curve corresponds to $M = 0.85$, representative of current subsonic transport aircraft performance). From inspection, we draw two conclusions:

1) The strict rule interpretation of f_z results in a performance curve (Fig. 6) whose knee visibly occurs near $M = 2$. (Because of the growth of the fourth term in Δt_C as M increases, f_z reaches a maximum of 0.797 for $M = 12.7$–12.8. To obtain 90% of that value, we require only that $M = 2.85$; for 80%, we require that $M = 1.76$.) An increase or decrease of the fixed-time portion of Δt_C would only move the curve in the vertical scale, by $\frac{1}{24}$th the amount of change

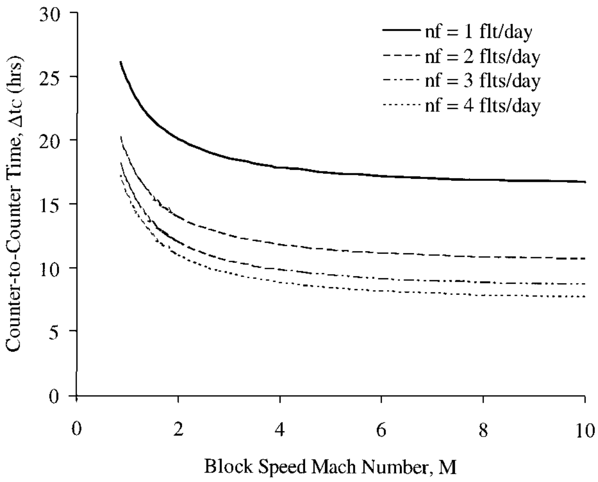

Fig. 7 ASAP delivery performance (R = 5200 n mile).

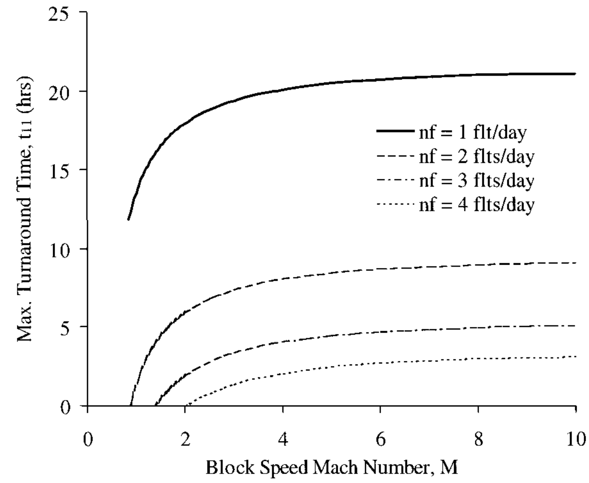

Fig. 8 Turnaround time requirement (R = 5200 n mile, n_V = 1).

in the term $\Sigma\ t_S$, and the knee of the curve would not change with respect to M. An increase of the flight range to 6000 n mile would elongate the curve in the direction of higher Mach numbers, by a factor proportional to $R/24c_S$ (which would be +15.4%). This would place the apparent knee of the curve nearer $M = 2.3$. No perceptible improvement in delivery performance occurs for $M > 4$.

2) The relaxed rule interpretation of f_z results in a performance curve that discontinuously jumps to unity at $M = 2.044$, beyond which increased speed provides no benefit.

ASAP Delivery Market Requirement

This delivery scenario consists of a customer at location A, who discovers an urgent requirement to ship a parcel to recipient B, who must receive it ASAP. In this case, the counter-to-counter time Δt_C is the relevant performance parameter, where the waiting time t_2 is included explicitly. This delivery time is graphed in Fig. 7, where the initial points on the curves again correspond to $M = 0.85$ (current subsonic airliners) and n_F varies from one to four flights per day. From inspection, we draw two conclusions:

1) The knee of the curve occurs near $M = 2$, regardless of the value of n_F. No perceptible improvement in delivery performance occurs for $M > 4$.

2) The influence of n_F on Δt_C is significant, comparable to the influence of Mach number. In fact, if one evaluates the derivatives of Δt_C with respect to Mach number and number of flights per day, one obtains $\mathrm{d}\Delta t_C/\mathrm{d}M = -(R/c_S M^2) = -9.07/M^2$, and $\mathrm{d}\Delta t_C/\mathrm{d}n_F = -(12/n_F^2)$. Thus, by comparing the square roots of the magnitudes of the coefficients, we conclude that n_F is actually 15% more influential than Mach number alone in reducing counter-to-counter time for ASAP delivery. However, the benefit appears to saturate for $n_F > 4$.

We can now begin to assess the standing of different solutions to the ASAP delivery fast freight problem. Consider, for example, a high-speed civil transport (HSCT), which is a supersonic passenger airliner designed for intercontinental travel (typically, $M = 2.4$). An HSCT would result in $\Delta t_C = 10.36$ h, at $n_F = 4$ flights/day. To match this performance at a reduced flight rate ($n_F = 3$ flights/day), the block speed requirement would increase to $M > 3.33$. To better this performance by 10% at a reduced flight rate ($n_F = 3$ flights/day, $\Delta t_C = 9.32$ h), the requirement would increase to $M > 5.9$. In other words, by comparison to HSCT performance levels, drastic increases in vehicle speed are required to produce marginal improvements in average delivery time.

Turnaround Time Requirement

To this point, we have considered the performance of a fast freight service only as it is experienced by the customer. Other requirements emerge if we consider the internal performance of a fast freight service, particularly the requirement on air vehicle turnaround time, that is, the time required for essential vehicle servicing and maintenance between flights. The air vehicle operational cycle (as distinct from the delivery process), was analyzed into the timestep sequence t_4–t_8 and then on to t_{11}, where the constituent time elements are defined as for the earlier analysis, except that here the turnaround time t_{11} has been introduced.

Because the duration of the operational cycle is simply the sum of these constituent time elements, it follows that this cycle must be no greater than some integer multiple of the interval between flights, as

$$t_4 + t_5 + t_6 + t_7 + t_8 + t_{11} \leq 24 n_V / n_F \tag{5}$$

where $(24/n_F)$ is simply the time interval (in hours) between flights and n_V is the number of fast freight vehicles supporting the route. (If $n_V = 1$, then the air vehicle must turn around quickly enough to perform the immediate return flight. If $n_V = 2$, then an air vehicle can lay over for one flight, while its partner vehicle makes the return flight, thus allowing the air vehicle's cycle time to be twice $24/n_F$.)

Based on the block speed requirements analysis, we can solve for t_{11}, to obtain

$$t_{11} \leq (24 n_V / n_F) - \sum t_T - (R/c_S M) - (c_S M / n_{\mathrm{AD}} g) \tag{6}$$

where we define $\Sigma\ t_T \equiv \Sigma\ t_S - t_3 - t_9 = 1.45$ h. (Vehicle servicing operations could overlap time segments t_4 and t_8, in which case $\Sigma\ t_T$ would have an effective value of 0.95 h.) The results for $n_V = 1$ (a single air vehicle servicing the flight rate) are presented in Fig. 8. From inspection, we draw two conclusions:

1) Again, the knee of the curve occurs near $M = 2$, with some sensitivity to the value of n_F. (As n_F increases, curve truncation at $t_{11} = 0$ forces the knee of the curve toward $M > 2$.) No significant improvement in allowed turnaround time occurs for $M > 4$.

2) The value of n_F strongly influences the required turnaround time, to a degree that enforces minimum Mach numbers for $n_F > 1$.

This requirement imposes severe operating constraints on different solutions to the fast freight problem. To consider the earlier example of an HSCT ($M = 2.4$) operating at 4 flights/day, the required turnaround time is ≤ 0.638 h (less than 38 min), which appears consistent with contemporary commercial airline service. A higher speed design solution (e.g., $M = 3.33$, as from the preceding discussion) operating at 3 flights/day would need to meet a maximum turnaround time of 3.64 h that may be difficult to accomplish if advanced propulsion systems and propellants are employed. (This high-speed requirement can be relieved by allowing $n_V = 2$, but a doubling of the service fleet is unlikely to prove economical.)

Conclusions

We believe the following findings are supported by our research and analysis:

1) As a candidate transportation market to which space transportation technology might be applied, express package delivery

(fast freight) offers a potential revenue estimated (at minimum) as hundreds of billions of dollars per year.

2) Integration of this service into the existing network of package carriers requires that any fast freight air vehicle be compatible with commercial airport facilities and operations.

3) If new ground infrastructure is required, it must be established at each operating site. This should not be an exceptional cost for a kerosene-fueled, air-breathing system.

4) Fast freight performance requirements are achieved for block speeds of Mach 2–4.

5) To be competitive with supersonic aircraft, vehicles using space transportation technology must demonstrate turnaround times of <5 h.

We, therefore, conclude that a fast freight service could successfully be accomplished with near-term supersonic (Mach ~2) aircraft and that higher-speed, space launcher-type solutions may not demonstrate significant mission benefits. The impressive economic potential of the fast freight market appears to be poorly matched to the objective of developing dual-use space transportation technology.

Appendix: Development of Acceleration–Deceleration Time

We assume a flight profile consisting of an initial constant acceleration phase at some acceleration a, an intervening cruise phase at some constant velocity v, and a final constant deceleration phase at the same acceleration a, all conducted to traverse a flight range of R. We can further describe these variables with

$$a = n_{\mathrm{AD}} g, \qquad v = c_S M$$

First, we evaluate the condition wherein the flight speed is so high, it is attained only momentarily, that is, the flight is occupied mainly with acceleration and deceleration. The time to the halfway point ($t_{1/2}$) is found from $\frac{1}{2}R = \frac{1}{2}at_{1/2}^2$. We know also that the maximum speed ($v_{\max}$) will be found from $v_{\max} = at_{1/2}$. On substitution and rearrangement, we can solve for $M_{\max}$ as $M_{\max} = (R\, n_{AD} g)^{1/2}/c_S$. For $n_{\mathrm{AD}} = 0.15\, g$ (approximately three times greater than that of current subsonic transport aircraft) and $R = 5200$ n mile, we obtain $M_{\max} = 12.76$, which is sufficiently high that analysis results for $M \leq 10$ should be consistent with this accelerate–cruise–decelerate representation. (For $R = 3000$ n mile we obtain $M_{\max} = 9.69$.) Note that no system solutions are possible (i.e., definable) for $M > M_{\max}$. Therefore, we assume in the following that $M \leq M_{\max}$.

To compose the general case for the flight time t_6 we have

$$t_6 = t_A + t_C + t_D \tag{A1}$$

where t_A, t_C, and t_D are, respectively, the time elements associated with acceleration, cruise, and deceleration, found from

$$t_A, t_D = c_S M / n_{\mathrm{AD}} g \tag{A2}$$

$$d_A, d_D = \tfrac{1}{2} n_{\mathrm{AD}} g t_A^2 \tag{A3}$$

$$t_C = (R - d_A - d_D)/c_S M = (R - 2d_A)/c_S M \tag{A4}$$

where $c_S M$ is a common denominator, d_D is the associated distance traversed while accelerating/decelerating, and t_C is found from flying the flight range less the acceleration/deceleration distances at the cruise Mach number. On substitution and rearrangement, we obtain

$$t_6 = (R/c_S M) + (c_S M / n_{\mathrm{AD}} g) \tag{A5}$$

For the cases analyzed ($R = 5200$ n mile), we can neglect the second term with small resulting error. (This may not be true for shorter range flights, where acceleration/deceleration can be a significant portion of t_6.)

Acknowledgments

The authors wish to thank David F. Pierce of Boeing Commercial Airplane Group for provision of air cargo market statistics and Malcolm J. Phillips of Boeing Commercial Space Company for reference to acceptable flight risk requirements.

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