# Development of a Global Fast Package Delivery System (From Idea to Concept)

by

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Submitted to the Department of Aeronautics & Astronautics
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## ABSTRACT

Fast Package Delivery is the delivery of packages over intercontinental distances in a significantly shorter time than existing air express delivery, by utilizing space or high-speed aviation systems.

Several modes of operation were analyzed. Two concepts which represented the extreme ends of all the operating possibilities, namely Scheduled and On-Demand flights, were pursued simultaneously to assess their relative merits, in terms of commercial value. Market, system requirements and operating costs were addressed in order to achieve this end.

The study found that the Scheduled Service could be fulfilled by a Mach 2 airplane, while a Mach 6 ramjet was better suited to On-Demand Service. An optimum concept, in which revenue is maximized, was found between the two.

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Most of all, I wish to thank my heavenly Father for blessing me with strength and health through all the late nights. To Him I owe everything.

# 1. INTRODUCTION

## 1.1 Definition

Fast Package is the delivery of high priority packages over intercontinental distances in a significantly shorter time using space or high-speed aviation systems.

Examples of the types of systems considered for this mission are shown in Fig. 1-1.

## 1.2 Objective

The objective of this thesis is to discuss the development of a Fast Package system from an abstract idea to a design concept. It is not the intention to dwell on any particular subsystem. Given the short time available to this work, the author felt it was more beneficial to study the broad ranging system issues which are critical for its implementation. Although the idea of Fast Package is not new, little is yet known about the key issues required to implement it. This is surprising since several developers of future reusable launch vehicles have cited Fast Package as a possible application of their system, without knowing fully what is required for Fast Package. This is the motivation for this thesis - to provide further insight into this problem. By understanding the key system issues, the future viability of Fast Package can be better assessed.

The system issues discussed include the potential market, business case, the mode of operation, flight regulations as well as technology.

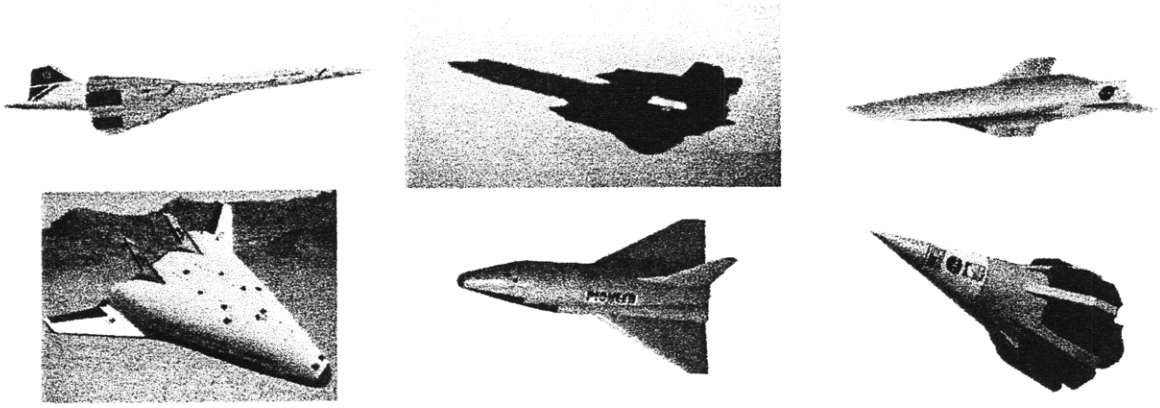


**Fig. 1-1: Space & High Speed Aviation Systems.**

## 1.3 Background

Express Package Delivery

Fast Package is an improvement over the existing express package delivery. Express package delivery, in today's context, means same business day delivery or overnight delivery for domestic destinations, and not longer than three working days for international destinations. The packages are typically transported in subsonic airplanes.

In addition to the delivery of perishable items and time-sensitive business documents, a rapidly growing need for Express Delivery stems from businesses wanting to reduce their inventory and warehousing costs while still meeting the customers' just-in-time supply demands. In today's competitive market, the tolerances for just-in-time are in the order of four hours [1]. In some hi-tech companies, the loss due to disruption in the production line can amount to $200,000 per hour [2]. One the other hand, the inventory cost can be so enormous that some businesses find it cheaper to purchase their own aircraft to rush the parts out to the customer when needed [2].

Businesses are now conducted on an increasingly global level. US businesses now need to respond to customers as far away as South East Asia. Due to current flight time, international express freight deliveries take from one to three days. Hence US businesses are forced to spend the extra inventory cost in order to provide just-in-time service to their global customers.

Finally, the cargo industry claims that customers are willing to pay 3-6% of the product's value on transportation [3]. This presents new possibilities for "first-class" delivery of high-value commodities, such as microcircuits, precious stones, and high-end electronic devices.

Fast Package Delivery

In contrast to the current express package delivery, Fast Package delivery can offer significantly shorter delivery times by exploiting the latest aerospace technologies. Nearly 40 years ago, on 8 June 1959, the submarine USS Barbero fired a rocket propelled guided missile (Fig. 1-2), carrying 3000 letters, at the Naval Auxiliary Air Station in Mayport, Florida [6]. A postal officer at that time remarked, "Before man reaches the moon, mail will be delivered within hours from New York to California, Britain, India or Australia by guided missiles."

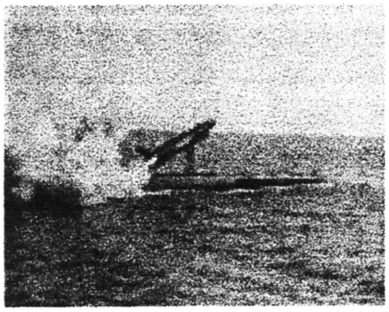


**Fig. 1-2: Missile Mail**

"Missile mail" was never put into commercial operation because of the high cost resulting from having to use a new missile for each flight. However, the space industry is currently at the next stage of evolution in reusable launch vehicle technologies. As these systems begin to provide robust operational characteristics, and low recurring cost, the idea of Fast Package was rekindled. Fast Package was one of the missions addressed in the 1994 Commercial Space Transportation Study (CSTS) [3]. The concept was further investigated at Boeing by Andrews [4] in 1997. More recently, Robert Zubrin of the Pioneer Rocketplane cited Fast Package Delivery as one of the applications for Rocketplane [5]. Last but not least, Fast Package Delivery is also part of NASA's Future-X strategy for space transportation technology development.

The CSTS addressed the market and requirements for such a vehicle. If made to work, it will have the highest flight rate among the various types of commercial space transportation. The demand will, however, be sensitive to the price because of the much cheaper (but slower) air freight cost. The key system requirement highlighted was a high delivery reliability, meaning the package will be delivered to the intended destination on time with a high degree of confidence (95%).

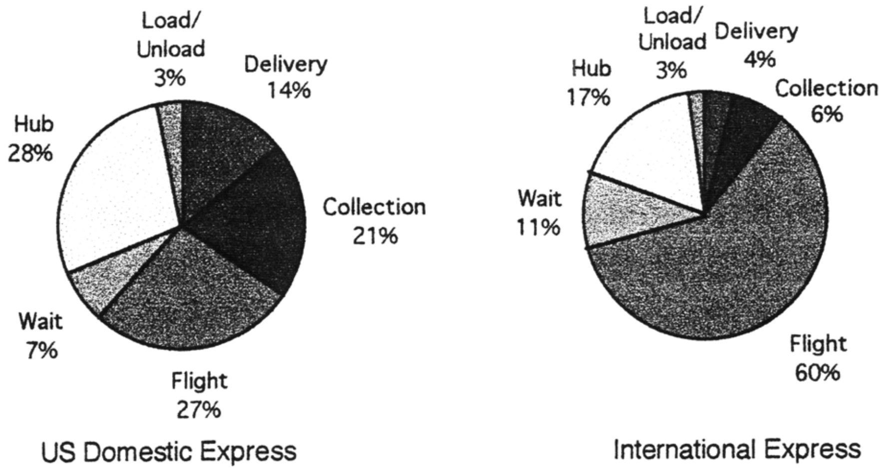
Andrews described Fast Package Delivery as a potential to create radical changes in our lives, just as Pony Express, Airmail and Overnight Delivery had revolutionized the way society operates. The key system requirements identified were low operating cost, quick turnaround and high reliability (99.99%). He further commented that these requirements, although stretching existing capabilities, were within reach of a well thought out technology development program.

Zubrin wrote that the key technologies required were reliable reusable rocket engines and a robust thermal protection system. According to him, advanced solutions which address the two were at hand. Like the CSTS, he also believed that the Fast Package will dwarf commercial satellite operations in the long run.

## 1.4 Market Assessment

### Projected Market Demand

Fig. 1-3 shows the percentage of time taken up by the flight in a typical package delivery in the within the US, and out of the US. It shows that improving the flight time for domestic delivery will not have significant impact on the total delivery time. The flight time for international package delivery, on the other hand, is a large 60%. Hence, Fast Package is better suited for international routes. In fact Fig. 1-4 shows that for the time saving to be significant, the distance should be at least 4000 miles. For this reason, this thesis considers only international package delivery.



US Domestic Express

International Express

Fig. 1-3: Delivery Time Breakdown

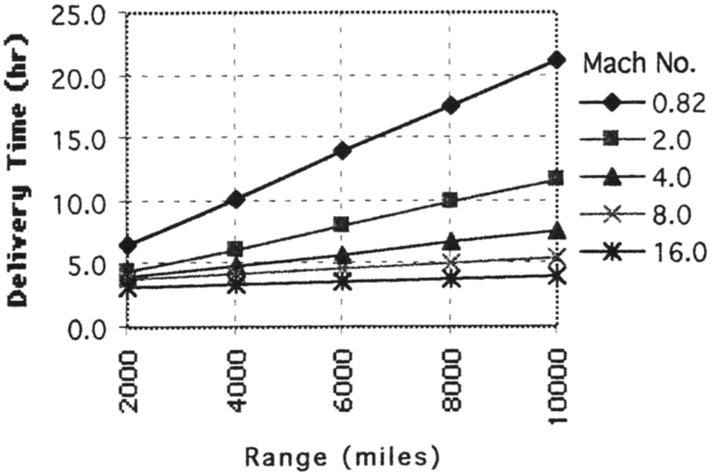


**Fig. 1-4: Delivery Time vs Range and Mach Number**

Since Fast Package is the high-end of express delivery service, it was reasonable to estimate its demand from the trend in the express delivery market. Using FedEx as a bench mark, the CSTS cited a $4 billion annual international express market. A Fast Package Delivery System would seek to capture a portion of this market. Fig. 1-5 gives the annual mass of commodities which a rapid delivery service would handle assuming a 0.5% and a 5% capture of the express market, and allowing for a 5% and 10% market growth. It was expected that the global air freight express market will grow at 7% per year through the year 2010 [3]. Assuming a price of $200 per pound is charged, the Fast Package market could be worth anywhere between 220 million to 14 billion dollars. This projection is conservative, since FedEx reports a growth of 12% in 1997.

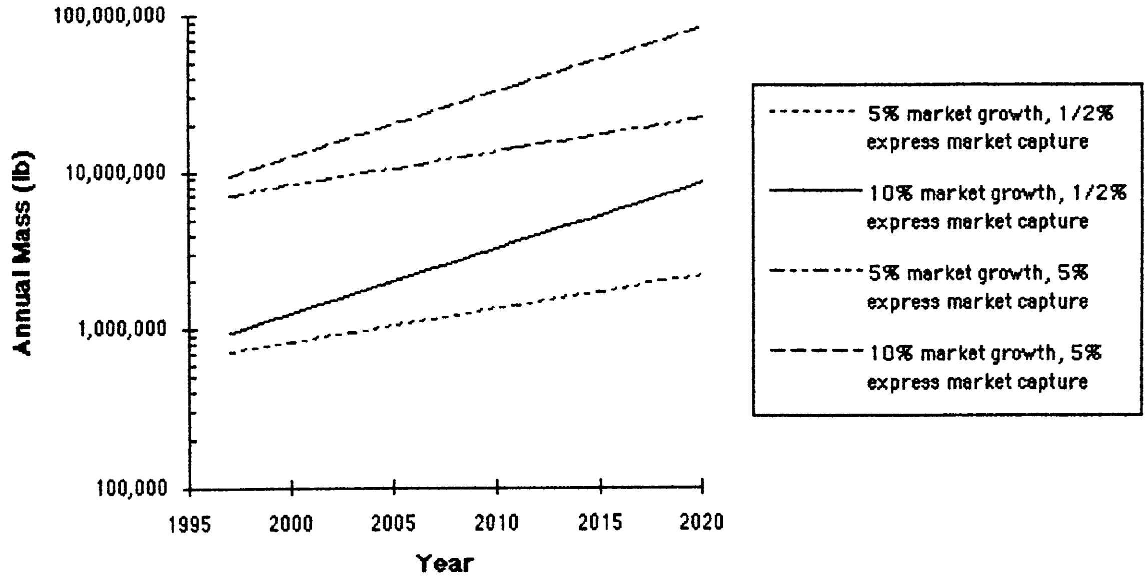


**Fig. 1-5: Estimate of Annual Fast Package Delivery Mass [3]**

One of the critical issues is how much the customer is willing to pay for this service. The CSTS surveyed several delivery companies and came up with a figure of $200 to $1000 per pound.

## 1.5 Fast Package Operations

CSTS report proposed the following modes of operation for Fast Package:

- Limited scheduled service between major city pairs, maximizing package volume while minimizing the number of vehicles in the fleet.
- Charter operations between major city pairs, maximizing revenue while minimizing the number of vehicles in the fleet and the number of cycles per vehicle.
- Charter operations between major embarkment points and many destinations,
- Scheduled service between many city pairs, which would maximize market penetration.

Fig. 1-6 depicts the traffic for the top air freight city pairs for 1991. It may be presumed that Fast Package could service each of these city pairs, since demand is high and delivery infrastructure is already in place. The size of the vehicle fleet could be determined by selecting a few of these top hubs, and the daily gross tonnage shipped from each.

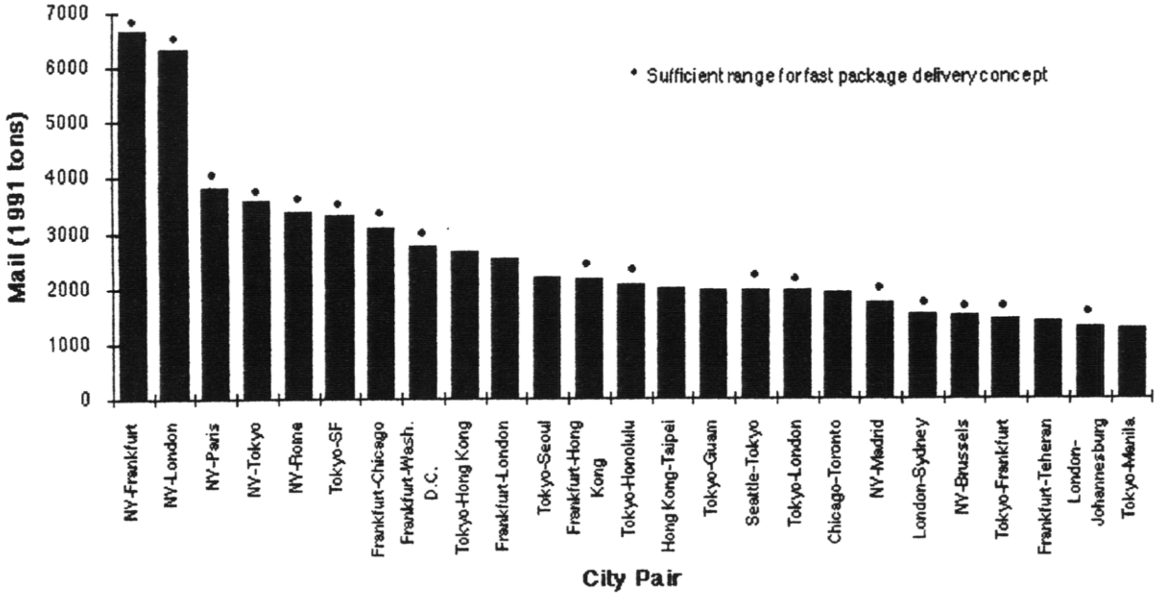


**Fig. 1-6:. Top Air Freight City Pairs [3]**

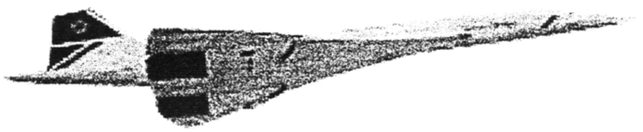
Charter operation is best suited to the nature of Fast Package because there is no waiting for the scheduled departure time. However, predicting its utilization is difficult and the uncertainty is unattractive to investors.

Scheduled service between many city pairs will create a larger and more stable demand for Fast Package. Experience with express mail market showed that there is a certain "critical mass" of network nodes at which the market explodes. For example, Federal Express (which was founded in 1971) became profitable only after they established a nationwide network in 1974 [3].

## 1.6 Existing Systems

This section gives a brief review of existing aerospace vehicles which may be used for Fast Package.

Anglo-French Concorde



Concorde is already considered by some to be the logical solution for Fast Package, since it is a well proven high speed transportation airplane. Its safety record is spotless. Based on current ticket prices, the Concorde could charge about $20/lb of cargo, which is much lower than the Fast Package price bracket ($200-1000/lb). Of course the flight time is significantly longer than targeted for Fast Package, but that is another matter which will be discussed later. Concorde is also integrated with air traffic network and can operate out of most major airports, if not for noise regulations. So why has no one used the Concorde for Fast Package? Concorde was designed in the late 1960's as a passenger transport only. In those days, it was inconceivable that a dedicated air cargo service could be as profitable as it is today. Today, Concorde is operating with sell-out capacity on every flight. Hence after filling the Concorde with passengers and their baggage, there is little space left for additional cargo. In fact with the little space left, companies like DHL do utilize Concorde for urgent package delivery. With the booming business they are getting for their supersonic passenger service, it does not make business sense for British Airways or Air France to trade even a few passengers for cargo space, since Fast Package is still an untested market. In any case, Concorde is approaching the end of its cycle life, hence it is too late to consider any modifications. Economics aside, Concorde does not have sufficient range for the market under consideration. Another limitation for Concorde is that its flight is restricted because of the sonic boom.

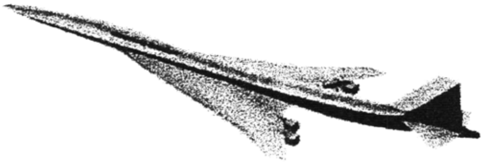
Orbital Sciences Corp - Pegasus

Pegasus is a small expendable launch vehicle capable of transferring a 1000 lb payload into LEO. It is considered here because it is probably the cheapest launch system available in the market. Although it started off badly, it has since demonstrated a flawless record. Pegasus is air-launched from a L1011. The air-launch not only enables Pegasus to operate from a standard runway, it also gives it a 40% higher payload to mass ratio. This vehicle is not reusable. With a launch cost of $12.5 mil (i.e. $12,500/lb), it is too expensive for Fast Package. However if the vehicle is modified to be reusable it may become a competitor for Fast Package. The vehicle's small design payload is closer to the needs of Fast Package. Larger vehicles may be operating with only partially filled cargo bays, thus driving up the cost for the service.

## 1.7 Future Systems

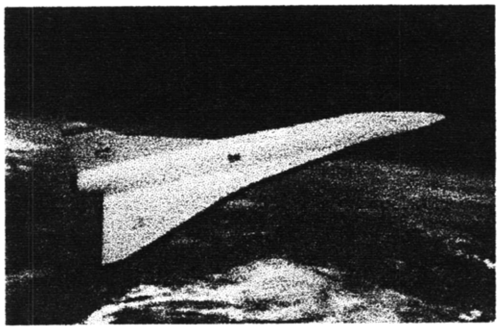
The following are some future aerospace systems which may be suitable for the Fast Package mission. They include new supersonic transport and reusable launch vehicles.

High-Speed Civil Transport (HSCT)

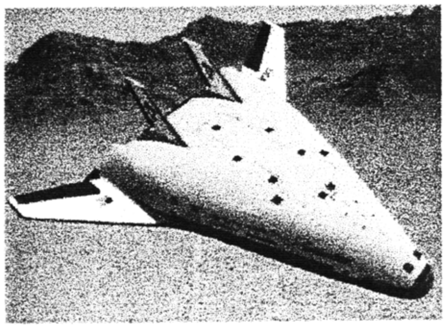


Boeing/NASA's HSCT is the next generation of supersonic passenger transport. It will have a cruise speed of Mach 2.5, a range of 5500 to 7500 nm., and carry 300 passengers. It will utilize latest technologies in gas turbine propulsion, materials and high-speed aerodynamics in order to achieve huge reduction in operating cost as compared to Concorde. If successful, the ticket price will cost only 10% more than existing subsonic prices.

### Kelly Space and Technology



The Astroliner by Kelly is a fully reusable tow launched rocket powered vehicle. It is towed from runway with conventional runway landing. The Astroliner is a suborbital vehicle. It releases a second stage which transfers the payload to LEO. The Astroliner itself does not have the range for transoceanic flight.

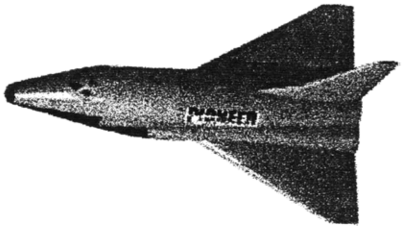


### Lockheed-Martin - Venture Star

Lockheed Martin's Venture Star is a SSTO RLV currently under development. It will carry 24,800 pounds to space station orbit at a price of $1000/lb. It is wholly rocket powered and utilizes the new aerospike nozzle for improved propulsive efficiency.

### Pioneer

Robert Zubrin's Pioneer rocketplane is actually designed with Fast Package and even passenger transportation in mind. Pioneer carries 2 jet engines for take-offs and landings from airports. In addition, it relies on in-flight fueling of liquid oxygen to get around cryogenic restrictions at airports. For Fast Package, the developers claim the cost will be around $200/lb, assuming a 5000 lb payload [5]. This price is reasonable according to the CSTS report.



## 2. DEFINING THE FAST PACKAGE PROBLEM

### 2.1 Overview of Approach

The approach was to look first at the system encompassing the overall delivery process - from the customer's door to the package's final destination. The purpose was to justify the necessity of a high-speed flight vehicle.

After establishing the need for a high-speed vehicle, a decision had to be made concerning how the system was operated, i.e. if it was a scheduled or an On-Demand service. Scheduled service means the flight vehicle will fly at a fixed time everyday, while On-Demand means the vehicle flies as and when needed. Only having defined the operation could the requirements be generated. When considering the scheduled operation, there was also a need to decide on how many flight per day. It was finally decided that the two extreme ends of the spectrum will be analysed, i.e. one flight per day scheduled service and On-Demand charter service. Since all other options fall in between these two, it was presumed that lessons learnt from the two would be scalable towards any middle option.

### 2.2 Current Air Express Delivery

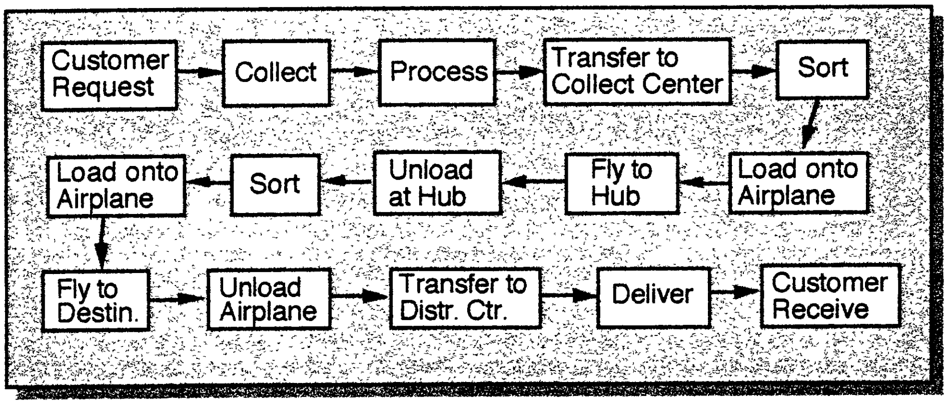


**Fig. 2-1: Express Package Delivery Process Flow.**

Since existing package delivery companies would be the likely operators of Fast Package, they were approached for information concerning the delivery process. Fig. 2-1 describes the process flow for a typical overnight package delivery within the US (courtesy of UPS). The precise timing varies from place to place, depending on distance to the airport and the traffic condition. Most of their customers have scheduled pickups, i.e. the collection van will go to the customer's location at a regular time over the week. Packages are picked up close to the end of the business day. Most of the paper work (logging of information, customs papers etc) is done by the customer, who is supplied with software to print the package labels and bar codes. If not, the driver is equipped to do the labelling and bar-coding. After making the collection run, the vans return to distribution center for sorting of the packages according to hubs. The packages are then loaded into cargo containers and trucked to the airport where they are transferred onto the airplane. The airplane typically takes-off for the hub at night, arriving at the hub at around midnight. At the hubs, the packages are sorted for their final destination, loaded onto the appropriate plane, flies to the final destination. The packages arrive at their destination before dawn on the day after the package was picked up. The cargo containers are trucked to the sorting centers where the packages are transfered to the delivery vans. The vans leave at 8. am and the package are delivered by 10.30 am.

For international delivery, there is an additional process step at the hub, where the packages undergo customs clearance before being loaded onto airplanes bound for foreign destinations. Only selected packages are inspected by the customs officer, so there is little delay due to the customs clearance.

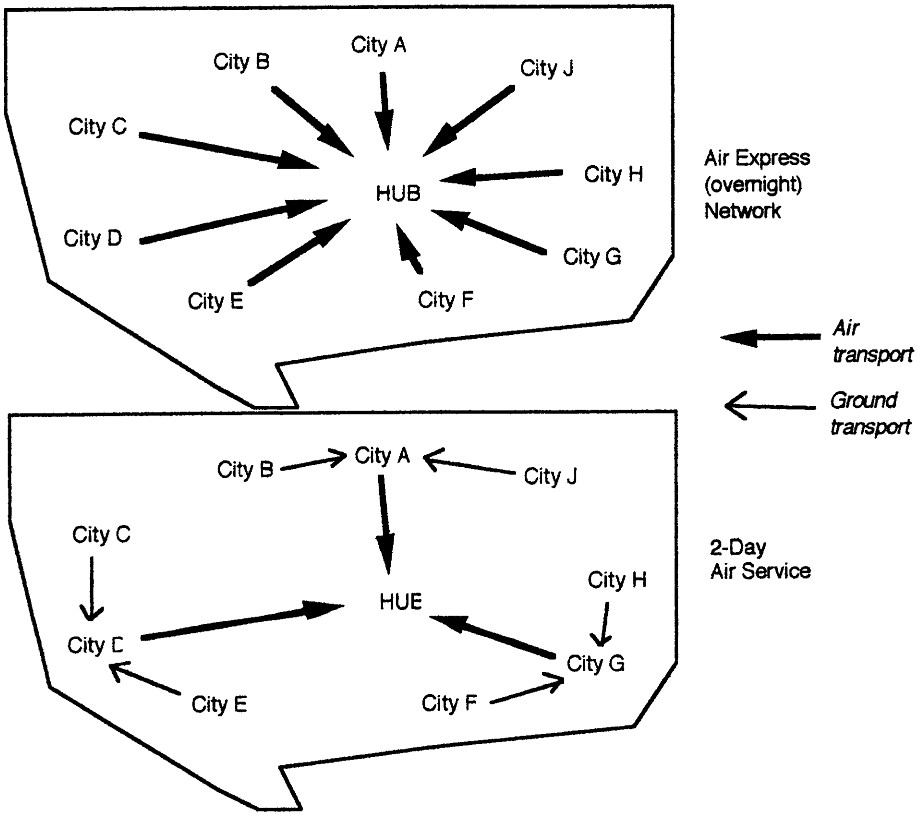


**Fig. 2-2: Differences in Air Networks.**

For the present delivery process, there is minimal value in collecting the packages earlier since the airplane leaves only at night. According to many delivery companies, the late pick up is advantageous to their customers because the customers have more time to work on the product before having to ship it. The late pickup also benefits the delivery company because they can maximize the number of pick ups per trip, thereby improving productivity. The latest pickup time is constrained by the departure time of airplane, which in turn is constrained by the hub schedule. The idea surrounding the 5 pm pick-up may no longer be feasible in the context of Fast Package, since the business day never closes in the global arena. Hence Fast Package customers are expected to be operating round the clock.

In certain cities, there are additional daytime flights for the 2-day delivery service. The two-day service air network is sparser because ground transportation is used over a wider radius (Fig. 2-2).

### Existing Delivery Process Time Line

Fig. 2-6 shows the delivery time line for current delivery of a package from the US to South East Asia. The local times shown are US Eastern Standard Time and Singapore time. Note that Singapore, Hong Kong and the Philipines are in the same time zone. Depending on the initial wait for a pick-up, the total delivery time ranges from 54 to 74 hours.

There are several reasons why the existing process fails to meet Fast Package requirements. These are evident from the time line. Firstly, up to 20 hours is spent waiting for the pickup if a customer misses the last pick up of the day. In addition, there is another 11 hours of waiting at the other end of the flight because the flight arrives at the Pacific hub before the sorting begins. Secondly, the flight takes 27 hours. Thirdly, having to deal with a large volume of packages slows down the process. These are evident in the long pick-up times and sorting times at the hubs, which contribute about 16 hours to the total time.

## 2.3 Options for Improving Delivery Time

### Using Subsonic Airplanes

From the time line, several approaches for improving delivery time were proposed. Fig. 2-7 shows some examples. Three approaches utilizing existing subsonic airplanes were proposed.

The first was to operate the hub twice a day. The delivery process is the same, except that the waiting time is reduced. Assuming the second shift is 12 hours after the first, two-thirds of the waiting time is eliminated. With the volume halved per flight, the handling time is also shorter per flight. This resulted in a saving of 24 hours.

The second approach was a Next Flight Out service, i.e. the package is put on the next available passenger flight headed for the desired destination. In this case, a driver goes out to pick up the package and sends it to the airport, where it is loaded onto the airplane. At the other end of the flight, the package is handed over to a driver who then sends it to the final location. There is still a long wait in the time line because not many international flights leave each day. In addition, it may be necessary to fly to another US airport if the local airport does not link to the destination country. As this is a custom pick-up and drop-off, the ground-handling time is minimal, and no sorting is required. The overhead at the Pacific hub is also avoided. The total time saved is also 24 hours.

The third approach was to have a dedicated long-range civil transport airplane ready to fly "On-Demand". When a request for delivery is made, a driver will go and get the package, and bring it to the awaiting airplane, which takes off for the destination country. Assuming the customer is no more than 1 hour from the airport, the total delivery time is reduced by 44 hours.

The On-Demand airplane is better than the Next Flight Out service as far as time is concerned, but the cost is orders of magnitudes higher. This is because the On-Demand customer has to pay for the entire flight. Furthermore, in order to service a reasonable number of cities and at the same time maintaining a dispatch reliability, a large fleet of airplanes will be needed for the On-Demand operator. This fleet cost will be passed on to the customer, thereby driving the price even higher. Next Flight Out, on the other hand, did not even need a fleet because it was assumed that aircraft from other carriers were used. This is why there are already delivery companies which offer Next Flight Out services. On-Demand service, using business jets, does exist for short to intermediate ranges. The jets are either chartered, or owned by the company for other official use. However, On-Demand service for long-range global reach is yet to be offered by anyone.

Operating the hub twice a day gave the same time saving as taking the Next Flight Out. Since all packages are routed through the hub, the volume of packages will be the greatest. The coverage (service radius) is also larger because the hub is the focal point of the nationwide network. However, the infrastructure cost involved with the additional hub operation is considerable. In the most conservative sense, it was assumed that existing airplanes could be used to fly a second time in the day. This turned out not to be feasible because the airplanes are utilized in the daytime for other services, such as 2 or 3-day delivery. Hence, new planes will be required. A disadvantage of the Next Flight Out is that the delivery company is not in control of the flight.

The above approaches using existing airplanes succeeded in reducing the delivery time, but they are still far from meeting the four-hour door-to-door time. This is because the flight time for the subsonic airplane is 24 hours. The next section discusses the outcome if a high-speed flight vehicle is introduced.

## Using High-Speed Vehicles

Six approaches utilizing a new high-speed vehicle were proposed. For this preliminary assessment, a one hour flight time was assumed for the high-speed vehicle.

The first approach was based on the current delivery process, except that the subsonic airplane was replaced by the high-speed vehicle from the centrally located US hub to the Pacific hub. Note that the flight is subsonic initially because of sonic boom restrictions. The high-speed flight enables the package to reach the Pacific hub in time for sorting the day before the subsonic airplane's arrival. Hence there is a 24-hour reduction on the delivery time. Depending on demand, a variation of this approach was to fly direct from the US hub to the destination (i.e. by passing the Pacific hub). This would save an additional 10 hours.

The second method assumed that the hubs (US and Pacific) operated an additional shift for our purpose, as in the case of the subsonic airplane. The shorter wait time result in total time saving of 36 hours. Again another 10 hours was saved by by-passing the Pacific hub.

The third approach was to fly direct (at a scheduled time) to the destination without going through any hub. This saved the time spent at the hub and avoided waiting for the shift to begin. The volume carried will be less because the packages are only from the local area. The total time saved was 46 hours. The time line shown is for a vehicle departing from the West Coast, otherwise it would have been necessary to add a subsonic segment to get to the coast before initiating high-speed flight.

The fourth approach was the same as the third, except more flights were scheduled to leave each day. Assuming regularly spaced flights, the total time saved was 58 and 62 hours for two and three flights per day respectively.

The fifth approach was an On-Demand service. The process is identical to the On-Demand subsonic airplane described previously, except that the subsonic airplane is replaced by the high-speed vehicle. The total time saved was 70 hours. In other words, the total delivery time was four hours, which meets the Fast Package goal.

The final and fastest approach considered was a Launch Anywhere Land Anywhere (LALA) high-speed vehicle. This means the high-speed vehicle has mobile launch capability and can be brought near the customer for launch. This reduced the ground handling time since the package need not be transported back to the launch site. At the destination, the vehicle either lands at the customer's "back yard", or the package can be airdropped with pin-point precision using TERCOM/GPS guidance. The estimated total delivery time for such a system was 2 hours.

Summary of Time Line Analysis

From the time line for the various approaches, the following was concluded:

- For just-in-time commodities, a new high-speed vehicle operating in "On-Demand" mode was the only solution.
- The delivery time improved significantly with the number of scheduled flights per day.
- If operating in the scheduled mode, one flight per day with the high-speed vehicle offered about the same time saving as having two subsonic flights per day. It is therefore necessary to perform a trade study to see which would be more economical.

## 2.4 Scheduled vs On-demand Operation

As outlined earlier, a decision had to be made concerning the operating mode (Scheduled or On-Demand flights) of the vehicle in order to perform the requirements analysis. From the previous discussion, it appeared that the On-Demand service was the way to go because only then could the just-in-time requirements be met. Such a service will be so far ahead of the closest competitor in terms of speed. However, since the entire launch cost is borne by one customer, will the price be so high that nobody will use it? The more economical approach may be to operate the high-speed vehicle once a day. This way more packages can be collected per flight, so we not only have benefit from economy of scale, but the cost is also spread over many customers, thus reducing the price paid by each customer. As shown earlier, the delivery time still beats existing services by one day. But now, is saving one day enough to justify choosing the more expensive high-speed service over the existing subsonic service? Is the best solution somewhere in between the two?

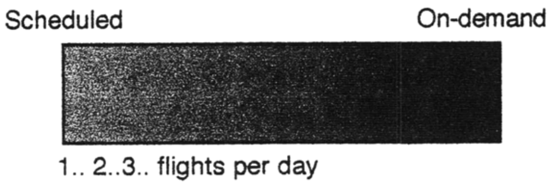


**Fig. 2-3: The Operating Mode Spectrum.**

To answer the above questions the development and operating cost for the system need to be known first. To get the cost the designs need to be pursued till there is sufficient resolution to make reasonable cost estimates. Rather than to design several vehicles - one for each possible modes of operation (On-Demand, one, two, three (etc) flights per day), it was decided that the best approach, given the project time constrain, was to look into the extreme ends of the spectrum (Fig. 2-3).

The Scheduled-end embodies cost effectiveness; the On-Demand-end embodies speed. Having obtained the two designs, the concepts and lessons learnt will be employed to find an optimum solution mid-way.

Scheduled Service

The reason for considering the Scheduled service was that it would be more economical because it would be carrying a much higher volume of packages than the On-Demand service. The best way to maximize the volume is to operate within the existing FedEx/UPS infrastructure, particularly to take advantage of the collection of packages at the hub. This way, the aircraft will be carrying all the Fast packages from US to some destination city for that day. The same applies for other hubs, such as Europe and Asia. Hence Fast Package service will be accessible to nearly everyone, and not be dependent on any particular city's business. With economy of scale, the price for the service would probably be cheaper, thus encouraging further demand for Fast Package. The fleet size will only depend on the number of destinations served. All these advantages do not apply to the On-Demand service.

The delivery process for scheduled service is shown in Fig. 2-4. The shaded region indicates the system boundary for the Fast Package system, since the system is operating within the existing air express delivery process (compare Fig. 2-1). Everything outside the Fast Package system boundary remains the same.

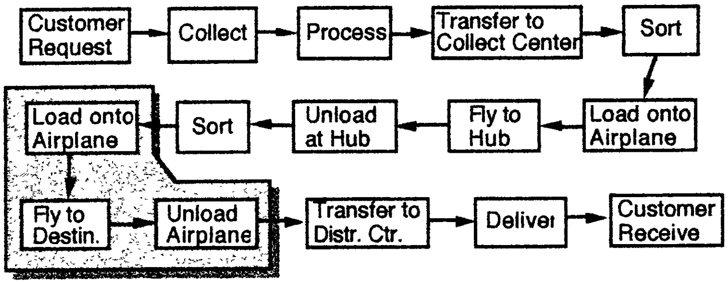


**Fig. 2-4: Fast Package system boundary for scheduled service.**

The time line for the above was discussed in the first approach for using the high-speed vehicle (Fig. 2-7). Subsonic approaches have similar and even better delivery times. However time is not the only factor in play. Setting up an additional shift at the hub may be more expensive to operate in the long run than using the Fast Package vehicle. As for the Next Flight Out option, it is not within the control of the delivery company, which makes it harder for them to provide high dispatch reliability for their customers. Finally, the On-Demand long-range subsonic airplane (such as a Boeing 747) will very likely cost more than this service since one customer is paying the entire flight cost of the airplane. Nevertheless, the delivery time is the disadvantage of this approach, and the chief driver for looking for something towards the middle of the spectrum.

How about the market? The Scheduled service is far from the goal of four hours, so it is not possible to capture the Fast Package market discussed earlier. However, it still saves one day over existing delivery time, so this system is targeting current users of existing international air express services who wish to have a shorter delivery time. It also means that this faster delivery will give them an additional day to work on the product before having to ship it and make the deadline. Based on growing international market trends, even if a small percentage of express users utilize this fast service, the volume would still be substantial.

On-Demand Service

The On-Demand service explores the fastest mode of operation for a Fast Package delivery system. Its delivery process is shown in Fig. 2-5, while its time line is in Fig. 2-7. It is necessary to depart from the existing delivery process because the latter consumes too much time. Hence the boundary for the On-Demand system has to include the entire process from customer to customer, as indicated by the coloured region. Since time is of the essence here, it is not desirable to wait for more packages to come in before launching. Hence it will generally be one customer per launch. This means all sorting activities are eliminated. It also means that the hub is irrelevant. However, the total delivery time is not bounded if there is no constraint on the transportation time from the customer to the launch site. Hence a limit of one hour was chosen as the service radius at both ends (origin and destination) One hour was chosen because, assuming a one-hour flight time and half hour at each end for loading and unloading, one hour is the limit for four-hour door-to-door time.

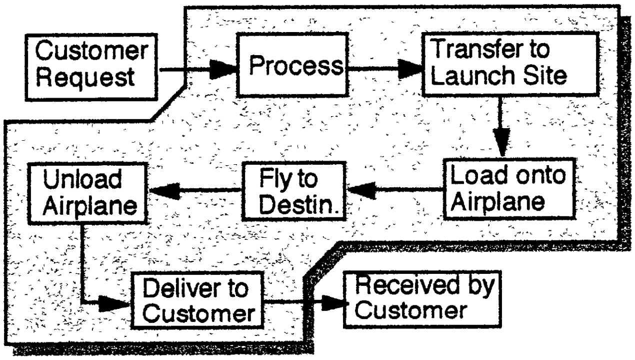


**Fig. 2-5: Fast Package system boundary for On-Demand service.**

Since the system boundary consisted of both the high-speed vehicle and the dispatch network, there are two problems to tackle here:

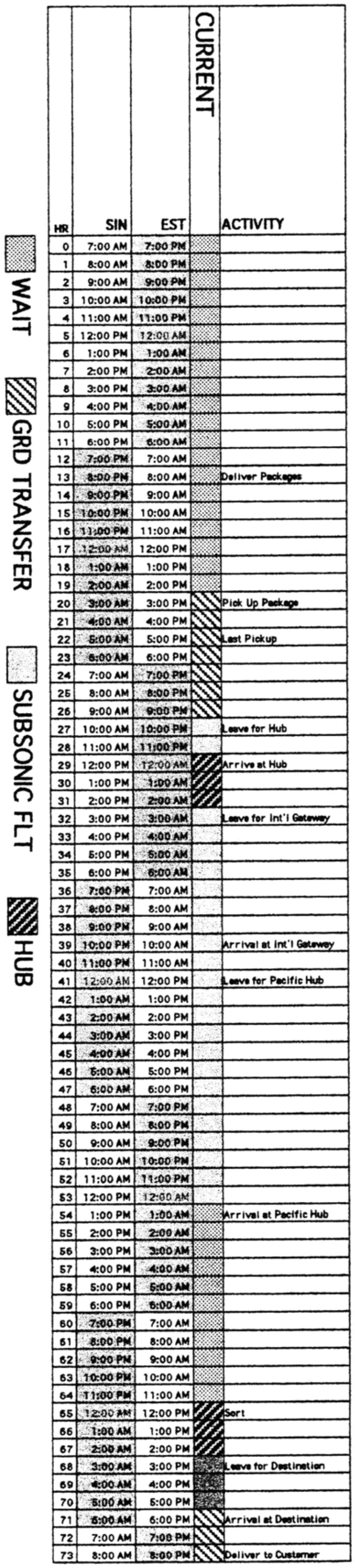
- Design of a rapid transfer of package from customer to launch site, hereafter referred to as the *package transfer.*
- Design of high-speed flight vehicle

The two appear to work intimately together, and in some sense, they do. If the package transfer time is shortened, there will then be more time for the flight, thereby reducing the demands on the high-speed vehicle; if the flight time is shortened, there will then be more slack time for package transfer. Alternatively, if the flight time cannot be achieved, it can be compensated by the package transfer time. On the other hand, the two are also independent because, functionally, they have little effect on each other. Hence once the time for each phase is prescribed, the two problems can be dealt with separately. If needed, the time allocation can be traded later. For now, the package transfer time is met by limiting the service radius. Improving the package transfer method therefore serves to increase the service radius, for the same transfer time.

Since there is only one customer per launch, the strain on the customer's pocket will be high. To alleviate this, the vehicle should not be bigger than necessary so as to minimize the fuel cost. This means the design payload size should be based not on the projected daily volume (as in the scheduled case), but on the average volume per order. Based on interviews with industry, the typical weight for just-in-time parts is only 10 to 20 pounds and has a size of an 18-inch pizza box. To account for the occasional large order, a maximum payload capacity of 200 lbs (20 pizza boxes) was selected. Many of the existing and upcoming systems are designed to carry thousands of pounds, and therefore may not be suitable for this mission.

## 2.5 Market Re-assessment

The CSTS predicted an average daily volume of 3000 lb per node for Fast Package. They also found that people were willing to pay between $200 and $1000 per pound for the service. It is natural to assume ([4], [5] for example) that the Fast Package revenue was a product of the two numbers. In the light of the above discussion on scheduled and on-demand operations, it becomes clear that such an assumption is incorrect. Firstly, the $200-$1000/lb price assumed that the total delivery time is in the order of a few hours. It was shown from the time line analysis that the only way to achieve that is through an On-Demand Service. However, the On-Demand flight is for one customer only, which according to industry sources, wishes only to send a 20-70 lb package. This is consistent with the kind of commodities earmarked by CSTS for Fast Package (precious stones, human organs, electronic components, etc). Hence the operating cost for such a vehicle cannot be more than 20-70 thousand dollars. On the other hand, if one waited for 3,000 lb of packages to be collected (i.e., once a day scheduled flight), the delivery time will be 24 hours or more. By scaling between domestic and international delivery times, Martin [16] showed that the price was more like $15 to $20 dollars in this case.



| HR | SIN | EST | CURRENT | ACTIVITY |
|---|---|---|---|---|
| 0 | 7:00 AM | 7:00 PM | ▒ | |
| 1 | 8:00 AM | 8:00 PM | ▒ | |
| 2 | 9:00 AM | 9:00 PM | ▒ | |
| 3 | 10:00 AM | 10:00 PM | ▒ | |
| 4 | 11:00 AM | 11:00 PM | ▒ | |
| 5 | 12:00 PM | 12:00 AM | ▒ | |
| 6 | 1:00 PM | 1:00 AM | ▒ | |
| 7 | 2:00 PM | 2:00 AM | ▒ | |
| 8 | 3:00 PM | 3:00 AM | ▒ | |
| 9 | 4:00 PM | 4:00 AM | ▒ | |
| 10 | 5:00 PM | 5:00 AM | ▒ | |
| 11 | 6:00 PM | 6:00 AM | ▒ | |
| 12 | 7:00 PM | 7:00 AM | ▒ | |
| 13 | 8:00 PM | 8:00 AM | ▒ | Deliver Packages |
| 14 | 9:00 PM | 9:00 AM | ▒ | |
| 15 | 10:00 PM | 10:00 AM | ▒ | |
| 16 | 11:00 PM | 11:00 AM | ▒ | |
| 17 | 12:00 AM | 12:00 PM | ▒ | |
| 18 | 1:00 AM | 1:00 PM | ▒ | |
| 19 | 2:00 AM | 2:00 PM | ▒ | |
| 20 | 3:00 AM | 3:00 PM | ▨ | Pick Up Package |
| 21 | 4:00 AM | 4:00 PM | ▨ | |
| 22 | 5:00 AM | 5:00 PM | ▨ | Last Pickup |
| 23 | 6:00 AM | 6:00 PM | ▨ | |
| 24 | 7:00 AM | 7:00 PM | ▨ | |
| 25 | 8:00 AM | 8:00 PM | ▨ | |
| 26 | 9:00 AM | 9:00 PM | ▨ | |
| 27 | 10:00 AM | 10:00 PM | ░ | Leave for Hub |
| 28 | 11:00 AM | 11:00 PM | ░ | |
| 29 | 12:00 PM | 12:00 AM | ▩ | Arrive at Hub |
| 30 | 1:00 PM | 1:00 AM | ▩ | |
| 31 | 2:00 PM | 2:00 AM | ▩ | |
| 32 | 3:00 PM | 3:00 AM | ░ | Leave for Int'l Gateway |
| 33 | 4:00 PM | 4:00 AM | ░ | |
| 34 | 5:00 PM | 5:00 AM | ░ | |
| 35 | 6:00 PM | 6:00 AM | ░ | |
| 36 | 7:00 PM | 7:00 AM | ░ | |
| 37 | 8:00 PM | 8:00 AM | ░ | |
| 38 | 9:00 PM | 9:00 AM | ░ | |
| 39 | 10:00 PM | 10:00 AM | ░ | Arrival at Int'l Gateway |
| 40 | 11:00 PM | 11:00 AM | ░ | |
| 41 | 12:00 AM | 12:00 PM | ░ | Leave for Pacific Hub |
| 42 | 1:00 AM | 1:00 PM | ░ | |
| 43 | 2:00 AM | 2:00 PM | ░ | |
| 44 | 3:00 AM | 3:00 PM | ░ | |
| 45 | 4:00 AM | 4:00 PM | ░ | |
| 46 | 5:00 AM | 5:00 PM | ░ | |
| 47 | 6:00 AM | 6:00 PM | ░ | |
| 48 | 7:00 AM | 7:00 PM | ░ | |
| 49 | 8:00 AM | 8:00 PM | ░ | |
| 50 | 9:00 AM | 9:00 PM | ░ | |
| 51 | 10:00 AM | 10:00 PM | ░ | |
| 52 | 11:00 AM | 11:00 PM | ░ | |
| 53 | 12:00 PM | 12:00 AM | ░ | |
| 54 | 1:00 PM | 1:00 AM | ░ | Arrival at Pacific Hub |
| 55 | 2:00 PM | 2:00 AM | ▒ | |
| 56 | 3:00 PM | 3:00 AM | ▒ | |
| 57 | 4:00 PM | 4:00 AM | ▒ | |
| 58 | 5:00 PM | 5:00 AM | ▒ | |
| 59 | 6:00 PM | 6:00 AM | ▒ | |
| 60 | 7:00 PM | 7:00 AM | ▒ | |
| 61 | 8:00 PM | 8:00 AM | ▒ | |
| 62 | 9:00 PM | 9:00 AM | ▒ | |
| 63 | 10:00 PM | 10:00 AM | ▒ | |
| 64 | 11:00 PM | 11:00 AM | ▒ | |
| 65 | 12:00 AM | 12:00 PM | ▩ | Sort |
| 66 | 1:00 AM | 1:00 PM | ▩ | |
| 67 | 2:00 AM | 2:00 PM | ▩ | |
| 68 | 3:00 AM | 3:00 PM | ▓ | Leave for Destination |
| 69 | 4:00 AM | 4:00 PM | ▓ | |
| 70 | 5:00 AM | 5:00 PM | ▓ | |
| 71 | 6:00 AM | 6:00 PM | ▨ | Arrival at Destination |
| 72 | 7:00 AM | 7:00 PM | ▨ | |
| 73 | 8:00 AM | 8:00 PM | ▨ | Deliver to Customer |

▒ WAIT ▨ GRD TRANSFER ░ SUBSONIC FLT ▩ HUB

Fig. 2-6: Time Line of Current Delivery Process

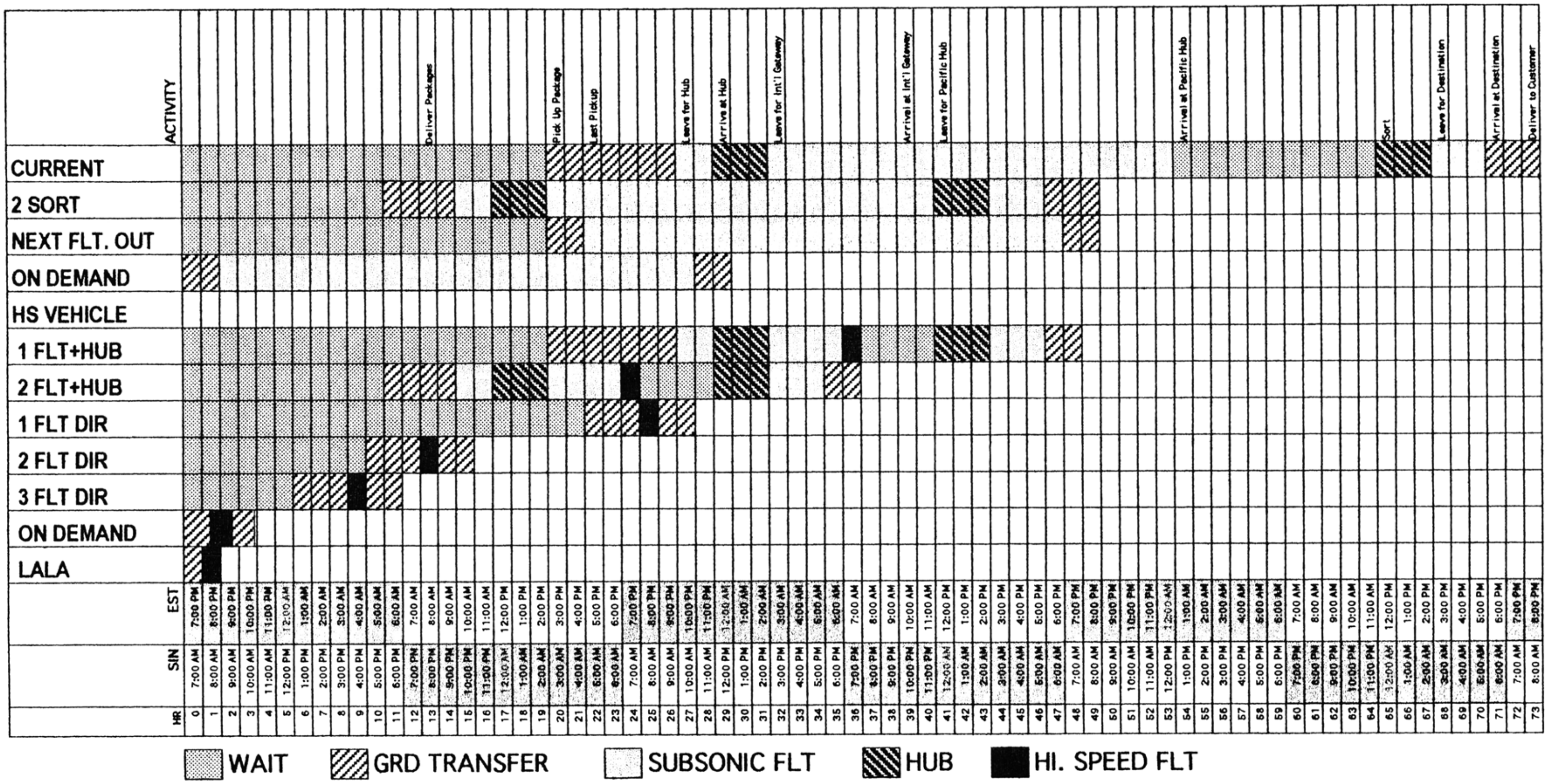


Fig. 2-7: Time Line for Fast Package Options

# 3. REQUIREMENTS ANALYSIS

Having defined the problem in the previous section, the next step was to look into the requirements for the Fast Package delivery system. The requirements were analyzed separately for Scheduled and On-Demand systems. In view of the scope of work and time available for this project, the requirements were defined with just enough detail to capture the essential elements of the concept.

The requirements for the Fast Package delivery system were derived from the Customer Needs. QFD (Quality Functional Deployment) was used as an aid in doing this. The "Customer Needs" were what the team perceived to be needs of the Fast Package operator. Many of the needs were identified in the CSTS report and Andrews (1997). Additional input was obtained by contacting representatives from package delivery companies (UPS and Emery Worldwide). Some of the requirements came from constraints.

## 3.1 Customer Needs

The following are the perceived needs of a Fast Package operator:

| CUSTOMER NEEDS | WEIGHT |
|---|---|
| Faster Delivery Time | 10 |
| Aircraft-like Reliability | 10 |
| High Reliability against Loss of Payload | 10 |
| Global Flight Coverage | 10 |
| High Dispatch Reliability | 9 |
| Turnaround Time of 24 Hours | 9 |
| Minimize Nonrecurring Costs | 8 |
| Minimize Operating Costs | 8 |
| Minimize Infrastructure Cost | 8 |
| Use Standard Cargo Containers | 5 |

The above list was sent to Emery Worldwide and UPS Sonic Air who then weighted the items according to importance. The final weightings incorporated some of their feedback, in particular, the importance of Faster Delivery Time and Reliability over Cost. Faster time was the most important because it is the selling point of the product. According to the industry, customers are prepared to pay a premium for fast delivery which is why cost was rated less important than speed. Reliability (i.e. the packages will arrive on time) was important because dependability is crucial for winning customers. Broken or damaged packages will also not be good for business. Note that Dispatch Reliability refers to the aircraft departing on time, while Aircraft-like Reliability refers to the aircraft arriving in one piece and on time at the destination. Global Coverage is the capability to reach as many cities as possible. Quick Turnaround Time is important for minimizing fleet size, as well as not to hold up the delivery process. The Nonrecurring Cost is the purchase cost of the vehicle, while Operating Cost is the cost of operating the vehicle. Infrastructure costs are the cost of renting or purchasing hangars, launch site etc. Using standard cargo containers was desirable if the packages need to be transferred to another aircraft during its journey.

The above are the needs for Fast Package in general and therefore apply to both the scheduled system and On-Demand system.

## 3.2 Constraints

The only constraint was having to comply with the civil airworthiness regulations.

### Regulations

Regulations are non-technical, but they have a profound effect on the performance of the vehicle. Concorde (and possibly all future supersonic transport) is restricted to certain routes because of noise and sonic boom restrictions.

If the vehicle is to operate freely in airspace, it needs to be certified as a commercial aircraft. Hence there is a need to comply with airplane regulations, as opposed to the newly-drafted regulations for RLVs. Another reason to get airplane certification is that the vehicle will also be operating in other countries. For global access, the vehicle must comply with both FAR and JAR (the European equivalent). For discussion's sake, consider registering the vehicle as an RLV, thus restricting it to Special Use Airspaces. This is not acceptable for Fast Package operation because 1) the Special Use Airspaces are few, 2) they are not located near the cities which Fast Package will be servicing, 3) most countries do not have such Special Use Airspace since they have no space program, and 4) very long lead time is needed when using these airspaces because of the lengthy approval procedures required by the FAA.

Complying with FAR is therefore a necessary constraint.

### Cost and Business Case

Cost is not a constraint. It does however come into play when trying to close the business case. From the point of view of the business case, minimizing the cost may not be the way to close the business case. If the only concern was minimizing the cost, the speed will end up being reduced. However the price that can be charged for this service decreases as the speed goes down, and so the revenue also goes down. There is therefore an optimum cost which will maximize the profit margin.

## 3.3 Quality Functional Deployment (QFD)

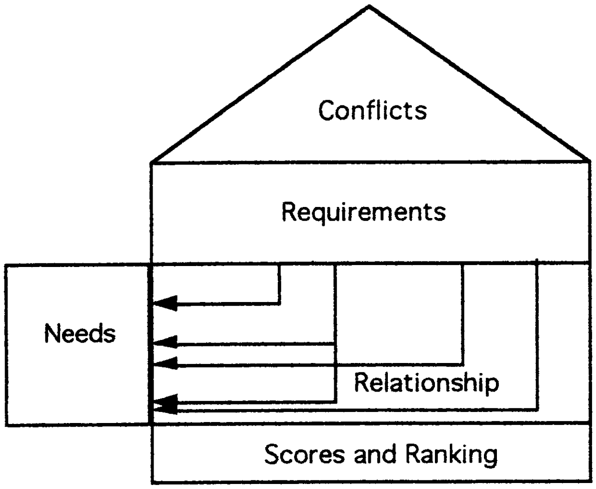


**Fig. 3-1: Elements of a QFD Matrix.**

In an effort to deal with the complexity of requirements definition, a QFD Matrix was used in the analysis. The elements of the QFD Matrix are explained in Fig. 3-1, while Figures 3-3 to 3-6 are the QFD Matrices for the Scheduled and On-Demand systems respectively. The QFD Matrix translates the "customer needs" into requirements. The customer needs are listed on the left of the matrix. For each customer need, requirements which enable the need to be satisfied are listed along the top row. For example in Fig. 3-3, the need for "Faster Delivery Time" can be achieved by Minimizing Flight Time and/or Minimizing Load/Unload Time. The Relationship Matrix indicates the strength of the relationship. In the analysis, a 9-3-1 scale was used to represent strong-moderate-weak relationships respectively. Hence for Faster Delivery Time, Minimizing Flight Time has a strong relationship since it will greatly reduce the delivery time. The Load/Unload time is a small fraction of the total delivery time, which is why it has only a weak relationship with achieving Faster Delivery Time. A blank means there is no relation. For example Minimizing Material Cost does nothing for Faster Delivery Time. Adverse relationship, i.e. conflicts, are also left blank in the Relationship Matrix. Conflicts are indicated in the Correlation Matrix on top in Fig. 3-1. Notice that the requirements may have more than one relationship with the list of needs. Here lies the power of the method, which will be evident in the next paragraph.

The QFD Matrix provides an objective approach to prioritizing requirements. If there is difficulty in achieving all the requirements, one would choose to satisfy the requirements of highest priority. QFD prioritizes requirements by considering their benefit over all the needs. The relationship values (9, 3 or 1) are factored by the weightings for the needs. The total score for each requirement is computed and written near the bottom. The requirements are then ranked by comparing the scores with each other. This scoring is the heart of the QFD Matrix. A requirement may contribute strongly to some need, but it may not rank highly because the weighting on the need is small. Alternatively, a requirement could rank highly if it is related to, albeit only moderately, many a few highly weighted needs. This way QFD helps to minimize human biases in prioritizing requirements, since at the end of the analysis, it is the scores that speak loudest. Of course, for the results to be credible, all the disciplines must be represented when completing the QFD Matrix. Another product of the prioritizing of requirements is the resolution of conflicting requirements. For example in Fig. 3-3 again, both Minimize and Maximize Fleet Size came out as requirements. The choice to go for minimization of fleet size was obvious from the scores. Finally, by following the relations, QFD allows all requirements to be traced back to their source.

The QFD does not end after the first matrix. The requirements from the first matrix replaces the "Customer Needs" for the second level matrix. New derived requirements form the horizontal axis of the new Relationship matrix. Figures 3-4 and 3-6 show the second level QFD Matrix for the Scheduled and On-Demand systems respectively. This process can be repeated as many times as necessary until all the requirements are defined. It can also be applied to choosing the process undertaken to achieve the requirements.

It is not hard to see where errors may enter into the QFD analysis. Firstly, weightings may not be scaled correctly relative to each other. It is easy to say one has a stronger relationship than another. However, the relative difference in weighting is based on judgment, and the final ranking of the requirements is based on these weightings. To overcome this, a cost model must be developed which captures the effect of each need on the final goal, be it profit or performance. Such a cost model requires extensive research and is beyond the scope of this project. Secondly, the relationship scale with only three degrees of freedom (9-3-1) is restrictive. Of course more elaborate schemes could be devised, but at the expense of simplicity. One way of reducing the uncertainty of the above, which was carried out, was to test the sensitivity of the results to changes in weighting and relationship. The sensitivity can also be inferred by plotting a histogram of the scores, also shown in Figures 3-3 to 3-6. Finally, the biggest difficulty encountered was trying to define requirements which were distinct from each other, the reason being that if they were not, the next level QFD will suffer from "double weighting" for some requirements thus erroneously inflating the actual value.

QFD is not meant to be applied blindly because of the pitfalls discussed previously. At the end of the day, a sanity check must be performed on the results.

## 3.4 Scheduled Service Requirements

Two QFD matrices were employed in the requirements analysis. The first (Fig. 3-3) was for the Top-Level Requirements, while the second (Fig. 3-4) was a translation of these Top-Level Requirements to Technical Requirements. One matrix was initially used, but the Needs were found to be too vague. Consequently some of the requirements had both positive and negative relationship to the Needs, depending on how the problem was approached. By introducing the another level of QFD for determining the "Top-Level Requirements," much of this vagueness was removed and it became easier to generate the Technical Requirements. The Top-Level Requirements were also better suited for the concept selection.

## Top-Level Requirements

The QFD Matrix for the Top-Level Requirements is shown in Fig 3-3. Most of the requirements and their relationship to the Needs are self-explanatory. To keep track of the constraints, they were incorporated into the Needs column.

A histogram of the scores were plotted (Fig. 3-3) as another means of assessing the sensitivity. The spikes in the distribution were grouped together and considered to be the key requirements. They are listed below according to their score:

1. Maximize System Reliability
2. Minimize Use of Support Equipment
3. Minimize Flight Time
4. Maximize Use of Existing Infrastructure
5. Maximize Vehicle Reusability
6. Minimize Fleet Size
7. Maximize Flight Hours per Maintenance Man-Hour

Maximize System Reliability was the most important requirement because of high emphasis on reliability by the customer.

Support Equipment are special structures, vehicles or heavy machinery required to support the operation of the vehicle. Examples are launch towers, airborne tankers, cranes, etc. Minimizing Use of Support Equipment will help to Minimize Infrastructure Cost. It also has a large impact on Global Coverage since there will not be the need to have expensive launch and recovery setups everywhere in the world. Support Equipment are expensive so minimizing their use will help reduce the Non-Recurring Cost.

Minimizing Flight Time is not only important for Faster Delivery, it also affects Global Coverage in the context of Fast Package Market. It is the speed that enables the system to service long distance destinations in Fast Package times.

Maximize use of Existing Facilities, in particular airports, reduces Infrastructure Cost since there is no need to build/purchase and operate a private facility. It also provides a better opportunity for Global Coverage if the system can be operated from any airport in the world.

Maximize Vehicle Reusability will Minimize Operating Cost because the vehicle will not be replaced after for each mission. This has been the lesson learnt from space transportation. In addition, Maximize Vehicle Reusability also refers to the speed with which the vehicle can be used again. Hence it also improves Turnaround Time.

Minimizing Fleet Size will logically minimize the Operating Cost. For a fixed volume of packages, it means to maximize the payload to exploit the economy of scale. It will also mean less vehicles to maintain. Buying fewer vehicles will probably mean that the Non-Recurring Cost for the operator is reduced for a given market.

Maximizing Flight Hours per Maintenance Man-hour will improve Turnaround Time. It also helps moderately in Minimizing Operating Cost since maintenance is part of the Operating Cost. Finally, easy maintenance will improve Dispatch Reliability.

Sensitivity tests showed that the above requirements remain in the top group even after tweaking some of the weightings and relationships.

Having only talked about the key requirements, it does not mean that the lower order requirements are thrown out. To do so the system will not work. For example, Cost requirements fall in the bottom half of the list, but we cannot say that cost is not an issue at all. What the QFD is saying is that in this case, we ought to relax cost a little in order to achieve the requirements which better satisfy the needs of the customer.

### Technical Requirements

The QFD Matrix for the Technical Requirements is shown in Fig 3-4. The Top-Level Requirements are now the "Needs". The weightings were derived by normalizing the scores from the Top-Level QFD to give values between one to ten.

From the distribution of the scores, six key Technical Requirements were identified:

1. Self Diagnostics Capability
2. Autonomous Flight Operations
3. Maximize Lift to Drag Ratio
4. Maximize Cruise Speed
5. Minimize Number of Stages
6. Maximize Functional Redundancy

Self Diagnostics Capability means an automated health monitoring system is needed. Currently these can be found in newer airplanes like the Boeing 777 and are typically used for avionics checks. A lot of on-going work is being carried out for engine HUMS (Health & Usage Monitoring Systems) which can also be implemented here. Research is also being conducted for structural health monitoring using Systems Identification approach. This approach correlates the structure's health to some measurable parameters, such as the natural modes. Self Diagnostics is the leading requirement because it improves System Reliability and Maintenance Man-hours, which are two important Top-Level Requirements. Recently, during the X-33 Phase I Integrated Propulsion Test Demonstrator (IPTD), the test bed (in addition to demonstrating a host of new technologies) showed that implementing health monitoring reduced system checkout time by 260 hours from baseline procedures - 2 weeks (1 shift 5 day-week) to 45 min [7].

Autonomous Flight Operations here means we can remove the pilot from the vehicle. This results in savings in Development Cost because life support systems are not needed. This is a lesson learnt from NASA's space program. Removing the crew and associated systems also reduces the weight, which eventually reduces fuel cost. Autonomous flight means the vehicle is not affected by poor visibility, hence increasing its All-Weather Capability. In the same way, the vehicle has better Night Capability. Notice that these Top-Level Requirements are not particularly weighty. However, because so many are affected, Autonomous Flight Operations ended up being so close to the top of the list.

Maximizing the Lift to Drag Ratio is critical for Long Range. It means that drag is minimized, which will help in attaining higher speeds and thus shorten Flight Time. Reducing drag also has some benefit on Minimizing Fuel Cost.

Maximizing Cruise Speed is important because of its strong relationship with Minimize Flight Time. This is evident from the time lines shown earlier. This is a consequence of the Long Range, where most of the flight is in cruise. It therefore follows that Time to Cruise and Landing Time have only a small effect on overall Flight Time. As mentioned earlier, high Cruise Speed is crucial for Long Range because the goal is to meet the four hour door-to-door time.

Minimizing Number of Stages will improve System Reliability significantly. Experience has shown that a lot can and does go wrong during staging. Fewer stages also mean less Maintenance in general.

Maximize Functional Redundancy will result in better System Reliability. It also allows maintenance to be relaxed a little. To illustrate the latter, the inspection frequency for the single-engine F-16 fighter is greater than the twin-engine F-5 because the F-5 can still make it back to base if one engine fails.

As before, a sensitivity check was performed to see if any of the above requirements would fall off the list. As expected, there was no change, since these key requirements were identified because their scores have a significant margin above the rest.

## FAA Requirements

The FAA requirements were extracted from Dunn [8]. The sonic boom on the ground must be within limits. There are noise levels to adhere to at take-off. The vehicle must integrate with the existing air traffic network. This includes the establishment of standard descent trajectories, the ability for the system to loiter in a holding pattern for at least 45 minutes, and be capable of taxiing. Unmanned aerial vehicles are currently considered according to size. Smaller vehicles, such as Predator, are allowed to operate unmanned out of commercial airports. For larger vehicles, the pilot must be physically on-board. The exact size limit for unmanned flight is not clear because UAVs operations are presently not significant to warrant new regulations. Finally, some method of safe abort must be provided for.

## Payload Requirement

Up to this point, the requirements for design speed, range and payload have not been determined. These requirements were driven by the market.

The payload for scheduled service vehicle was taken from Andrews [4]. In his study, Andrews assumed an average daily volume of 6000 lbs per city pair. This figure can be obtained from data shown in Fig. 1-6. The average annual mail tonnage per city pair was about 3000 billion in 1991. This means an average daily volume of about 18,000 lbs. Multiplying by an annual growth of 10% (recent figures are around 12%), plus the growth in express market share, the projected Fast Package average daily volume is about 6,000 lbs by year 2014, assuming Fast Package captures 7% of the express delivery market.

The scheduled service vehicle would be operating between the US and Pacific hubs. It will therefore be carrying packages to more than one destination. This means the payload will be greater than 6000 lb. Assuming that the Pacific hub serves four major cities in the region, the payload capacity needs to be 24,000 lbs.

## Range Requirement

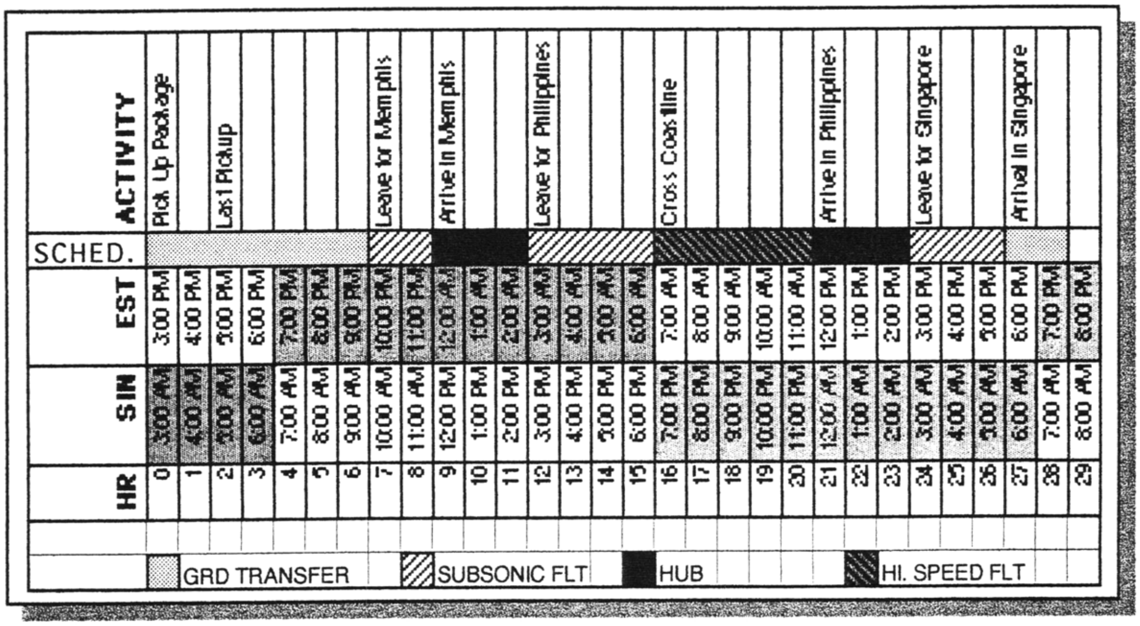
Dunn [8] showed that, based on 1991 mail tonnage, a range of 6000 mi. was sufficient to capture the bulk of the package delivery market. He also mentioned that recent trends suggested the market was evolving to demand a non-stop range of greater than 6000 mi. A range of 9000 mi. was selected in order to connect the US to the growing East Asian economies (Table 3-1).

**Table 3-1: Distance Between US and Major East Asian and Pacific Cities**

| From | To | Distance (mi.) |
|---|---|---|
| Los Angeles | Hong Kong | 7260 |
| Los Angeles | Tokyo | 5470 |
| Los Angeles | Singapore | 8780 |
| Los Angeles | Manila | 7300 |
| Los Angeles | Shanghai | 7370 |

### Flight Speed Requirement

The required flight speed was obtained from the delivery time line (Fig. 3-2)



| HR | SIN | EST | SCHED. | ACTIVITY |
|---|---|---|---|---|
| 0 | 3:00 AM | 3:00 PM | ░ | Pick Up Package |
| 1 | 4:00 AM | 4:00 PM | ░ | |
| 2 | 5:00 AM | 5:00 PM | ░ | Last Pickup |
| 3 | 6:00 AM | 6:00 PM | ░ | |
| 4 | 7:00 AM | 7:00 PM | ░ | |
| 5 | 8:00 AM | 8:00 PM | ░ | |
| 6 | 9:00 AM | 9:00 PM | ░ | |
| 7 | 10:00 AM | 10:00 PM | ▨ | Leave for Memphis |
| 8 | 11:00 AM | 11:00 PM | ▨ | |
| 9 | 12:00 PM | 12:00 AM | ■ | Arrive in Memphis |
| 10 | 1:00 PM | 1:00 AM | ■ | |
| 11 | 2:00 PM | 2:00 AM | ■ | |
| 12 | 3:00 PM | 3:00 AM | ▨ | Leave for Philippines |
| 13 | 4:00 PM | 4:00 AM | ▨ | |
| 14 | 5:00 PM | 5:00 AM | ▨ | |
| 15 | 6:00 PM | 6:00 AM | ▨ | |
| 16 | 7:00 PM | 7:00 AM | ▩ | Cross Coastline |
| 17 | 8:00 PM | 8:00 AM | ▩ | |
| 18 | 9:00 PM | 9:00 AM | ▩ | |
| 19 | 10:00 PM | 10:00 AM | ▩ | |
| 20 | 11:00 PM | 11:00 AM | ▩ | |
| 21 | 12:00 AM | 12:00 PM | ■ | Arrive in Philippines |
| 22 | 1:00 AM | 1:00 PM | ■ | |
| 23 | 2:00 AM | 2:00 PM | ■ | |
| 24 | 3:00 AM | 3:00 PM | ▨ | Leave for Singapore |
| 25 | 4:00 AM | 4:00 PM | ▨ | |
| 26 | 5:00 AM | 5:00 PM | ▨ | |
| 27 | 6:00 AM | 6:00 PM | ░ | Arrival in Singapore |
| 28 | 7:00 AM | 7:00 PM | ░ | |
| 29 | 8:00 AM | 8:00 PM | | |

░ GRD TRANSFER ▨ SUBSONIC FLT ■ HUB ▩ HI. SPEED FLT

Fig. 3-2: Delivery Time Line for Scheduled Service

The allowable flight time was first determined. This is the time between the plane's departure from the US hub and the start of operations in the Pacific hub, which is about nine hours. Since the US hub is centrally located, sonic boom regulations restrict the initial flight to transonic until the airplane is over the ocean. At Mach 0.8, it would take the airplane roughly 3.5 hours to get to the west coast. Thus there is a 5.5-hour period for the vehicle to get from, say, Los Angeles to the Philippines, which means the vehicle's minimum speed is 1330 mph (Mach 2). If a one-hour stop-over is added, the vehicle will need to go at least Mach 2.5 to make up for the stop-over.

## 3.5 On-Demand Service Requirements

The Top-Level Requirements and Technical Requirements for On-demand Service were derived in the same manner as Scheduled Service.

### Top-Level Requirements

The QFD Matrix for this case is shown in Fig. 3-5. There were some differences in the Needs. Quick Turnaround Time is typically needed because the vehicle may be called to fly again at any time. The need for Wide Collection Radius now arises since the operation is no longer within the existing delivery network.

There were also new requirements to consider because Processing and Transit Time is included. Processing Time refers to the paper work, while Transit Time is the time it takes to pick up the package and transfer it to the launch site. Vehicle Prep Time is the time needed to prepare the vehicle for flight.

From the histogram of the scores, ten key Top-Level Requirements were identified:

1. Maximize System Reliability
2. Minimize Use of Support Equipment
3. Minimize Flight Time
4. Long Range
5. Minimize Vehicle Prep Time
6. Maximize Use of Existing Facilities
7. Maximize Vehicle Reusability
8. Minimize Fleet Size
9. Minimize Transit Time
10. Maximize Flight Hours per Maintenance Man-Hour

The key requirements were very similar to that of the Scheduled Service. The differences are highlighted below.

The first difference is Long Range. This is because when the flight time is short, a stop-over will negate the time saved. The second difference is Vehicle Prep Time, since vehicle needs to be ready to by the time the package is transferred from the customer to the launch site. Although the system is no longer operating within the existing package delivery infrastructure, there is still the need to Maximize use of Existing Facilities (such as airfields) in order to Minimize the Cost of the new Infrastructure. If the system can integrate with airports, it will also make it easier to set up operations in anywhere in the world. Minimize Transit Time is important because if not controlled, valuable time will be lost.

## Technical Requirements

The QFD Matrix for the Technical Requirements for On-demand Service is shown in Fig. 3-6. Again the Top-Level Requirements have replaced the "Needs" on the left of the Matrix. The weightings are obtained by scaling the scores of the Top-Level Requirement from one to ten.

From the histogram of the scores, the top Technical Requirements were the same, though reordered slightly, as the Scheduled Service:

1. Self Diagnostics Capability
2. Minimize Number of Stages
3. Maximize Lift to Drag Ratio
4. Maximize Cruise Speed
5. Autonomous Flight Operations
6. Maximize Functional Redundancy

## FAA Requirements

The FAA requirements are the same as the scheduled service.

## Range Requirement

The range is the same as the scheduled service.

## Speed Requirement

Unlike the scheduled service, the greater the speed, the faster the delivery. The initial target was door to door delivery in fours hours. With three hours given to the pre- and post-flight activities, the remaining time for the flight was one hour. For 9000 mi., that meant a block speed of Mach 14.

## Payload Requirements

The payload in this case has to accommodate one customer's shipment. Hence it would be far less than the volume carried by the scheduled service. From conversations with representatives from express delivery companies, it was ascertained that the typical package was between 10 to 70 lb, and about the size of a 18-inch pizza box. To account for the occasional large shipment, a payload capacity of 200 lb and 2 $ft^3$ was defined.

|  | Weightings | Min Flight Time | Min Load / Unloade Time | Min Material Costs | Min Design Costs | Min Manufacturing Costs | Min Fleet Size | Max Flight Hrs / Maint Hrs | Min Fuel Cost | Max Vehicle Reusability | Nominal Ground Crew | Max Use of Existing Facilities | Min Use of Support Equipment | Max System Reliability | Max Fleet Size | Max Payload Protection in Flight | All Weather Capability | Day / Night Capability | Long Ragne | Accommodate Standard LD Containe | Accommodate 6000 pound Payload | Accommodate Payload Size | Conform to Noise Levels | Conform to Emission Levels | Safe Abort |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Faster Delivery Time | 10 | 9 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | 1 |  |  |  |  |  |  |
| Minimize Non-Recurring | 8 |  |  | 9 | 9 | 9 | 9 |  |  |  |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |
| Minimize Operating Cost | 8 |  |  |  |  |  | 9 | 3 | 9 | 9 | 1 |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Minimize Infrastructure Cost | 8 |  |  |  |  |  | 1 |  |  |  |  | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  |
| Turnaround Time (24 Hours) | 9 |  |  |  |  |  |  | 9 |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Aircraft-LikeReliability | 10 |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |
| High Dispatch Reliability | 9 |  |  |  |  |  |  | 3 |  |  |  |  |  | 9 | 9 |  | 9 | 9 |  |  |  |  |  |  |  |
| High Reliability Against Loss of Payload | 10 |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  | 9 |  |  |  |  |  |  |  |  |  |
| Global Flight Coverage | 10 | 9 |  |  |  |  |  |  |  |  |  | 9 | 9 |  | 3 |  |  |  | 9 |  |  |  |  |  |  |
| Use Standard Cargo Containers | 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |
| 6000 lbs Payload | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |  | X |  |  |  |  |
| 600 ft^3 Payload | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| FAA Certification | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X | X | X |
| Score |  | 180 | 10 | 72 | 72 | 72 | 152 | 132 | 72 | 153 | 8 | 162 | 186 | 269 | 111 | 90 | 91 | 81 | 100 | 45 | N/A | N/A | N/A | N/A | N/A |
| Rank |  | 3 | 18 | 13 | 13 | 13 | 6 | 7 | 13 | 5 | 19 | 4 | 2 | 1 | 8 | 11 | 10 | 12 | 9 | 17 | N/A | N/A | N/A | N/A | N/A |
| Next Level Weightings |  | 8 | 1 | 3 | 3 | 3 | 7 | 6 | 3 | 7 | 1 | 7 | 8 | 10 | 5 | 4 | 4 | 4 | 4 | 2 | N/A | N/A | N/A | N/A | N/A |

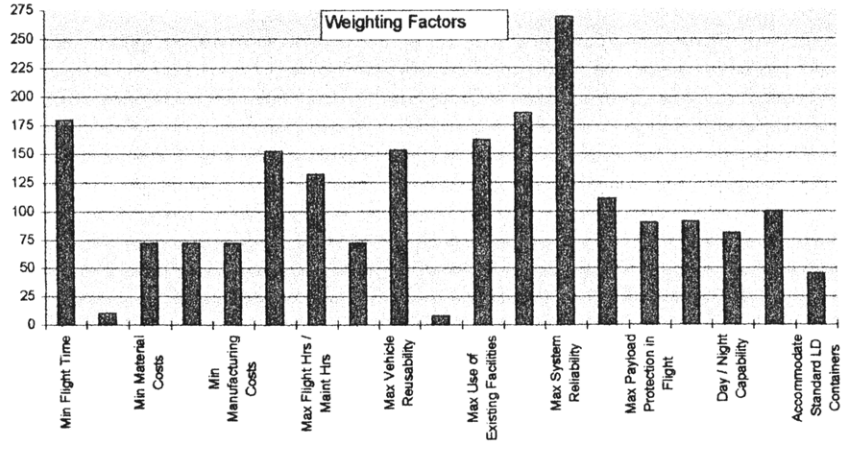


Fig 3-3: Top-Level Requirements QFD for Scheduled Service

|  | Weightings | Max Cruise Speed | Min Time To Cruise | Min Landing Time | Max Access to Cargo Bay | Min Cooling Time | Max Use of Standard Materials | Max Use Off-the-Shelf Components | Min Subsystem Reusability | Min Assembly Effort | Min Part Count | Min Manufacturing Effort | Min Fault Diagnostic Effort | Min Part Replacement Effort | Max Use of Inexpensive Fuels | Min Fuel Transport / Storage Cost | Use Multiple Stages | Max Fuel Efficiency | Max Use of Composite Materials | Autonomous Flight operations | Provide Satellite Comms/Data Link | Max Subsystem Reusability | Unassisted Taxi Capability | Min Number Of Stages | Nominal Take-Off/Landing Distance | Max Integration With Grd Veh | Min Use of Hazardous Materials | Min Start Up Effort | Nominal g Loads | Nominal Env Conditions in Bay | Min Effect of Weather on Mission | Max Functional Redundancy | Max L/D | Carry 200lb Payload | Accom 2'X2'X4' Payload | Min Sonic Boom Audibility on Ground | Min Operating Noise | Min Undesirable Noise | Alternate Landing Site Capability | Integrate With Air Traffic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min Flight Time | 8 | 9 | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |
| Min Load / Unload Time | 1 |  |  |  | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Min Material Cost | 3 |  |  |  |  |  | 9 |  |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Min Development Costs | 3 |  |  |  |  |  | 3 | 9 | 9 |  | 3 |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Min Manufacturing Costs | 3 |  |  |  |  |  | 3 | 3 |  | 9 | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Max Flight hrs / Maint hrs | 6 |  |  |  |  |  |  |  |  |  | 1 |  | 9 | 9 |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |
| Min Fuel Cost | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 | 9 | 9 | 9 | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |  |
| Max Vehicle Reusability | 7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Min Ground Crew | 1 |  |  |  | 1 |  |  |  |  |  |  |  | 3 | 3 |  |  |  |  |  |  |  |  | 9 |  |  | 1 |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |
| Max Use of Existing Facilities | 7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  | 9 | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Max System Reliability | 10 |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  | 1 |  |  | 9 |  |  |  | 1 | 1 |  |  | 9 |  |  |  |  |  |  |  |  |
| Provide Payload Protect in Flight | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 | 9 |  |  |  |  |  |  |  |  |  |  |
| All-Weather Capability | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 | 1 |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |
| Day / Night Capability | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Long Range | 4 | 9 |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  | 9 | 9 | 9 |  | 3 |  |  |  |  |  |  |  | 1 |  |  |  | 9 |  |  |  |  |  |  |  |
| Accommodate Standard LD Containers | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Carry 6000 Pounds Payload | N/A |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |  |  |  |
| Accommodate 2' X 2' X 2' Payload | N/A |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |  |  |
| Conform to Noise Level | N/A |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X | X |  |  |  |
| Conform to Emission Level | N/A |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |
| Safe Abort | N/A |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |
| Score |  | 108 | 8 | 8 | 10 | 9 | 45 | 36 | 27 | 27 | 63 | 27 | 147 | 57 | 27 | 27 | 63 | 63 | 63 | 126 | 30 | 63 | 30 | 96 | 63 | 65 | 72 | 13 | 59 | 36 | 36 | 96 | 117 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Rank |  | 4 | 31 | 31 | 29 | 30 | 17 | 18 | 23 | 23 | 9 | 23 | 1 | 16 | 23 | 23 | 9 | 9 | 9 | 2 | 21 | 9 | 21 | 5 | 9 | 8 | 7 | 28 | 15 | 18 | 18 | 5 | 3 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

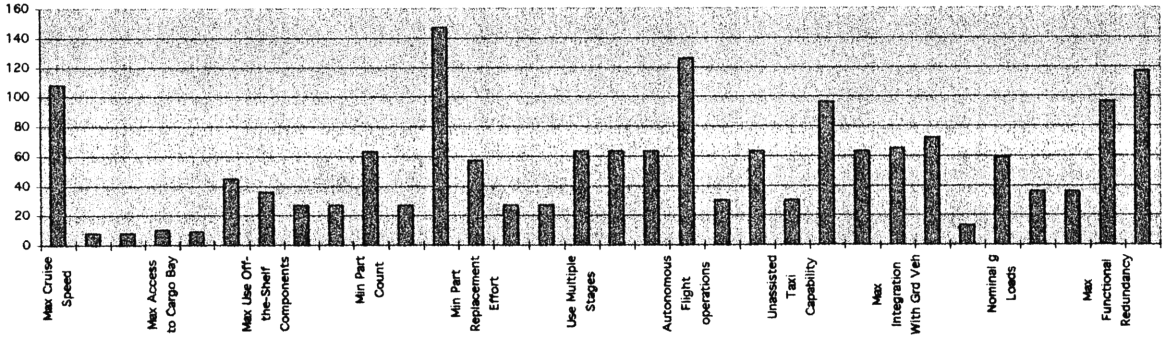


Fig 3-4: Technical Requirements QFD for Scheduled Service

|  | Weightings | Min Flight Time | Min Processing Time | Min Load / Unload Time | Min Transit Time | Min Material Costs | Min Design Costs | Min Manufacturing Costs | Min Fleet Size | Max Flight Hrs / Maint Hrs | Min Fuel Cost | Max Vehicle Reusability | Min Ground Crew | Max Use of Existing Systems | Min Use of Support Equipment | Min Vehicle Prep Time | Max System Reliability | Max Fleet Size | Max Payload Protect in Transit | Max Payload Protection in Flight | All Weather Capability | Day / Night Capability | Long Range | Max Pakage Collect Radius | Accommodate 200 pound Payload | Accommodate Payload Size | Conform to Noise Levels | Conform to Emission Levels | Safe Abort |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Faster Delivery Time | 10 | 9 | 1 | 1 | 9 |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  | 1 |  | 1 |  |  |  |  |  |  |
| Minimize Non-Recurring | 8 |  |  |  |  | 9 | 9 | 9 | 9 |  |  |  |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Minimize Operating Cost | 8 |  |  |  |  |  |  |  | 9 | 3 | 9 | 9 | 3 |  |  | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |
| Minimize Infrastructure Cost | 8 |  |  |  |  |  |  |  | 1 |  |  |  |  | 9 | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Quick Turnaround Time | 9 |  |  |  |  |  |  |  |  | 9 |  | 9 |  |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Aircraft-LikeReliability | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |
| High Dispatch Reliability | 9 |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  | 9 | 9 |  |  | 9 | 9 |  |  |  |  |  |  |  |
| High Reliability Against Loss of Payload | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  | 9 | 9 |  |  |  |  |  |  |  |  |  |
| Global Flight Coverage | 10 | 9 |  |  |  |  |  |  |  |  |  |  |  | 9 | 9 |  |  | 3 |  |  |  |  | 9 |  |  |  |  |  |  |
| Wide Collection Radius | 5 | 1 | 1 | 1 | 9 |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  | 3 |  |  | 9 |  |  |  |  |  |
| 200 lb Payload | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X | X |  |  |  |  | X |  |  |  |  |
| (2' X 2' X 2') Payload | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| FAA Certification | NA |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | X | X | X |
| Score |  | 185 | 15 | 15 | 135 | 72 | 72 | 72 | 152 | 132 | 72 | 153 | 24 | 177 | 186 | 179 | 269 | 111 | 90 | 90 | 106 | 81 | 100 | 45 | N/A | N/A | N/A | N/A | N/A |
| Rank |  | 3 | 22 | 22 | 8 | 16 | 16 | 16 | 7 | 9 | 16 | 6 | 21 | 5 | 2 | 4 | 1 | 10 | 13 | 13 | 11 | 15 | 12 | 20 | N/A | N/A | N/A | N/A | N/A |
| Next Level Weightings |  | 8 | 1 | 1 | 6 | 3 | 3 | 3 | 7 | 6 | 3 | 7 | 1 | 8 | 8 | 8 | 10 | 5 | 4 | 4 | 5 | 4 | 4 | 2 | N/A | N/A | N/A | N/A | N/A |

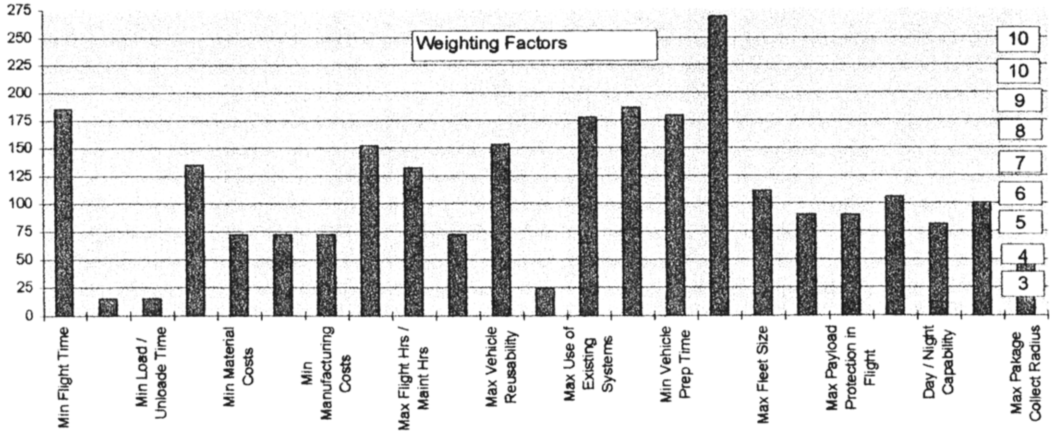


Fig 3-5: Top-Level Requirements QFD for On-Demand Service

| | Weightings | Max Cruise Speed | Min Time To Cruise | Min Landing Time | Max Concurrent Processing Activities | Max Access to Cargo Bay | Min Cooling Time | Real Time Info on Traffic / Route | Min Collect / Dist Radius | Max Velocity of Transfer Mech | Max Use of Standard Materials | Max Use Off-the-Shelf Components | Min Subsystem Reusability | Min Assembly Effort | Min Part Count | Min Manufacturing Effort | Min Fault Diagnostic Effort | Min Part Replacement Effort | Max Use of Inexpensive Fuels | Min Fuel Transport / Storage Cost | Use Multiple Stages | Max Fuel Efficiency | Max Use of Composite Materials | Autonomous Flight operations | Provide Satellite Comms/Data Link | Max Subsystem Reusability | Unassisted Taxi Capability | Min Number Of Stages | Nominal Take-Off/Landing Distance | Max Integration With Grd Veh | Min Use of Hazardous Materials | Min Fuel Time | Min Start Up Effort | Nominal g Loads | Nominal Env Conditions in Bay | Min Effect of Weather on Mission | Max Functional Redundancy | Max L/D | Carry 200lb Payload | Accom 2'X2'X4' Payload | Min Sonic Boom Audibility on Ground | Min Operating Noise | Min Undesirable Noise | Alternate Landing Site Capability | Integrate With Air Traffic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min Flight Time | 8 | 9 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 9 | | | | | | | |
| Min Processing Time | 1 | | | | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Min Load / Unload Time | 1 | | | | | 9 | 9 | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| Min Transit Time | 6 | | | | | | | 3 | 9 | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Min Material Cost | 3 | | | | | | | | | | 9 | | | | 3 | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | |
| Min Development Costs | 3 | | | | | | | | | | 3 | 9 | 9 | | 3 | | | | | | | | | 9 | | | | | | | | | | 1 | | | | | | | | | | | |
| Min Manufacturing Costs | 3 | | | | | | | | | | 3 | 3 | | 9 | 9 | 9 | | | | | | | | | | | | | | | 3 | | | 1 | | | | | | | | | | | |
| Max Flight hrs / Maint hrs | 6 | | | | | | | | | | | | | | 1 | | 9 | 9 | | | | | | | | | | 1 | | | | | | | | | 1 | | | | | | | | |
| Min Fuel Cost | 3 | | | | | | | | | | | | | | | | | | 9 | 9 | 9 | 9 | 9 | 9 | | | | | | | | | | | | | | 3 | | | | | | | |
| Max Vehicle Reusability | 7 | | | | | | | | | | | | | | | | | | | | | | | | | 9 | | | | | | | | | | | | | | | | | | | |
| Min Ground Crew | 1 | | | | | 1 | | | | | | | | | | | 3 | 3 | | | | | | | | | 9 | | | 1 | | | 3 | | | | | | | | | | | | |
| Max Use of Existing Facilities | 8 | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | | 9 | 9 | 9 | | | | | | | | | | | | | | |
| Min Vehicle Prep Time | 8 | | | | | | 1 | | | | | | | | | | 9 | | | | | | | | | | | 9 | | | | 9 | 9 | | | | | | | | | | | | |
| Max System Reliability | 10 | | | | | | | | | | | | | | | | 9 | | | | | | | | 1 | | | 9 | | | | | 1 | 1 | | | 9 | | | | | | | | |
| Provide Payload Protect in Flight | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 9 | 9 | | | | | | | | | | |
| All-Weather Capability | 2 | | | | | | | | | | | | | | | | | | | | | | | 9 | 1 | | | | | | | | | | | 9 | | | | | | | | | |
| Day / Night Capability | 4 | | | | | | | | | | | | | | | | | | | | | | | 9 | 1 | | | | | | | | | | | | | | | | | | | | |
| Long Range | 4 | 9 | | | | | | | | | | | | | 3 | | | | | | 9 | 9 | 9 | | 3 | | | | | | | | | 1 | | | | 9 | | | | | | | |
| Max Package Collection Radius | 2 | 1 | 1 | 1 | 1 | | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Carry 200 Pounds Payload | N/A | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | |
| Accommodate 2' X 2' X 2' Payload | N/A | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | |
| Conform to Noise Level | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | | | |
| Conform to Emission Level | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | |
| Safe Abort | N/A | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | |
| Score | | 110 | 10 | 10 | 11 | 10 | 17 | 20 | 54 | 56 | 45 | 36 | 27 | 27 | 63 | 27 | 219 | 57 | 27 | 27 | 63 | 63 | 63 | 108 | 28 | 63 | 33 | 168 | 72 | 74 | 81 | 72 | 85 | 59 | 36 | 18 | 96 | 117 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Rank | | 4 | 35 | 35 | 34 | 35 | 33 | 31 | 20 | 19 | 21 | 22 | 26 | 26 | 12 | 26 | 1 | 18 | 26 | 26 | 12 | 12 | 12 | 5 | 25 | 12 | 24 | 2 | 10 | 9 | 8 | 10 | 7 | 17 | 22 | 32 | 6 | 3 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

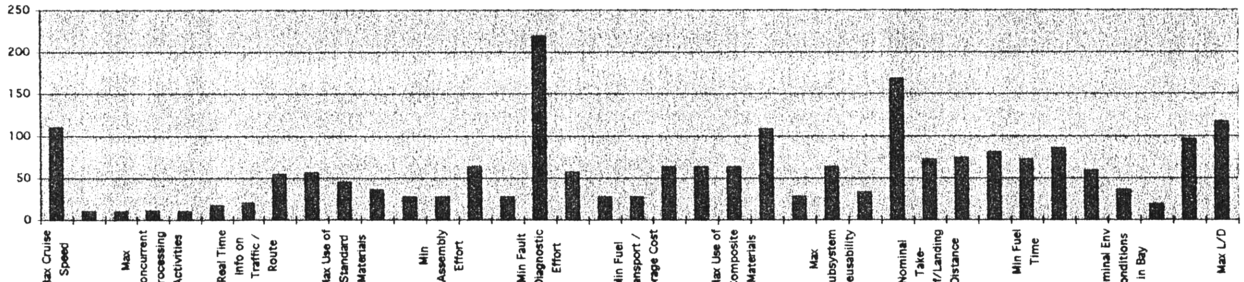


Fig 3-6: Technical Requirements QFD for On-Demand Service

# 4. VEHICLE CONCEPT SELECTION

This chapter describes how the vehicle concept was selected. A summary of the process is shown in Fig. 4-1. In this discussion, the "mission" refers to the flight portion of the mission performed by the Fast Package vehicle.

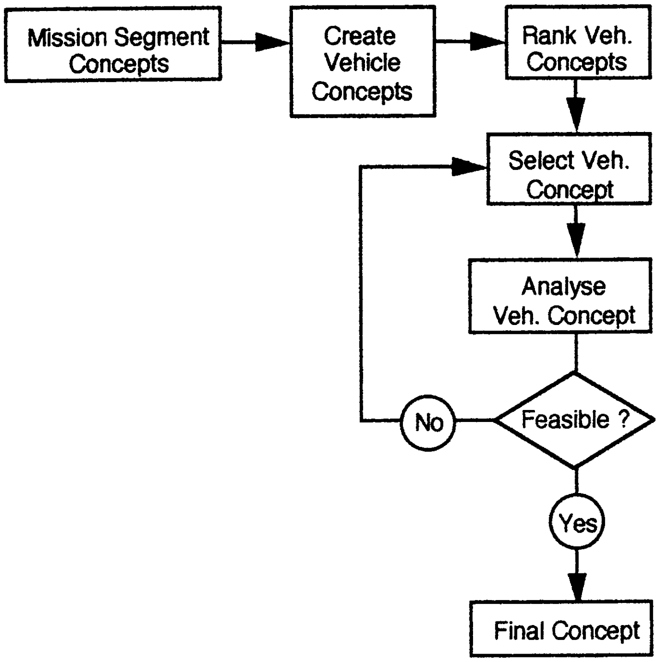


**Fig. 4-1: Vehicle Concept Selection Process.**

The first step was to consider several concepts for each mission phase: Launch, Cruise, and Terminal. The Launch phase includes takeoff, climb, and staging (if any). The Terminal phase is the descent or re-entry, and the landing.

The next step was to create several vehicle concepts by mixing and matching the Launch, Cruise and Terminal flight segment concepts. The list of vehicle concepts were then ranked according to how well they satisfied the Fast Package requirements. In principle, the vehicle concept which ranked the highest would be selected. In reality, because a lot of assumptions had to be made during the ranking, the highest ranked concept may not be feasible after more detailed analysis is in hand. If so, the next highest ranking vehicle concept would be selected. The iteration is repeated until a feasible solution is found.

## 4.1 Mission Segment Concepts

Launch Phase

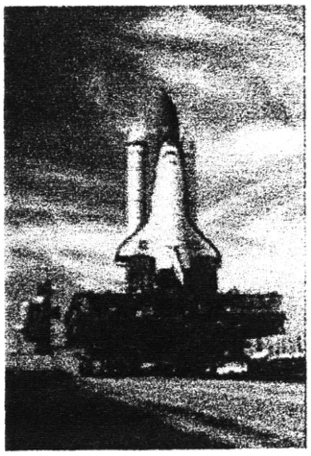


Fig. 4-2: Ground Based Vertical Launch.

*Conventional Ground-Based Vertical Launch.* - (Fig. 4-2) The advantage of vertical launch is that it requires less space than a runway. It is attractive if there is the need to have dedicated launch sites built. The disadvantage is that a lot of thrust is required to overcome gravity. Variants of ground based vertical launch are fixed platform and mobile truck. The latter allows for some flexibility in the location of the launch, and is feasible only for a small vehicle.

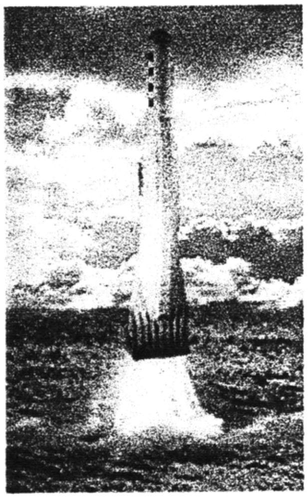


Fig. 4-3: Sea Launch.

*Ocean-based Vertical Launch* - (Fig. 4-3) The advantage here is that the vehicle is launched at a safe distance from populated areas. Apart from the fact that this will only work for coastal cities, there is also the problem of taking the vehicle out to sea without losing too much time. Another problem is that this launch concept would be unusable under rough water conditions. Again a lot of thrust is required to overcome gravity.

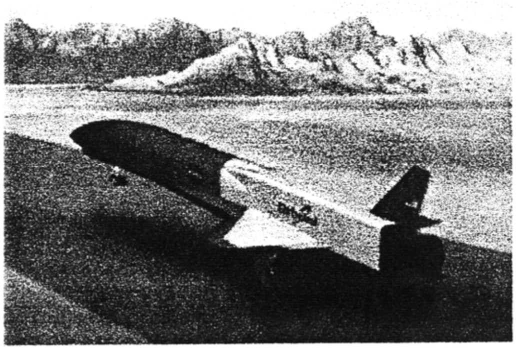


Fig. 4-4: Horizontal take-off.

*Horizontal Take-off* - (Fig. 4-4) This has a possibility of launching from a commercial airport. Less thrust is needed since gravity effect is minimal. The saving on the propulsion plant may however be offset by the weight of the extra lifting surface (i.e. wings) needed for horizontal take-off. A regulatory issue is whether or not rockets will be permitted for such launches from commercial airports.

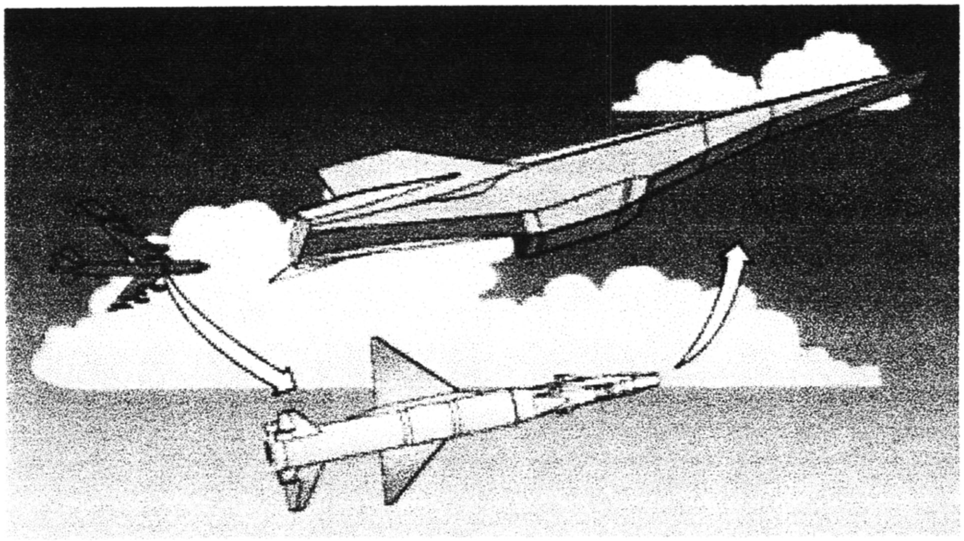


**Fig. 4-5: Air-Launched.**

*Air-launched* - (Fig. 4-5) Useful for rocket powered vehicles, since it is not likely that a rocket vehicle would be permitted to launch from a conventional airport runway. Elias [9] also pointed out that an air launch system has the ability to launch the rocket to an orbit of any inclination, regardless of weather conditions, increasing the effective Isp of the rocket engines, and reducing drag and gravity losses by starting the vehicle off above the thickest part of the atmosphere.

## Cruise Phase

The main differences in cruise concept is the type of propulsion system used.

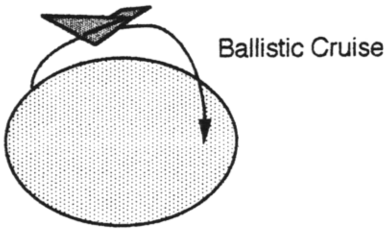


**Fig. 4-6: Rocket propelled ballistic cruise.**

*Rocket* - (Fig. 4-6) A ballistic cruise is implied. Rockets are well-established for high speed propulsion. They can also operate outside of the atmosphere, thereby minimizing the exposure time to aeroheating. The problem with current rockets is that their reusability and reliability are not suitable for Fast Package operations. For now, it was assumed that reusability and reliability for a new rocket engine can be improved if they were made to design requirements. Although the rocket engine is much lighter than a gas turbine engine, the weight of the fuel may result in a heavier system, especially at longer ranges. Multiple stages may be required.

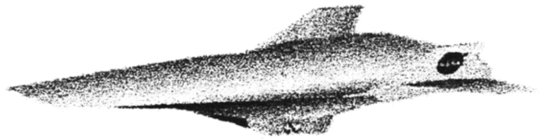


**Fig. 4-7: Scramjet vehicle.**

*Scramjet* - (Fig. 4-7) Scramjets (Supersonic Combustion RAMJET) can be used from Mach 6 to 16. Its advantage over the rocket is in the fuel consumption. It uses atmospheric air so the oxidizer need not be carried on board, thereby reducing the weight even more. However, this leads to one of the major obstacles, which is the prolonged aeroheating during cruise. An important issue with regard to scramjets is that it is still under development and will be unlikely to see service for quite some time.

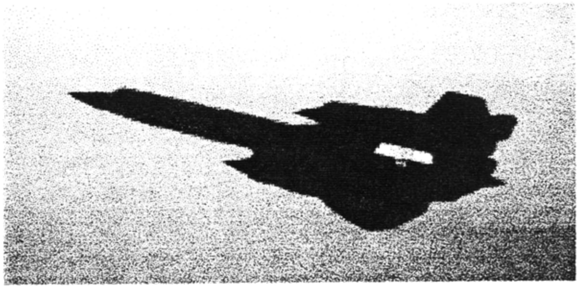


**Fig. 4-8: Turbojet/Ramjet vehicle.**

*Ramjets* - (Fig. 4-8) Ramjets can be used between Mach 2 to 6. There is insufficient external (ram) compression below Mach 2, while the heat from the compression is so high that the work done by the engine (and hence the thrust) diminishes above Mach 6. This is why the scramjet is needed above Mach 6.

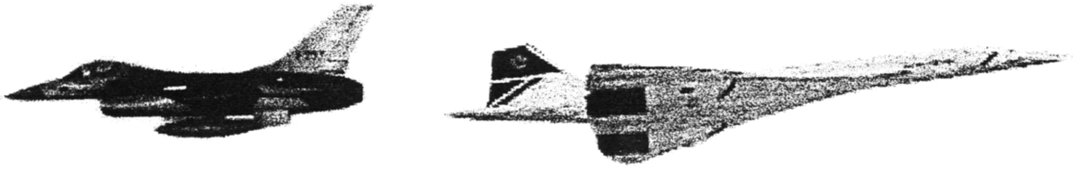


**Fig. 4-9: Turbofan (left) and turbojet vehicles.**

*Turbojets or Turbofans* - (Fig. 4-9) Conventional turbojet and turbofan engines have good reliability and reusability. They are, however, limited to a maximum speed of Mach 3.

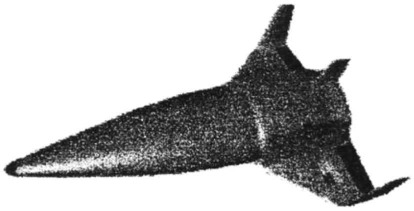


**Fig. 4-10: RBCC vehicle.**

*Rocket Based Combined Cycle (RBCC)* - (Fig. 4-10) The trajectory is still ballistic because of the short burn time. However, a RBCC vehicle needs less oxider than an equivalent rocket vehicle because the engine is capable of operating in an airbreathing mode.

### Terminal Phase

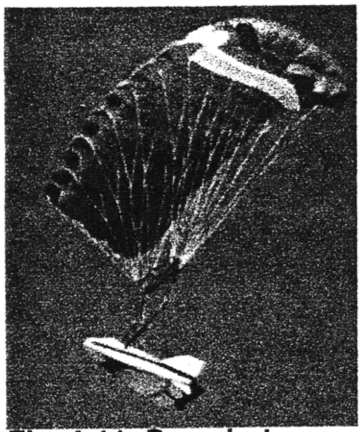


**Fig. 4-11: Parachute landing.**

*Parachute* - (Fig. 4-11) Parachutes are inexpensive and simple in construction. They do not add much weight to the vehicle. There is a vast amount of experience with parachutes. The disadvantage is that parachutes are prone to wind conditions, resulting in low reliability. This may be improved by incorporating precision guidance and control into the parachute system, so that the vehicle will land accurately in the designated area. Another disadvantage is that the maneuverability is limited, so it cannot make large corrections in trajectory.

**Fig. 4-12: Rotor assisted landing.**

*Rotor* - (Fig. 4-12) Rotor blades are deployed which will autogyrate to slow the vehicle's decent. This concept is less prone to wind conditions than a parachute. It is however heavier. Without power, it is also limited in maneuverability and it cannot make large corrections in trajectory. This problem can of course be solved by connecting the rotor to an engine, much like a helicopter, but the weight and complexity of the system will increase.

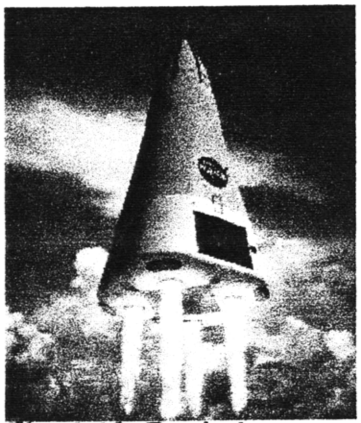


**Fig. 4-13: Rocket powered vertical landing.**

*Powered vertical landing* - (Fig. 4-13) Flight path can be controlled, resulting in better reliability than parachutes and unpowered rotors in landing. A small area is sufficient for landing. The major problem with this approach is that the fuel needed for landing will reduce the payload mass fraction significantly.

*Airdrop Package* - (Fig. 4-14) One concept that was initially explored was ejecting the payload container prior to landing. The payload will then parachute to its final destination, under its own guidance system. In the meantime, the vehicle will continue on to a landing site. The advantage of this approach is that the landing site need not be close to populated areas, since the time needed to get the package from the landing site to the customer is minimized. The major obstacle to this option is getting clearance from authorities to drop packages in populated areas. From discussions with faculty members who worked with the FAA, it was very unlikely that approval would be granted. Hence this concept was abandoned.

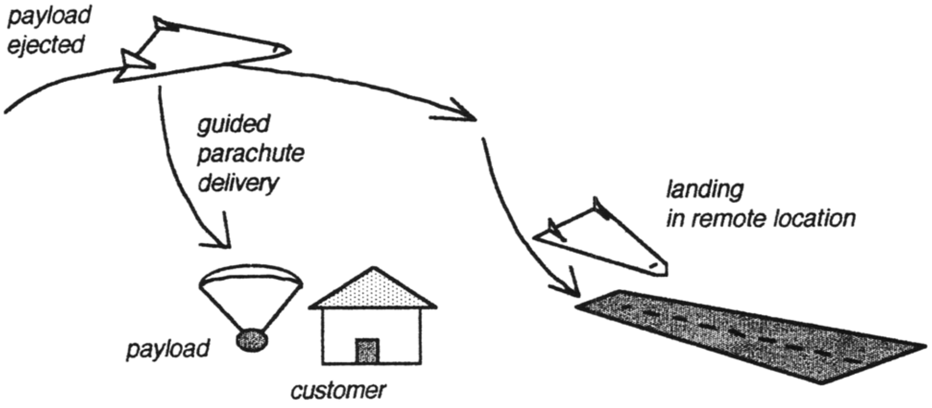


**Fig. 4-14: Airdropped Package**

## 4.2 Vehicle Concepts

Fig. 4-15 illustrates how the mission segment concepts could be linked to form a vehicle concept.

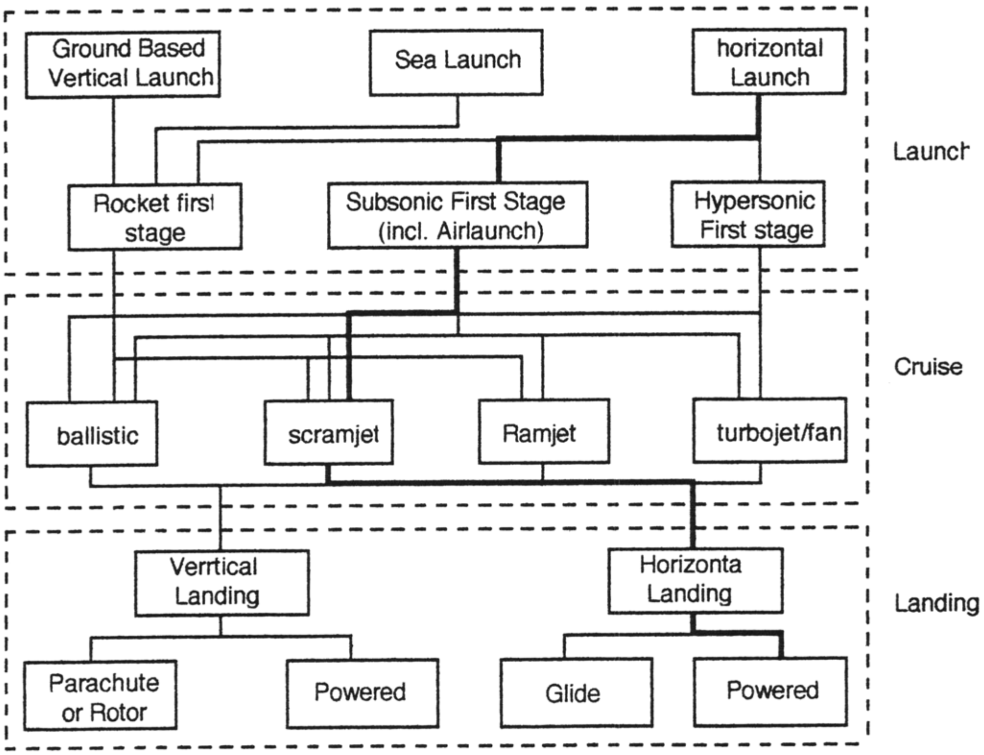
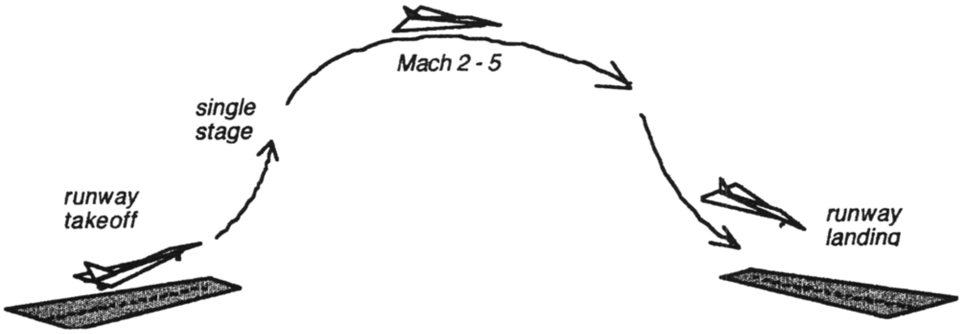


**Fig. 4-15: Synthesis of Vehicle Concepts.**

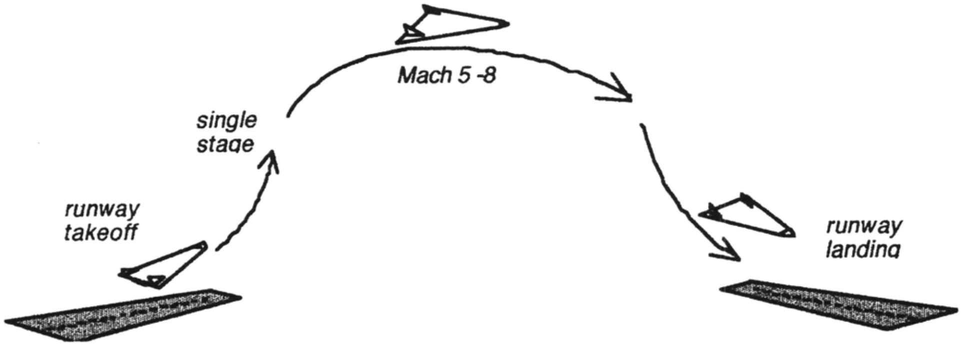
The following are the vehicle concepts which were derived from the mission segment concepts above.

Concept #1: Mach 2 to 5 supersonic airplane



- Single stage
- Runway takeoff and landing
- Turbofan/ramjet propulsion
- Mach 2 to 5 atmospheric cruise

Concept #2: Mach 5 to 8 scramjet airplane



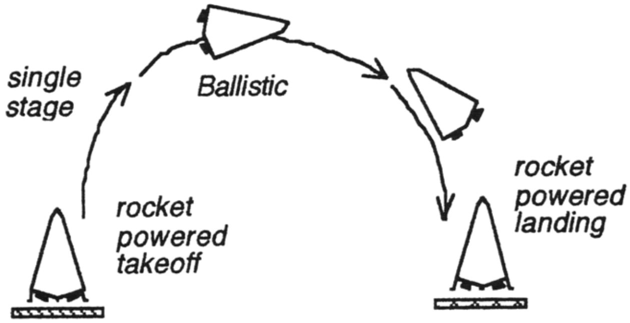
- Single stage
- Runway takeoff and landing
- Multi-mode Scramjet propulsion
- Mach 5 to 8 atmospheric cruise

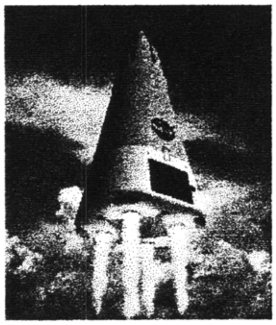
The difference between this and Concept #1 was the cruise speed.

Concept #3: Mach 8+ Scramjet Airplane

This is the same as Concept #2, except a higher cruise speed. This was introduced to improve the system reliability.

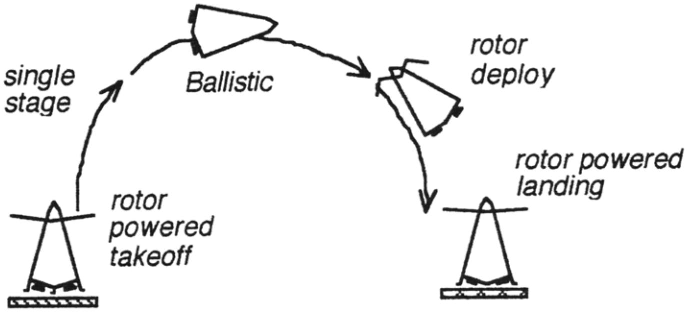
## Concept #4: Vertical Takeoff & Landing Rocket

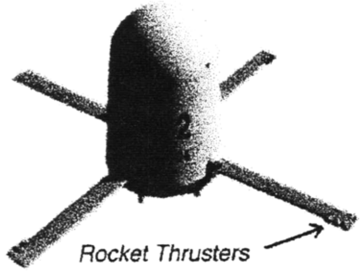




- Single stage
- Vertical takeoff and landing
- Rocket propulsion
- Exoatmosphric ballistic cruise (~ Mach 24)

## Concept #5: Rocket-Powered Rotor



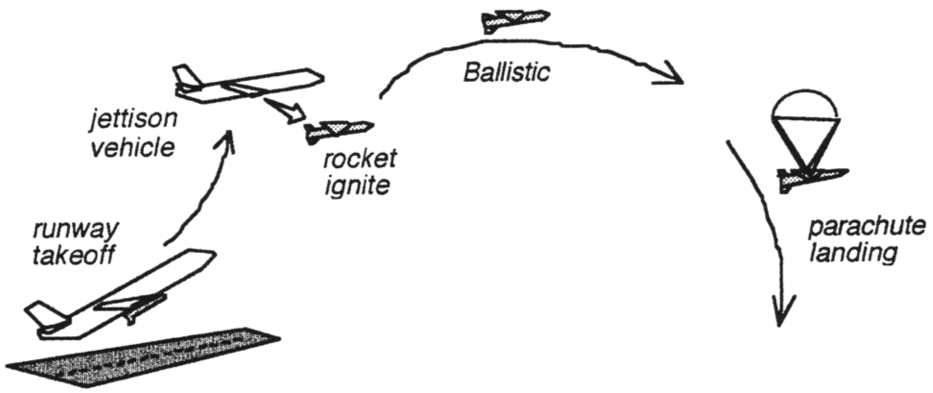


- Single stage
- Vertical takeoff and landing
- Rocket driven rotors to power takeoff and landing
- Rocket propulsion
- Exoatmospheric ballistic cruise (~ Mach 24)

## Concept #6: Airbreathing Rotor+Rocket Cruise

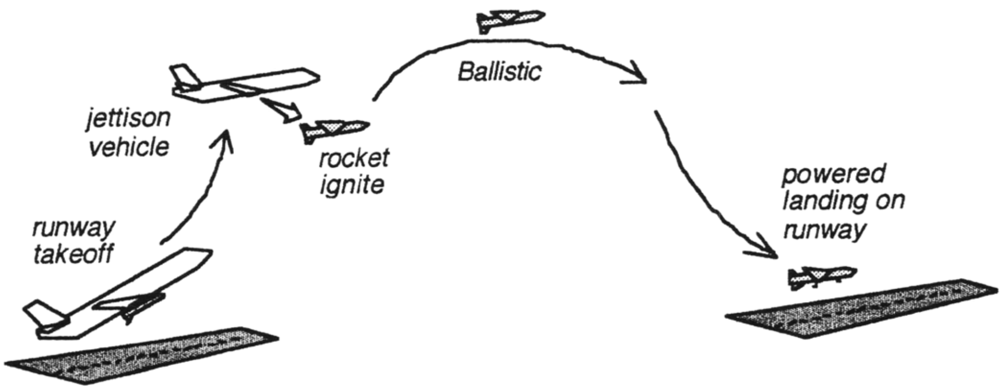
The is the same as Concept #5, except that the rotor is driven by a gas turbine engine in this case. This concept will therefore be less noisy than Concept #5. The cruise is still a rocket propelled ballistic trajectory.

## Concept #7: Airdropped, Rocket Cruise, Parachute Landing



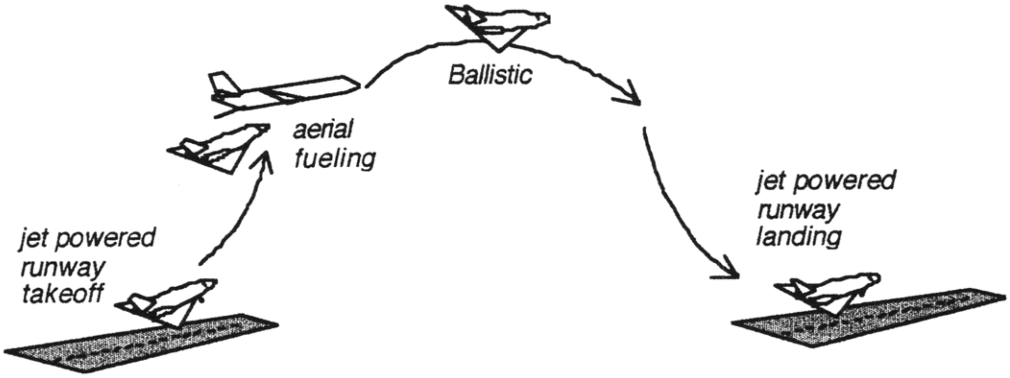
- Runway takeoff
- Airlaunch vehicle
- Rocket propelled
- Exoatmospheric ballistic cruise (~Mach 24)
- Parachute landing

## Concept #8: Air-dropped, Rocket Cruise, Powered Landing



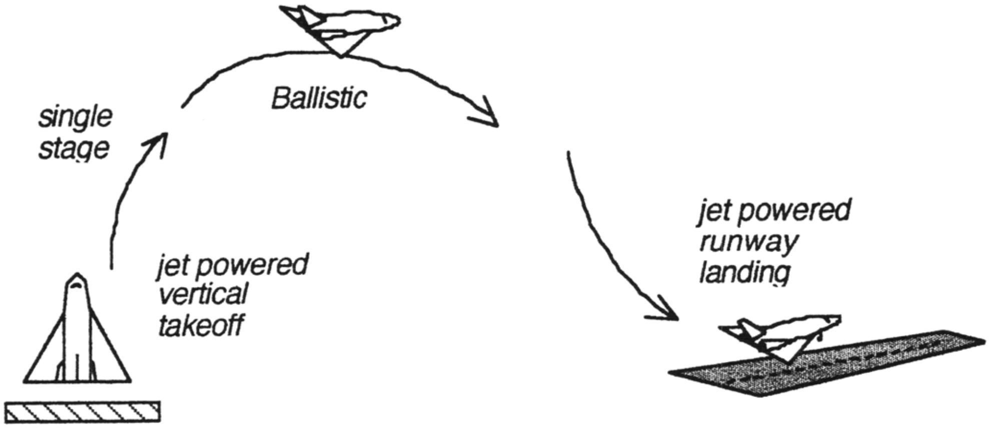
This concept is similar to Concept #7 except that the vehicle lands on a runway powered by its engines.

## Concept #9: Horizontal Airbreathing Takeoff & Landing, Rocket Cruise, Horizontal Landing (Pioneer)



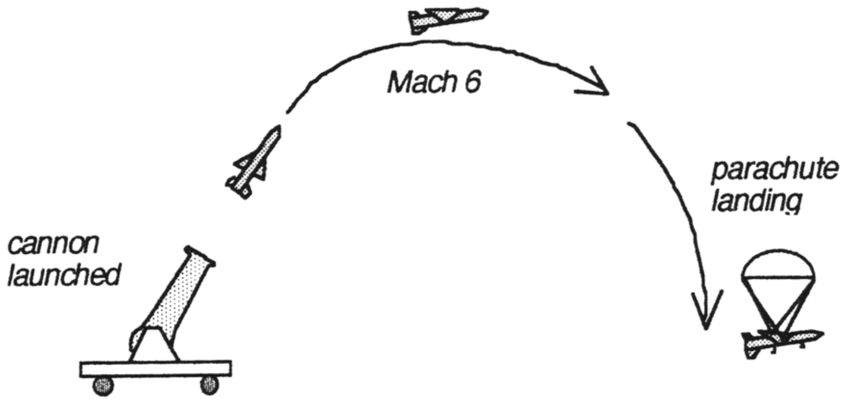
- Stage-and-a-half (airborne tanker)
- Runway takeoff using auxiliary jet engines
- Aerial refuel
- Rocket propelled
- Exoatmospheric ballistic cruise (~Mach 24)
- Runway landing using auxiliary jet engines

## Concept #10: Airbreathing Vertical Take-off, Rocket Cruise, Horizontal Landing



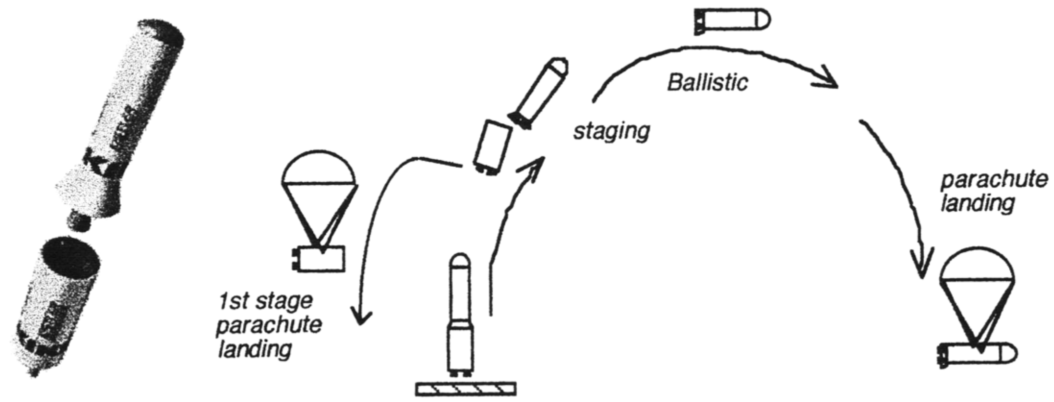
- Vertical takeoff using jet engines
- Single stage
- Rocket propelled ballistic cruise
- Jet powered runway landing

Concept #11: Cannon Launch, Advanced Airbreathing Cruise, Parachute Landing



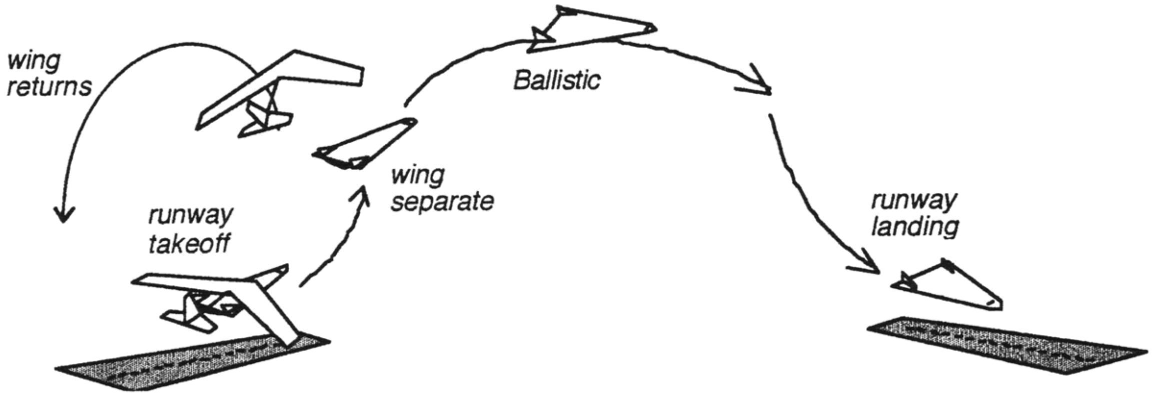
- Cannon launch (boost to > Mach 2)
- Advanced Turbo Ramjet engine
- Atmospheric cruise (~Mach 6)
- Parachute landing

Concept #12: Fully Reusable Two-Stage Rocket, Parachute Landing



- Two stage (both reusable)
- Ground based vertical launch
- Rocket propelled ballistic cruise (~Mach 24)
- Parachute launch

Concept #13: Wing Assisted Horizontal Take-off, Ramjet, Rocket, Glide, Powered Landing



- Wing assisted take-off and climb
- Wing powered by own turbofan engines
- Wing returns to based after releasing Fast Package vehicle
- RBCC (Ejector-Ramjet-Rocket) engine
- Ballistic cruise
- Runway landing under engine power

The purpose of the wing is to get the vehicle 100 miles out to sea before being permitted (sonic boom regulations) to go supersonic. Otherwise, the engine would consume too much fuel during this segment of the flight.

## 4.3 Vehicle Concept Selection

The concepts were assessed relative to one another using a modified Pugh matrix. The matrix consists of a list of the Fast Package requirements on the left axis, with the concepts listed a the top (Fig. 4-16). Each concept was given a score (from a scale of -3 to 3) against a list of Fast Package requirements on the left. The baseline for comparison was the Concorde. Scoring could be described as being subjective, since no analysis was performed yet at this stage. However, it was hoped that the subjectiveness was minimized by the team effort and the mix of teammate backgrounds and interests.

The final score for each concept was obtained after multiplying the appropriate weighting from the requirements. This is similar to the QFD approach discussed earlier. In theory, various concepts could be ranked to denote how well each satisfied the multiple requirements.

The concepts were analyzed separately for Schedule Service and On-Demand Service vehicles, since their requirements were slightly different.

| | Weighting | Concorde (Baseline) | Small High Speed Aircraft, Mach 3 - 5 (High Speed Gulfstream) | Small Hypersonic Aircraft, Mach 5 - 8 | Ultra High Speed Lifting Body, Mach 8+ (National Aerospace Plane) | Vertical Take-Off and Landing Rocket (DC-X) | Rocket Powered Rotor Tips | Airbreathing Rotor, Rocket Cruise | Aircraft Drop TO, LH/LOX Cruise, Parachute Landing (Pegasus) | Air Dropped, Kerosene/LOX Cruise, Powered Landing (X-34) | Horizontal Airbreathing Take-off, Rocket Cruise, Horizontal Landing (Pioneer) | Air Breathing Verticle Take-Off, Rocket Cruise, Horizontal Landing | Cannon Launched, Advanced Airbreathing Cruise, Parachute Landing | Two Reusable Stages, Parachute Landing (Kistler) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min Flight Time (8000 mile < 6 Hours) | 8 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max System Reliability | 10 | | 1 | -1 | -3 | -1 | -3 | -2 | -1 | -1 | -1 | -2 | -3 | -2 |
| Min Development Costs | 3 | | 0 | -1 | -3 | 0 | -3 | -3 | 1 | 0 | 0 | -1 | -3 | 1 |
| Min Manufacturing Costs | 3 | | 1 | -1 | -2 | 1 | -1 | -1 | 3 | 2 | 1 | 1 | -2 | 2 |
| Max Flight Mile / Maint Hours | 6 | | 0 | 0 | -1 | -1 | -3 | -3 | -1 | -1 | -1 | -1 | -1 | -1 |
| Min Fuel Costs | 3 | | 0 | -1 | -2 | -3 | -2 | -2 | -2 | 1 | 0 | -1 | 2 | -2 |
| Max Reusability | 7 | | 0 | 0 | -1 | -2 | -2 | -2 | -3 | -3 | -3 | -3 | -3 | -3 |
| Min Ground Crew | 1 | | 0 | 0 | -1 | 0 | -1 | -1 | -2 | -2 | -1 | -2 | -1 | -3 |
| Max Use of Existing Launch Facilities | 7 | | 0 | 0 | 0 | -1 | -1 | -1 | -3 | 0 | 0 | 0 | -3 | -2 |
| Min Need For Support Equipment | 8 | | 0 | 0 | 0 | -1 | -1 | -1 | -3 | -3 | -3 | -2 | -1 | -3 |
| All Weather Capability | 4 | | 0 | 0 | 0 | 1 | -1 | -1 | -2 | 0 | 0 | 0 | -1 | -1 |
| Noise Regulations | N/A | | | | | X | X | | | | | | X | X |
| | Score | | 21 | -11 | -57 | -39 | -92 | -82 | -78 | -46 | -51 | -60 | -92 | -81 |
| | Rank | | 1 | 2 | 6 | 3 | 11 | 10 | 8 | 4 | 5 | 7 | 11 | 9 |

**Fig. 4-16: Scheduled Service Vehicle Concept Matrix.**

## 4.4 Scheduled Service Concept

From the concept matrix (Fig. 4-16), it can be seen that the best concept for Scheduled Service was the Mach 2 to 5 airplane (Concept #1). This was expected since, if not for speed, there is little doubt that a supersonic airplane will beat a reusable launch vehicle in terms of reusability, reliability, maintenance, support equipment and integration with existing facilities. Jet engine noise is also less than with rockets.

Even the hypersonic airplane fared better than the rocket concepts. The best rocket concept was the vertical takeoff and landing rocket.

## 4.5 On-Demand Vehicle Concept

The concept matrix for the on-demand service is shown in Fig. 4-17. Again, the Mach 2-5 airplane scores the highest. However, this was not acceptable because it was considered too slow. The matrix failed to rule it out because the range on the rating was too small to have any effect. It would have been better to omit it from the matrix.

The next highest concept was selected instead. This was the wing-assisted-ramjet/rocket vehicle (Concept #13). This concept scored for flight time, system reliability, maintenance, use of existing facilities and range.

|  | Weighting | Concorde (Baseline) | Turbojet Take-Off, ScramjetCruise (Mach 12), Turbojet Landing | Vertical Take-Off and Landing Rocket (DC-X) | Rocket Powered Rotor Tips | Airbreathing Rotor, Rocket Cruise | Aircraft Drop TO, LH/LOX Cruise, Parachute Landing (Pegasus) | Air Dropped, Kerosene/LOX Cruise, Powered Landing (X-34) | Horiztontal Airbreathing Take-off, Rocket Cruise, Horizontal Landing (Pioneer) | Air Breathing Verticle Take-Off, Rocket Cruise, Horizontal Landing | Cannon Launched, Advanced Airbreathing Cruise, Parachute Landing | Two Reusable Stages, Parachute Landing (Kistler) | Wing Assisted Horizontal Take-Off, Ramjet, Rocket, Glide, Powered Land |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min Flight Time | 8 |  | 2 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| Max System Reliability | 10 |  | -1 | -1 | -3 | -2 | -1 | -1 | -1 | -2 | -3 | -2 | -1 |
| Min Development Costs | 3 |  | -2 | -1 | -2 | -1 | 1 | 0 | 0 | 0 | -3 | 1 | 0 |
| Min Manufacturing Costs | 3 |  | -1 | 1 | -1 | -1 | 3 | 2 | 1 | 1 | -2 | 2 | 1 |
| Max Flight Mile / Maint Hours | 6 |  | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -1 | 0 | -1 | -1 |
| Min Fuel Costs | 3 |  | -1 | -3 | -2 | -2 | -2 | 1 | 0 | -1 | 2 | -2 | -1 |
| Max Reusability | 7 |  | -1 | -2 | -2 | -2 | -2 | -2 | -2 | -2 | -2 | -3 | -1 |
| Min Ground Crew | 1 |  | -1 | 0 | -1 | -1 | -2 | -2 | -1 | -2 | -1 | -3 | -2 |
| Max Use of Existing Launch Facilities | 8 |  | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | -3 | -2 | 1 |
| Min Need For Support Equipment | 8 |  | 0 | -1 | -1 | -1 | -3 | -3 | -3 | -1 | -1 | -3 | -2 |
| Min Prep Time | 8 |  | -1 | -1 | -1 | -1 | -3 | -3 | -1 | -1 | 0 | -3 | -2 |
| All Weather Capability | 5 |  | 0 | 1 | -1 | -1 | -2 | 0 | 0 | 0 | -1 | -1 | 0 |
| Long Range (9000 miles) | 4 |  | 3 | 0 | 3 | 3 | 3 | 3 | 0 | 3 | 3 | 3 | 3 |
| Noise Regulations | N/A |  |  | X | X |  |  |  |  |  | X | X |  |
|  | Score |  | 0 | -18 | -57 | -36 | -48 | -19 | -20 | -6 | -55 | -80 | -13 |
|  | Rank |  | 1 | 4 | 10 | 7 | 8 | 5 | 6 | 2 | 9 | 11 | 3 |

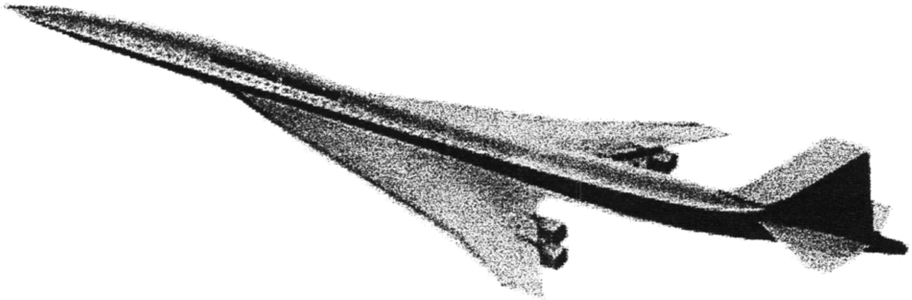
Fig. 4-17: On-Demand Service Vehicle Concept Matrix.

## 5. SCHEDULED SERVICE VEHICLE

It was determined in Section 3.4 that the Scheduled Service needed a block speed of Mach 2 (or Mach 2.5 with a one-hour stop-over), and a payload capacity of 24,000 lbs. The concept selection process then identified the best concept to be a supersonic airplane. A possible design for such a vehicle is proposed in this chapter.

The sizing of the vehicle was carried out by Palmer [10] according to the procedure laid out in Raymer [11]. The method, which is based on statistical trends, predicted a vehicle size in the order of the High-Speed Civil Transport. This was surprising since the payload capacity of HSCT is ten times greater, which was why it was initially thought to be too big for Fast Package. Upon inspection, it was found that the drag and propulsion performance were conservative relative to HSCT. Rather than to duplicate the work carried out for HSCT, it was decided that HSCT will be the proposed vehicle for the Scheduled Service. Using HSCT is also advantageous because most of the development cost will be borne by the passenger transportation market.

Fig. 5-1 shows the HSCT and some of its attributes.

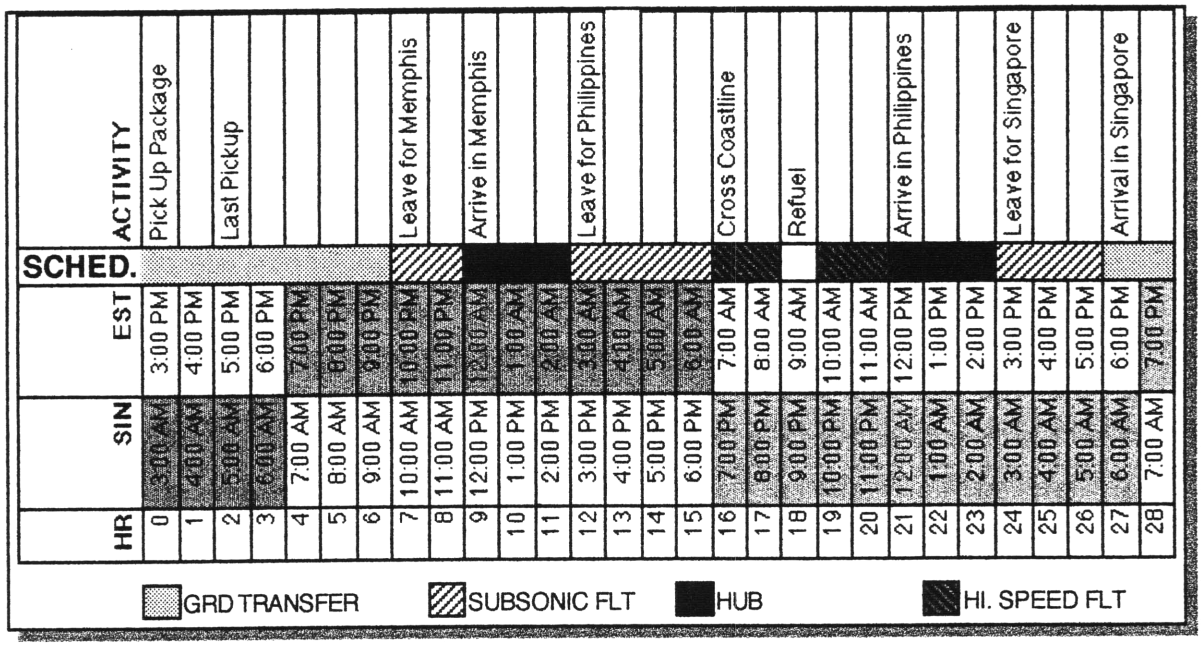


- Cruise speed : Mach 2.5
- Non-stop Range : 5,500 nm.
- Payload capacity : 300 passengers (~63,000 lb)
- Price : $15 per pound of payload
-

**Fig. 5-1: High-Speed Civil Transport**

Note that one stop-over is required because the non-stop range is insufficient. However, the cruise speed is fast enough to make up for the time.

The delivery time line is shown in Fig. 5-2.



| HR | SIN | EST | SCHED. | ACTIVITY |
|---|---|---|---|---|
| 0 | 3:00 AM | 3:00 PM | ░ | Pick Up Package |
| 1 | 4:00 AM | 4:00 PM | ░ | |
| 2 | 5:00 AM | 5:00 PM | ░ | Last Pickup |
| 3 | 6:00 AM | 6:00 PM | ░ | |
| 4 | 7:00 AM | 7:00 PM | ░ | |
| 5 | 8:00 AM | 8:00 PM | ░ | |
| 6 | 9:00 AM | 9:00 PM | ░ | |
| 7 | 10:00 AM | 10:00 PM | ▨ | Leave for Memphis |
| 8 | 11:00 AM | 11:00 PM | ▨ | |
| 9 | 12:00 PM | 12:00 AM | ■ | Arrive in Memphis |
| 10 | 1:00 PM | 1:00 AM | ■ | |
| 11 | 2:00 PM | 2:00 AM | ■ | |
| 12 | 3:00 PM | 3:00 AM | ▨ | Leave for Philippines |
| 13 | 4:00 PM | 4:00 AM | ▨ | |
| 14 | 5:00 PM | 5:00 AM | ▨ | |
| 15 | 6:00 PM | 6:00 AM | ▨ | |
| 16 | 7:00 PM | 7:00 AM | ▩ | Cross Coastline |
| 17 | 8:00 PM | 8:00 AM | ▩ | |
| 18 | 9:00 PM | 9:00 AM | | Refuel |
| 19 | 10:00 PM | 10:00 AM | ▩ | |
| 20 | 11:00 PM | 11:00 AM | ▩ | |
| 21 | 12:00 AM | 12:00 PM | ■ | Arrive in Philippines |
| 22 | 1:00 AM | 1:00 PM | ■ | |
| 23 | 2:00 AM | 2:00 PM | ■ | |
| 24 | 3:00 AM | 3:00 PM | ▨ | Leave for Singapore |
| 25 | 4:00 AM | 4:00 PM | ▨ | |
| 26 | 5:00 AM | 5:00 PM | ▨ | |
| 27 | 6:00 AM | 6:00 PM | ░ | Arrival in Singapore |
| 28 | 7:00 AM | 7:00 PM | ░ | |

░ GRD TRANSFER ▨ SUBSONIC FLT ■ HUB ▩ HI. SPEED FLT

Fig. 5-2: Scheduled Service Time Line Using HSCT

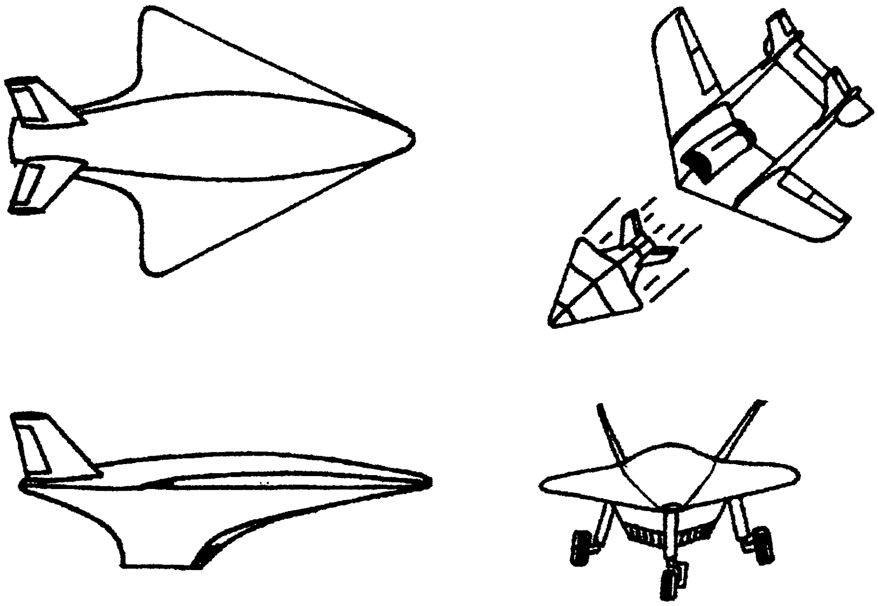
# 6. ON-DEMAND SERVICE VEHICLE

Even having selected the concept, there were several iterations before settling on a final configuration. This was because a number of unforeseen issues arose when detailed calculations were performed. This chapter presents how the final design was derived from the concept which was selected by the concept matrix.

## 6.1 Initial Concept

Mach 16 was initially the chosen speed in order to achieve the four-hour door to door delivery time. This was not an unreasonable speed since it was within the capability of most reusable launch vehicles. In addition, the payload capacity was 200 lbs and the range 9000 mi.

The concept selected for On-Demand service was a wing-assisted-ramjet/rocket vehicle. Fig. 6-1 shows such a concept.



RBCC Vehicle

| | |
|---|---|
| Max speed | : Mach 24 |
| Range | : 9000 mi. |
| Trajectory | : Boost-glide |
| Payload | : 200 lb |
| Empty Wt | : 6,000 lb |
| Fuel Wt | : 35,000 lb |
| Propulsion | : Ejector Ramjet-Scramjet-Rocket |
| Cruise L/D | : 4 |

Winged Vehicle

| | |
|---|---|
| Max speed | : Mach 0.7 |
| Range | : 200 mi |
| Payload | : 41,000 lb |
| Empty Wt | : 67,000 lb |
| Fuel Wt | : 25,000 lb |
| GTOW | : 132,000 lb |
| Propulsion | : 2 Turbofan engines |
| Cruise L/D | : 16 |

**Fig. 6-1: Initial On-Demand Concept (Palmer [10])**

Note that the Mach 24 cruise was greater than what was specified in the requirements. This was because the speed was driven by the range requirements. Mach 24 was needed to achieve the required ballistic range, even with a 900-mile glide assumed at the end of the flight.

## 6.2 Further Design Iterations

Propulsion was the key design driver. Preliminary calculations showed that the amount of fuel would decrease significantly if the cruise was in scramjet mode. Hence it was possible to carry a jet engine (in addition to the Scramjet) for the subsonic flight segments, thereby removing the winged first stage. This change was justified because the requirements analysis established the importance of keeping to single-stage. The change also resulted in the reduction of flight speed, since Scramjets have a operating limit of Mach 16.

As further work was carried out, the design speed was pushed lower and lower, as illustrated in Fig. 6-2.

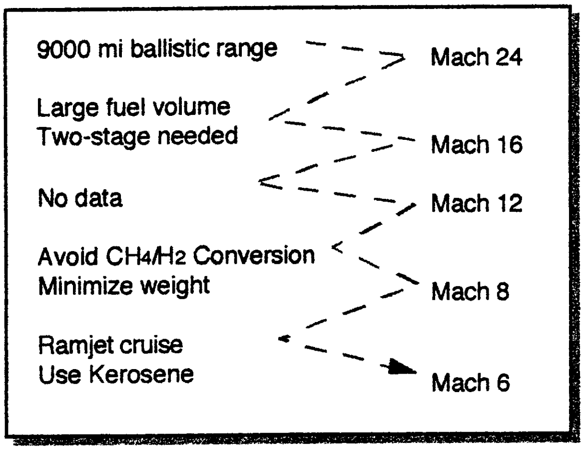


**Fig. 6-2:**
**Reduction in design speed.**

As the flight speed went down, it became increasingly harder to close the business case. This will be discussed under the cost analysis of the vehicle.

## 6.3 Final On-Demand Vehicle Configuration

Final vehicle configuration is shown in Fig. 6-5. The internal layout showing major subsystems is given in Fig. 6-6.

The vehicle is powered by a 70,000 lbf thrust ramjet and two turbofan engines, with a combined thrust of 52,000 lbf. The ramjet utilizes fore-body compression and internal compression between the cowl lip. There is a movable ramp in the intake which adjusts for different Mach Numbers. The propulsion system is discussed in greater detail by Karasi [12].

The vehicle carries on-board systems for navigation, health monitoring, control of subsystems, and data link. The autonomous flight management system assumes the role of the pilot, but can be overridden by the controller in the ground station. The details of the avionics are discussed in Glas [13].

## Mission Profile

The mission profile is shown in Fig. 6-3. After taking-off, the vehicle climbs to 30,000 ft. It cruises at Mach 0.85, powered by the two turbofans, until it has gone 100 mi beyond the coast line. It then rolls on its back and dives to accelerate to supersonic speed, where the ramjet takes over. The turbofans shut down and the subsonic intake is stowed away inside the fuselage. The vehicle climbs to 80,000 ft and cruises at Mach 6. When it is roughly 500 mi from its destination, it begins its descent. When it is time to restart the turbofans, the subsonic intake pops out and the turbofans start wind milling. By the time the vehicle is 100 mi from the destinations coast line, the turbofans are restarted and the vehicle cruises in at Mach 0.85 at 40,000 ft. The ramjet would have stopped operating at around Mach 1.2. The vehicle can loiter for no more than 20 min before making its final descent and approach for landing.

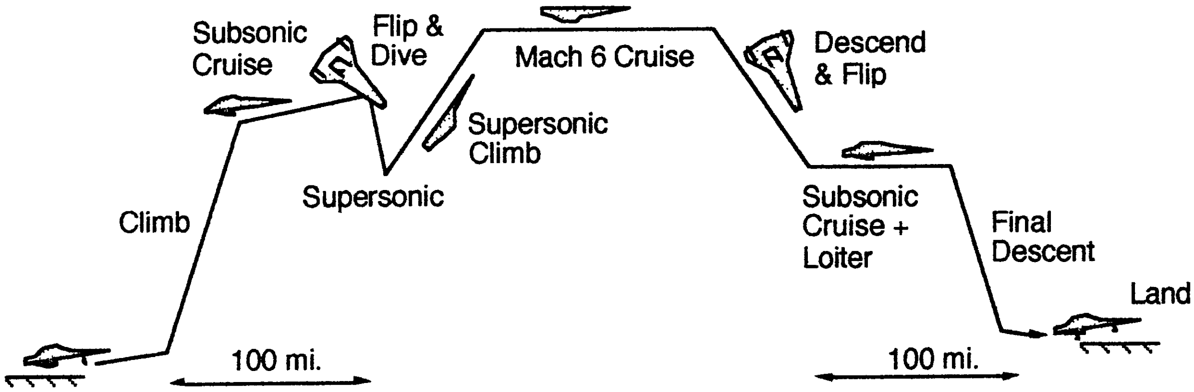


**Fig. 6-3: On-Demand Vehicle Mission Profile**

## Inverted Cruise

From the discussion of the mission profile, one may note that the vehicle is cruising in the inverted orientation. The reason for doing so is discussed in this section.

Firstly, the vehicle lands and takes-off with the ramjet on top for the following reasons:

- Shorter landing gears
- Jet engine and intake need not compete with ramjet for space

For the cruise, it is better to have the ramjet below because :

- Forebody flow compression required by the ramjet provide high pressures that act in the same direction as the lift.
- Landing gears and sensors for landing are on cooler side of fuselage
- Jet engine intake on windward side during low speed (high angle-of-attack) flight
- Avoids possible interference from jet engine intake on ramjet intake.

From the engineering perspective, there is no reason why the inverted cruise cannot work, as long as the following is considered:

- All sub-systems must be operable in both orientations.
- Payload bay is swiveled so that the payload is kept upright at all times, since some commodities may be damaged if carried inverted.

## 6.4 Comparison with Closest Competitor

Reviewing the list of systems presented in Sections 1.6 and 1.7, the only one which came close to meeting the Fast Package system requirements was Pioneer Rocketplane's Pathfinder. However, Pathfinder still could not achieve the range, even if the payload is totally replaced by fuel (Fig. 6-4). Fig. 6-4 illustrates the unique capability of the On-Demand Fast Package vehicle.

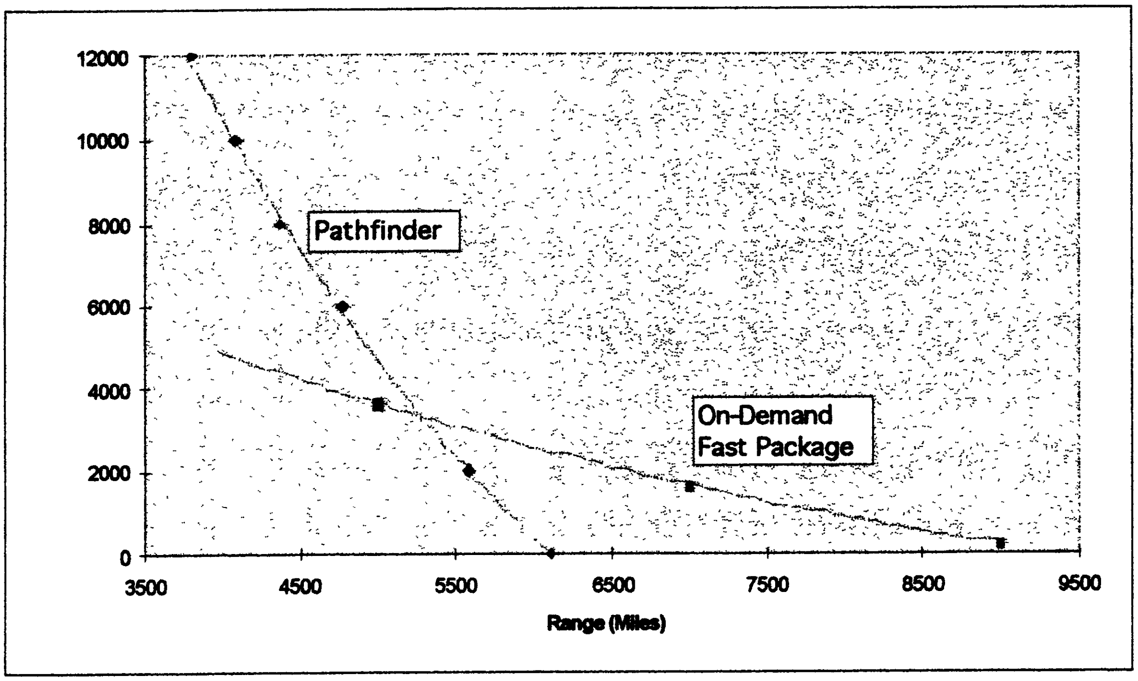


Fig. 6-4: Payload vs Range Comparison

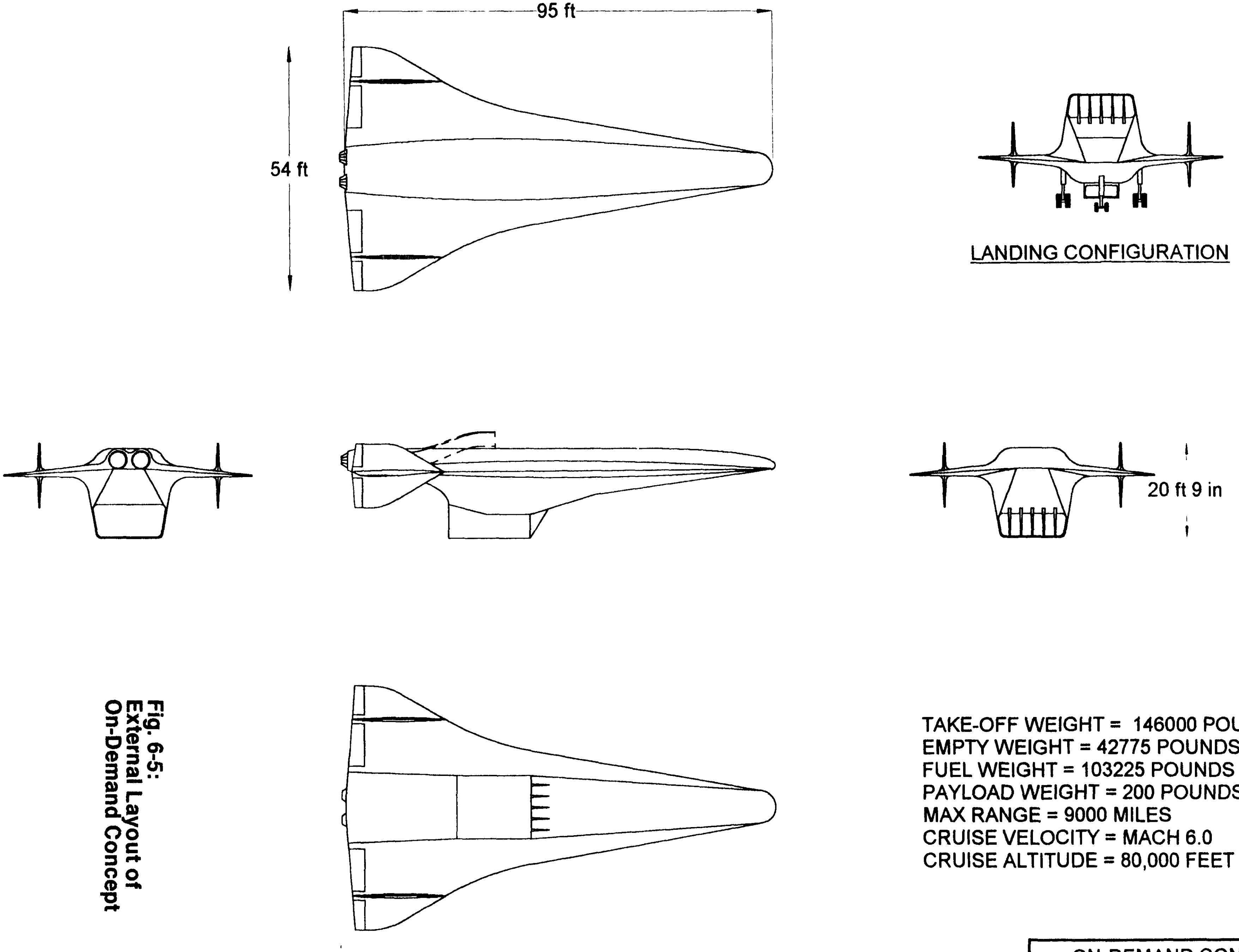


**Fig. 6-5:**
**External Layout of**
**On-Demand Concept**

TAKE-OFF WEIGHT = 146000 POUNDS
EMPTY WEIGHT = 42775 POUNDS
FUEL WEIGHT = 103225 POUNDS
PAYLOAD WEIGHT = 200 POUNDS
MAX RANGE = 9000 MILES
CRUISE VELOCITY = MACH 6.0
CRUISE ALTITUDE = 80,000 FEET

ON-DEMAND CONCEPT
FAST PACKAGE DELIVERY
SCALE
1" = 30'
DRAWN BY: KURT PALMER
DATE: APRIL 28, 1998

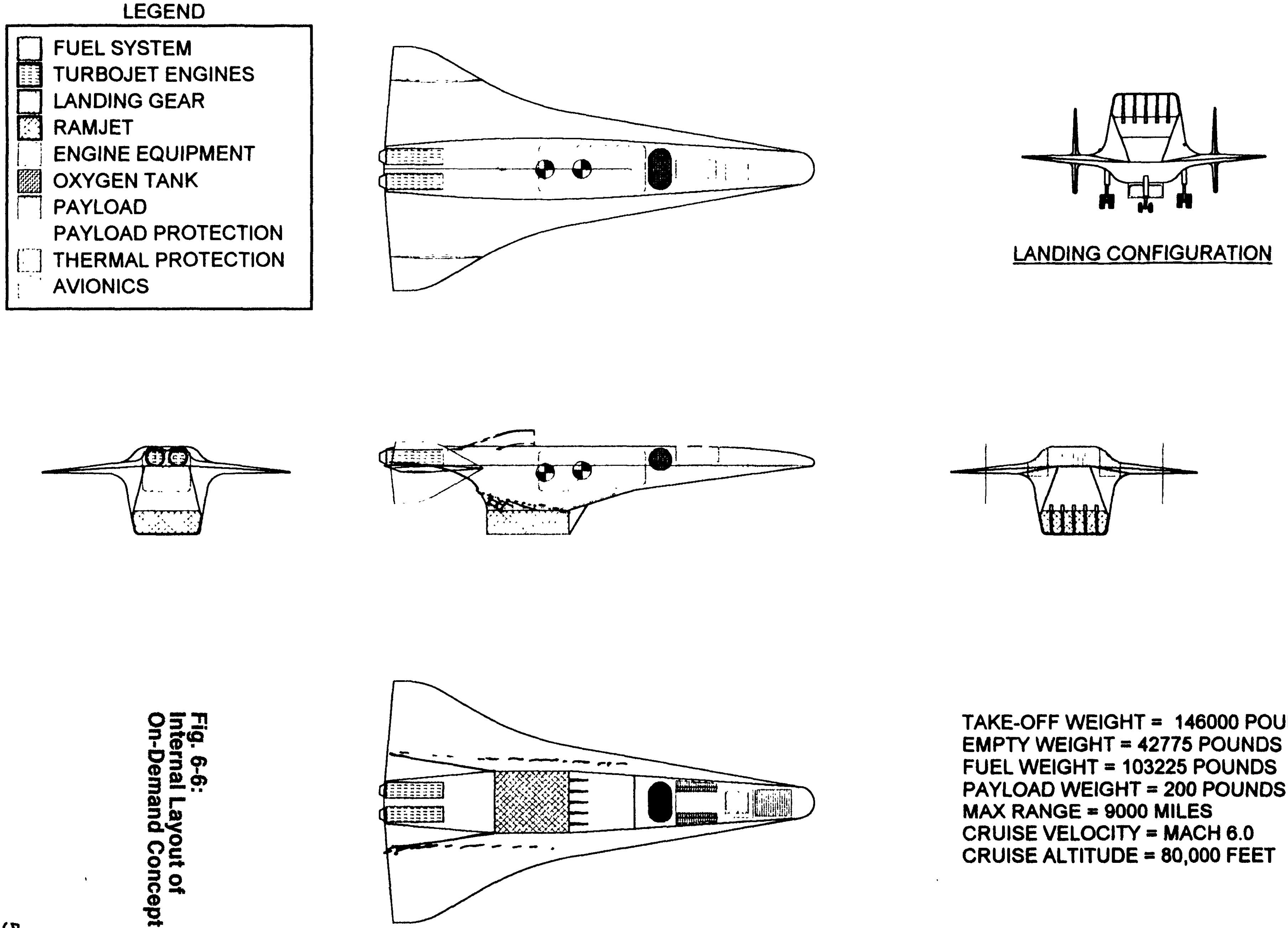


Fig. 6-6: Internal Layout of On-Demand Concept

TAKE-OFF WEIGHT = 146000 POUNDS
EMPTY WEIGHT = 42775 POUNDS
FUEL WEIGHT = 103225 POUNDS
PAYLOAD WEIGHT = 200 POUNDS
MAX RANGE = 9000 MILES
CRUISE VELOCITY = MACH 6.0
CRUISE ALTITUDE = 80,000 FEET

ON-DEMAND CONCEPT
FAST PACKAGE DELIVERY

| SCALE<br>1" = 30' | DRAWN BY: KURT PALME<br>DATE: APRIL 28, 199[illegible] |
|---|---|

## 7. AERODYNAMIC HEATING

One of the biggest concerns in high speed flight is the thermal loads resulting from aerodynamic heating. The temperatures can reach levels beyond that which conventional aircraft materials can handle. This chapter describes the estimation of the thermal loads over the critical hot spots, namely the stagnation region on the nose, the leading edges and the bottom surface of the vehicle.

### 7.1 Analysis Methodology

An approximate method to obtain a rapid estimate of the temperatures was described in Hankey [15]. The method is based on Reynolds' Analogy, which relates the skin friction coefficient (Cf) to the Stanton Number (St):

Reynolds' Analogy: $St = Cf / 2$ ....(1)

The aerodynamic heating rate q is given by:

$$q = St\, \rho_e\, V_e\, (H_{aw} - H_w) \qquad ....(2)$$

where $H_{aw}$ = adiabatic wall enthalpy
$H_w$ = wall enthalpy
$\rho_e$ = flow density
$V_e$ = flow velocity

The flow parameters (pressure, density) were computed using Newtonian impact theory, which basically states that the pressure is proportional to the sine of the surface inclination to the flow (Fig. 7-1).

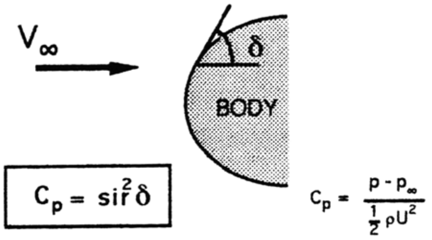


**Fig. 7-1: Newtonian theory.**

Stagnation Region Heating

The stagnation region on the nose is the most critical for aerodynamic heating.

The following semi-empirical formulae were derived from the equations (1) and (2), and Newtonian flow:

$$q_{S\ \text{laminar}} = 21\, (\rho_\infty / R)^{0.5}\, (V_\infty / 1000)^3 \qquad ....(3)$$

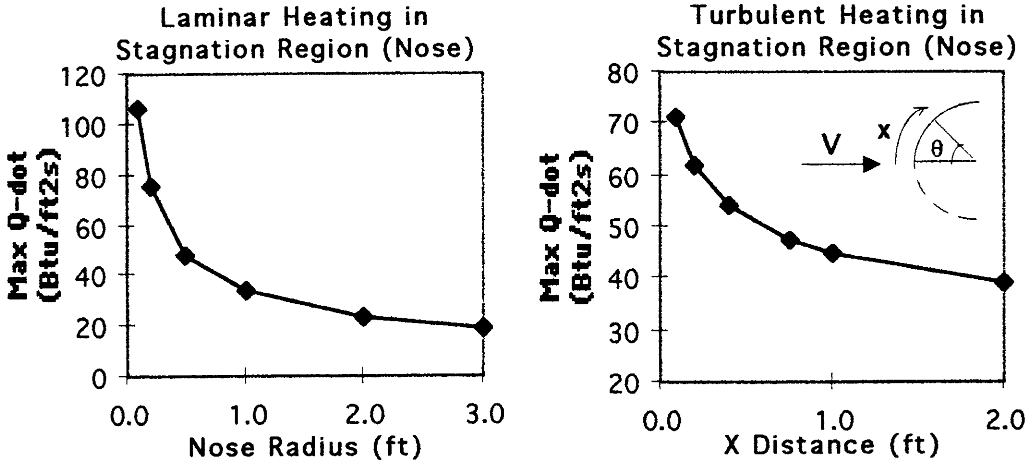
$$q_{s\ \mathrm{turbulent}} = (4/x^{0.2})\,(\rho_\infty/\rho_0)^{0.5}\,(V_\infty/1000)^3 \qquad ....(4)$$

where R = nose radius

$\rho_0$ = air density at sea level

and q is in Btu/ft$^2$s, $\rho$ in slug/ft$^3$, R and x in ft, and $V_\infty$ in ft/s.

Equations (3) and (4) are plotted in Fig. 7-2 for Mach 6 at 80,000 ft. Transition was assumed to occur at a Reynolds Number of $10^6$. This corresponds to 0.23 m from the stagnation point.



Laminar Heating in Stagnation Region (Nose)

Turbulent Heating in Stagnation Region (Nose)

**Fig. 7-2: Heating at Stagnation Region.**

It can be seen from Fig. 2 that the aeroheating can simply be reduced by increasing the nose radius. However, increasing the nose radius will also increase the drag, which may result in loss of range. Hence a careful balance must be struck between these two conflicting requirements.

## Leading Edge Heating

After the nose, the next most critical aerodynamic heating region is at the wing leading edges. Unlike the nose, the leading edges arecylindrical in shape. The heating for the two geometries are related as follows:

$$q_{\mathrm{cylinder}} = q_{\mathrm{sphere}}/2^n \qquad ....(5)$$

where n = 0.5 for laminar flow; 0.2 for turbulent flow

The heating is less for swept leading edges because it is the velocity component normal to the leading edge which contributes to the heating. From geometry, it can be shown that:

$$q = q_{cylinder} \Lambda_e \qquad \text{....(6)}$$

where $\Lambda e$ = effective sweep angle = $\sin^{-1}(\sin\Lambda \cos\alpha)$

Lower Surface Heating

The final area of concern is the lower surface. The heating relationship there is given by:

$$q_{flat\ plate} = (K/x^n)\ (V_\infty/1000)^3\ (\rho_\infty \sin^2\alpha \cos\alpha)^{1-n} \qquad \text{....(7)}$$

where K = 12.1 for laminar flow; 4220 for turbulent flow
n = 0.5 for laminar flow; 0.2 for turbulent flow
*see equation (4) for units*

Fig. 7-3 is a plot of equation (7) for $\alpha$=5° at Mach 6 and at 80,000 ft altitude. The heating is less as distance from the leading edge increases because the boundary layer is getting thicker.

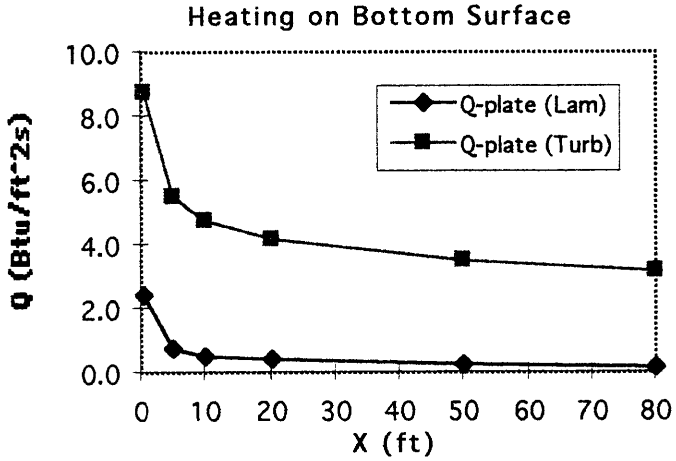


**Fig. 7-3: Aerodynamic heating on lower surface of flat plate at $\alpha$=5°**

Radiation Equilibrium Temperature

The above aerodynamic heating relationships give the heating rates. Hence the temperature on the body will keep rising until the heating rate equals the rate of heat loss. In this case, heat is assumed to be lost only through radiation, hence the final temperature is called the radiation equilibrium temperature. This is given by:

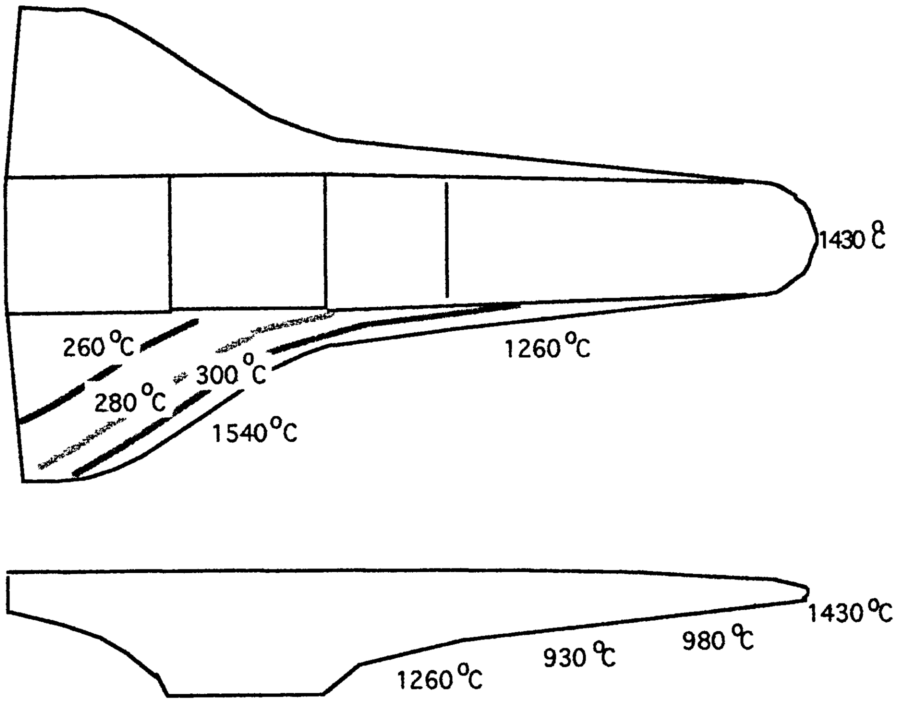
$$q_{in} = q_{out} = \varepsilon\, \sigma\, T_w^4 \qquad \text{....(8)}$$

where $\varepsilon$ = emissivity

$\sigma$ = Stephen-Boltzmann constant ($0.481 \times 10^{12}$ Btu/ft$^2$s$^\circ$R$^4$)

## 7.2 Temperature Summary

Using the relationships discussed above, the temperatures at critical areas on the vehicle were estimated (Fig. 7-4).



Altitude : 80,000 ft
Speed : Mach 6
Alpha : 1°
Nose radius : 0.5 ft
LE radius : 0.1 ft
LE sweep : 80°, 60°

**Fig. 7-4: Temperatures Where Aerodynamic Heating is Most Severe.**

# 8. COST ANALYSIS FOR ON-DEMAND VEHICLE

## 8.1 Total Operating Cost

This chapter discusses the total operating cost per flight. Fig. 8-1 illustrates the cost components. The total cost is the sum of the Direct Operating Cost (DOC) and the Indirect Operating Cost (IOC). DOC consists of fuel, maintenance, crew, insurance and depreciation. Depreciation is the cost of purchasing the vehicle factored over the life of the vehicle. The purchase price of the vehicle in turn consists of the flyaway (i.e. production) cost and the RDT&E (research, development, test & evaluation) cost. The IOC includes the ground facilities and equipment, sales and customer service, and administrative overheads. The following method for estimating the operating cost was obtained from Raymer [11].

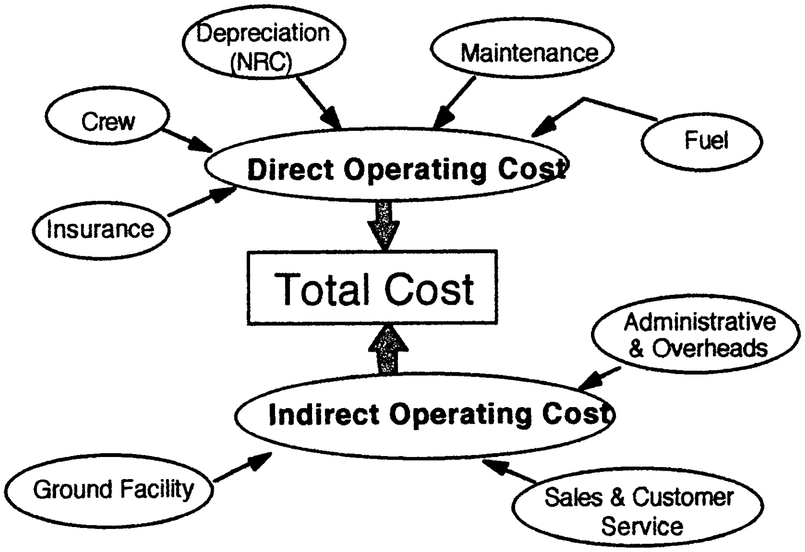


Fig. 8-1: Cost Breakdown.

RDT&E + Flyaway Cost

The components of RDT&E + Flyaway cost are illustrated in Fig. 8-2.

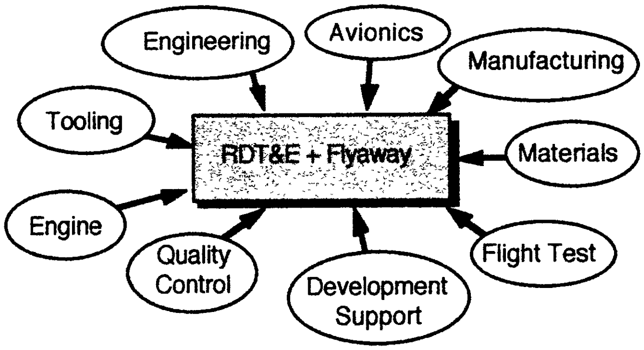


Fig. 8-2: Components of RDT&E + Flyaway Costs.

"Engineering" includes the airframe design and analysis, test engineering, configuration control, systems engineering, and the integration of propulsion and avionics. Most of the engineering effort goes into RDT&E. "Tooling" includes all the preparation for production as well as tooling support during production. "Manufacturing" is the direct labor to build the aircraft from machining to assembly and installation of engines etc. "Quality Control" is all the inspections carried from production to delivery of aircraft to the customer. "Development Support" is the non-recurring cost of manufacturing support of RDT&E, such as mock ups and test items. "Flight Test" cost covers all cost incurred during certification. The cost for the test aircraft is accounted for as part of the production-run cost estimate. "Materials" includes purchase of raw materials, equipment and hardware used to build the aircraft; It covers everything on the aircraft except the engine and avionics.

The RDT&E and flyaway cost of the vehicle was estimated using a Modified DAPCA IV Cost Model [11]:

$$\text{Engineering Hours} = 4.86\ We^{0.777}\ V^{0.894}\ Q^{0.163} = H_E$$

$$\text{Tooling Hours} = 5.99\ We^{0.777}\ V^{0.696}\ Q^{0.263} = H_T$$

$$\text{Manufacturing Hours} = 7.37\ We^{0.82}\ V^{0.484}\ Q^{0.641} = H_M$$

$$\text{QC Hours} = 0.133\ H_M = H_Q$$

$$\text{Development Support Cost} = 45.42\ We^{0.630}\ V^{1.3} = C_D$$

$$\text{Flight Test Cost} = 1243.03\ We^{0.325}\ V^{0.822}\ FTA^{1.21} = C_F$$

$$\text{Manufacturing Materials Cost} = 11\ We^{0.921}\ V^{0.621}\ Q^{0.799} = C_M$$

$$\text{RDT\&E+flyaway} = (1+f_{avionics})(H_E R_E + H_T R_T + H_M R_M + H_Q R_Q + C_D + C_F + C_M)$$

where

$We$ = empty weight (lb)
$V$ = max. velocity (knots)
$Q$ = production quantity (50)
$FTA$ = number of flight test aircraft (1)
$f_{avionics}$ = avionics cost factor (10% of flyaway cost)
$R_E$ = \$60
$R_T$ = \$61
$R_Q$ = \$55
$R_M$ = \$50

Note that a production quantity of 50, and one flight test aircraft is assumed. Avionics typically costs between 5-25% of flyaway cost. A moderate value of 15% was chosen because the vehicle is unmanned, yet not as sophisticated as a military aircraft.

The above will give costs in 1986 dollars. Assuming yearly inflation of 3%, the cost in 1998 dollars is:

$$1998\ \text{Cost} = (1.03)^{12}\ (1986\ \text{Cost})$$

The model is for conventional aluminium airframe. For this vehicle, a lot of Titanium (or other advanced materials) will probably be used because of high temperatures from aerodynamic heating. In such cases, Raymer suggests that the cost be increased by a factor of between 1.7 to 2.2. A value of 2 was chosen.

So far, the cost does not include the engine. The list price for aircraft jet engines is determined by the engine thrust. The current price per pound thrust is $120 [15]. It is reasonable to use the same value for the ramjet because the much higher complexity of the jet engine offsets the high flight speed for the ramjet. Given the thrust for the vehicle is 70,000 lb, the engine will cost $8.4 mil to purchase.

Using this model, the estimated purchase price of the vehicle is $464 mil. In comparison, Andrews [4] quoted $500 million in his paper on Fast Package, while the X-33 cost NASA $1 billion for the first vehicle.

### Depreciation Cost

The depreciation per flight is the cost of purchasing the vehicle spread over the entire cycle life. The likely cycle life will be about 2000, assuming an operating life of 5 years and a flight rate of once per day. Hence the depreciation per flight is $231,730.

### Fuel Cost

The fuel cost was a straightforward calculation from the fuel weight. Kerosene was the selected fuel, which typically costs 10 cents per pound. However following the example of HSCT studies, a better grade of kerosene costing 20 cents per pound was assumed. Given the fuel weight for a 9000 mile mission is 103,271 lb, the fuel cost is $20,654.

### Maintenance

The maintenance cost consists of man-hour and material costs. A maintenance man-hour per flight hour value had to be assumed. Typical aircraft values range from 3 (business jet) to 50 (bomber). The worst case was chosen because of the hypersonic speed. The estimated man-hour cost is $72 in 1998.

The material cost was computed using the following relation given by Raymer:

$$\text{material cost/FH} = 3.3C_a + 7.04 + N_e(58C_e - 13)$$

$$\text{material cost/cycle} = 4C_a + 4.6 + N_e(7.5C_e + 2.8)$$

where

$C_a$ = aircraft cost less engine (in millions)

$C_e$ = cost per engine (in millions)

$N_e$ = number of engines (1)

Again the cost above is for 1986 dollars, so it had to be converted to 1998 dollars. For a fight time of about 2.2 hours per trip, the total maintenance per trip is $16,854.

### Crew Cost

One controller (or pilot) is needed to monitor the flight. (Two controllers are involved in each flight, but each controller handles half of the flight.) A moderate rate of $850 per hour (in 1998 dollars) was obtained from Raymer. For a 9000 mile mission, the pilot cost is $1930.

### Indirect Operating Cost

The IOC is assumed to be 50% of the DOC. This figure was obtained from a presentation by Gillette (1997). Raymer suggested using an initial estimate of 100% DOC for a typical airline. However, the vehicle is more expensive than the typical airplane, so the lower proportion IOC is justified.

### Total Cost

The cost per flight for the On-Demand vehicle is summarized in Fig. 8-3.

The biggest cost factor is the depreciation, followed by the IOC. Surprisingly, fuel is only 4% of the cost, considering that the fuel makes up 70% of the gross take-off weight.

Based on the above cost, to get a ROI of 20%, the price charged would be $620,000 per flight, which is roughly $3000 per pound. This far exceeds the $1000 per pound limit for which the market is willing to pay. Hence it seems unlikely that the business case will close.

| | |
|---|---|
| ◆ Vehicle Depreciation<br>($464 mil over 2000 cycles) | $231,700 |
| ◆ Fuel Cost per Flight | $20,700 |
| ◆ Crew (1) cost per flight | $1,900 |
| ◆ Maintenance cost /flight | $16,900 |
| ◆ Insurance per flight | $2,800 |
| ◆ IOC (50% DOC) | $135,600 |
| **Total** | $409,600 |

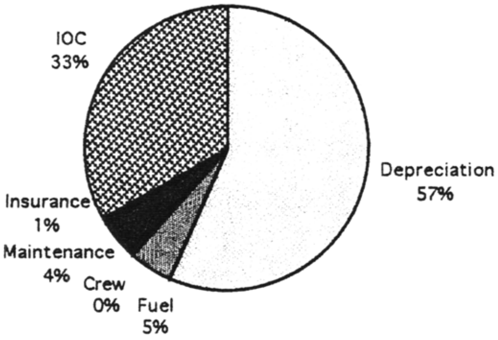


**Fig. 8-3: Cost Breakdown per Flight.**

## 8.2 Validity of Cost Analysis

The major contribution to the final cost is the non-recurring cost (note that the preliminary IOC estimation is also linked to it). It is granted that the cost estimation may not be accurate because it is based on statistical trends derived from existing airplanes, which do not go beyond Mach 2+. However, it could be argued that the cost estimated this way would be more conservative. This seems to be supported by the fact that the vehicle costs as much as larger reusable launch vehicles [4]. It is very likely that there is a model for estimating the cost of space systems. However, it would probably be better to use a model for airplanes because the reliability and cycle life required for Fast Package is closer to that of airplanes. Perhaps if space systems were built with the same airplane-like reliability and cycle life, their estimated cost for this mission will be just as high, if not worse.

## 8.3 Effect of Production Quantity on Cost

Fig. 8-4 is based on the cost model used in the present the cost estimation. It shows the effect of production quantity on the RDT&E+flyaway cost of the vehicle, which translates directly to the depreciation cost. From Fig. 8-4, it is evident that one reason for the high non-recurring cost is the low production volume of the Fast Package vehicle. Using the cost model, a production lot of 600 units is needed in order to close the business case. It is unlikely that so

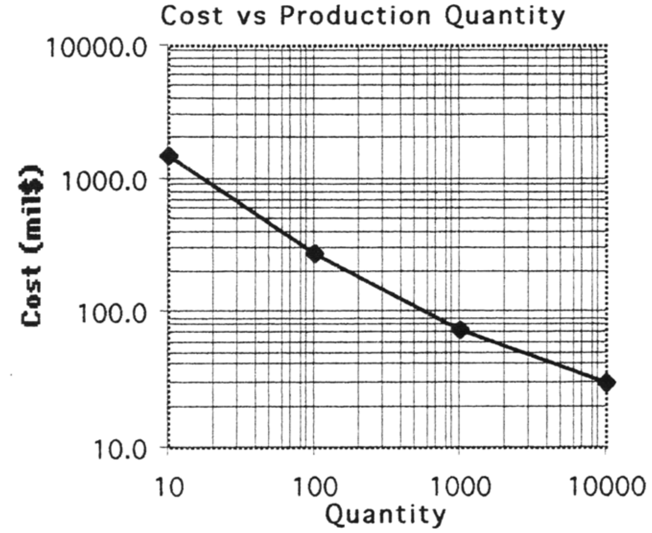


**Fig. 8-4: Non-Recurring Cost vs. Production Quantity**

many vehicles will be needed for the Fast Package market, hence one will have to seek out new markets for this vehicle in order to close the business case. This conclusion is supported by the fact that existing express package delivery companies utilize airplanes designed primarily for the passenger transportation market.

# 9. CONFIGURATION OPTIMIZATION

## 9.1 Optimization Objective

So far this thesis has addressed the two ends of the spectrum (Fig. 9-1). This chapter discusses if there indeed is an optimal configuration between the two ends. Note that other than the extreme On-Demand end, all other possibilities are considered scheduled service, the variable being the number scheduled flights per day.

The analysis was carried out for package delivery between two cities only. The distance between the two cities was 9000 miles.

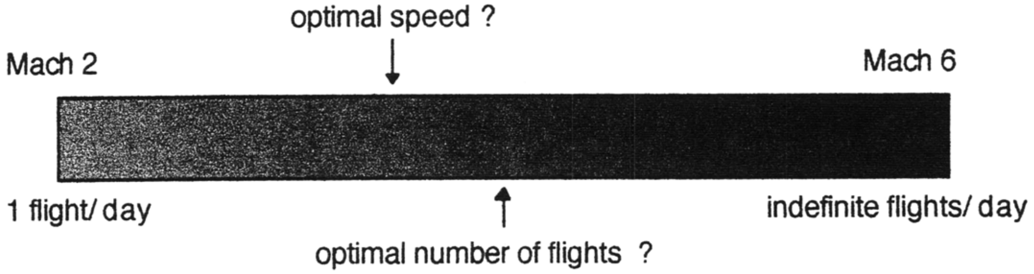


**Fig. 9-1: Feasible Region of Optimization Problem.**

The question was modeled as an optimization problem, where the objective function was to minimize the delivery time:

Minimize Z = range/ (flight speed) + 24 hours/ (no. of flights per day)

Subject to a 20% Return on Investment (ROI).

Another objective was to maximize profit, which would be the goal of any business. The objective function in this case was to maximize the discounted profits:

Maximize Z = Net Present Value of Projected Profits - Vehicle Cost

The problem was set up according to a 24-hour cycle. As discussed earlier, the delivery time comprised the flight time and the package transfer time. Range divided by average flight speed gives flight time. The package transfer time was assumed to be set by the time between flights. This assumption was consistent with previous analysis, which showed that more flights reduced the delivery time because of shorter waiting time. To simplify the problem, it was assumed that the flights would depart at equal intervals throughout the 24 hour day. (This followed the argument that Fast Package will serve a global community.) Hence the worst case package transfer time would be 24 hours divided by the number of flights per day.

In both cases, the decision variables were:

x1= flight speed
x2= no. flights per day
x3= fleet size
x4= price ($/lb)
x5= payload size

The independent variables were flight speed, number of departures and the fleet size. Price per pound depended on the total delivery time, which in turn depended on flight speed and the number of flights per day. Payload capacity was assumed to be the daily market volume divided by the number of flights per day. Although not independent, the latter two variables were included as decision variables since their values were of interest to the problem.

The optimization problem was complex because of the interaction between the variables, many of which were non-linear (Fig. 9-2). There was an exponential increase in the price the customer was willing to pay for faster delivery times (Fig. 9-15), while at the same time, operating and development costs increased exponentially with design speed.

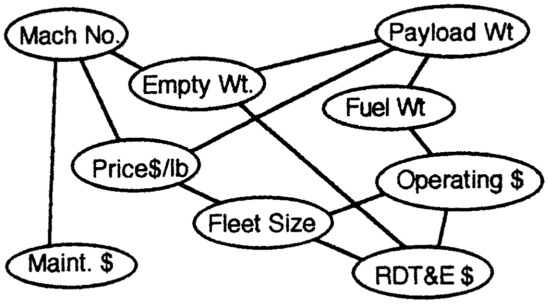


**Fig. 9-2:**
**Interaction of Driving Factors**

## 9.2 Cost Model used in the Optimzation

Cost Model

Cost was the fundamental issue. The cost model used in this optimization was the same as the one used for the cost analysis in the previous chapter. However, additional models had to be incorporated to account for the variation in empty weight, fuel weight, materials and L/D as functions of Mach Number and payload.

Empty Weight

The empty weight was computed using a statistical sizing method. The following variables affect the empty weight:

- Range
- Isp (Mach Number dependent)
- L/D (Mach Number dependent)

The empty weight was computed for nine data points (Table 9-1). A surface fit through the nine points allowed for convenient interpolation at other Mach Numbers and payloads. (Fig. 9-3). The surface was defined using a nine-noded quad finite element.

Fig. 9-4 shows the increase in production and development cost per vehicle (excluding engine) as the design speed increases.

**Table 9-1: Empty Weight Data**

| | Payload (lb) | | |
|---|---|---|---|
| **Mach** | **10** | **3000** | **6000** |
| **0.8** | 27800 | 34600 | 39900 |
| **3** | 16725 | 22870 | 27700 |
| **6** | 42400 | 49300 | 55300 |

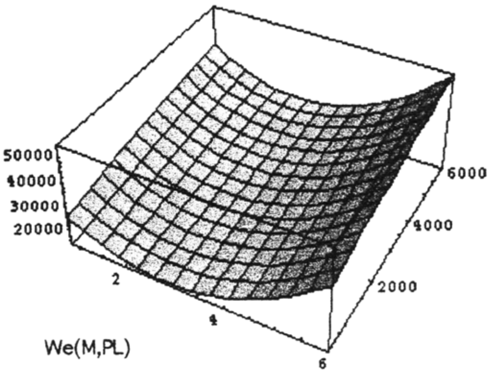


**Fig. 9-3:**
**Vehicle Empty Weight**

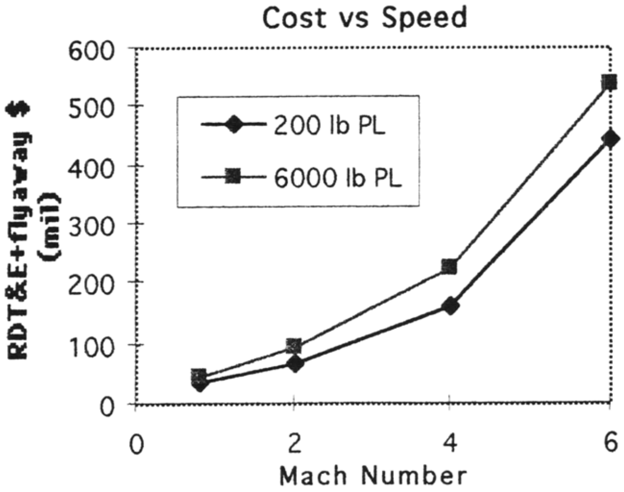


**Fig. 9-4:**
**Airplane Cost (excl. Engine) vs. Speed**

## Fuel Weight

In addition to empty weight, the fuel weight was also obtained during the sizing. A surface was also fit through the nine data points (Fig. 5). The fuel cost was then a straight forward calculation from the fuel weight.

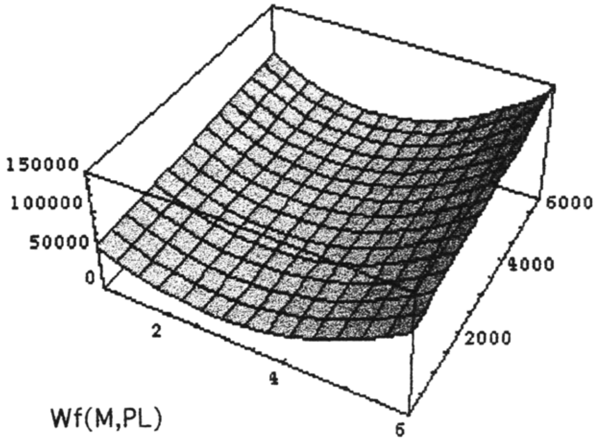


**Fig. 9-5:**
**Vehicle Fuel Weight**

## L/D Ratio

The L/D ratio was used in the engine cost estimation. It was computed using the formula given in Kuchamann:

$$L/D = (3+M) / M$$

Fig. 9-6 shows the increase in engine cost as the flight speed and payload increases.

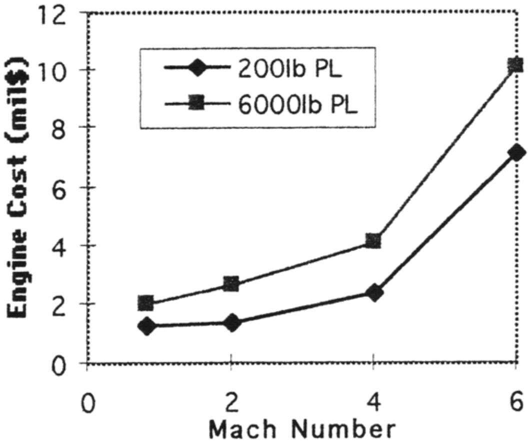


**Fig. 9-6:**
**Engine Cost vs. Speed**

## Material Cost Factor

Recall that a factor of 2 was added to account for the increase in cost due to the use of titanium instead of aluminum. With the reduction of flight speed, the aeroheating is reduced. Consequently, the use of titanium also decreases. Hence this material cost factor was expected to decrease with flight speed. Fig. 9-7 shows the likely decrease, which could be modeled as fourth order polynomial. It is stressed that this curve was based on engineering judgment, not analysis. Hence no claim of accuracy is made with respect to it.

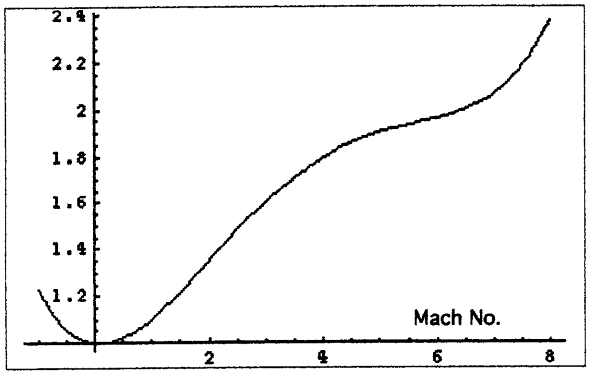


**Fig. 9-7:**
**Cost Factor for Titanium or other Advanced Materials.**

## Total Operating Cost

The variation of the total operating cost with flight speed and payload is shown in Fig. 9-8. Note the minimum at around Mach 2.

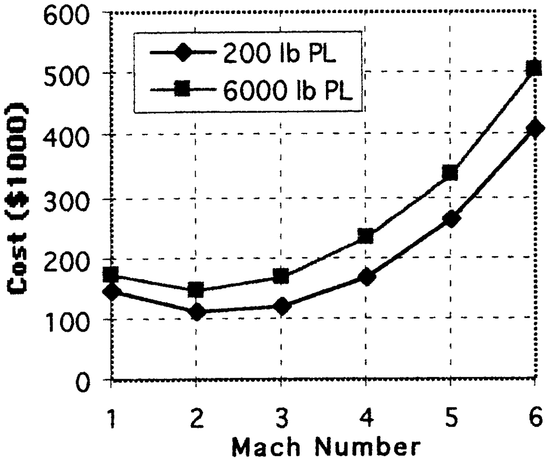


**Fig. 9-8:**
**Total Operating Cost**

## 9.3 Price Model

Having determined the cost as a function of speed, the next question was how much the customer was willing to pay. To get the answer, it was necessary to look into the question of the "value of time".

The value of time refers to how much the customer is willing to pay for the time saved. Similar work concerning the value of time has emerged from feasibility studies concerning High-Speed Civil Transport, high-speed rail, business jets, and express package delivery. Martin [16] estimated the value of time for Fast Package using data accumulated from the 1997 FedEx Annual Report and the pricing for various services offered by FedEx for both US domestic and international markets. Fig. 9-15 portrays the cost of these services for various traffic routes as a function of total delivery time.

## 9.4 Optimization Procedure

Case (1): Minimizing Delivery Time

As mentioned before, the primary objective function is to minimize the delivery time as given by:

$$\text{Time} = \frac{\text{Range}}{\text{Speed}} + \frac{24}{\text{No. of Departures}}$$

The independent variables were:

- Flight Mach number (x1)
- Number of departures per day (x2)
- Fleet size (x4)

Note that the number of departures and fleet size were integers while the Mach number is a real number.

The constraints were:

- 0 ≤ Total Payload ≤ Daily Market Volume
- 0.8 ≤ Flight Mach ≤ 6
- No. of Departures/day ≥ 1
- Fleet Size ≥ 1
- Time b/w Departures ≥ Return-Flight Time/Fleet Size
- NPV(20% ROI) - Vehicle Cost ≥ 0

The Total Payload was the vehicle payload multiplied by the number of departures. The Flight Mach number was bounded between 0.8 and 6, which was the region of interest. The Return-Flight Time was the total time taken to complete a return journey. It consisted of the time required to fly to the destination, unload, refuel, load, and fly back. The Return-Flight Time determined the fleet size required to provide the desired number of departures per day. For example, two aircraft were needed to provide two flights a day if it took 20 hours for the first aircraft to return to base. A turnaround time of 3 hours was assumed in the calculation of the Return-Flight time.

The vehicle is assumed to have a life of 8000 cycles. Each flight represents one cycle. Hence the operating life in years is the cycle life over the number of flights per year. Assuming one return flight per day, the operating life for this vehicle would be about 10 years.

The problem was optimized using the non-linear solver in Microsoft Excel. This was convenient because the cost model was also set up in Excel. As there was no integer programming capability, the solution was obtained in the following way:

- activate non-linear solver to find optimum real values.
- manually search for nearest feasible and best integer for x2 and x4.
- reoptimize Mach number around these integer values of x2 and x4.
- validate solution by recomputing results around optimum values.

Case (2): Maximize ROI

The Net Present Value for the vehicle, based on some ROI, is given by the equation below. The ROI is achieved if the break-even point is reached before the end of the vehicle's life.

$$\left[ \sum_{n=1}^{\text{Life}} \frac{\text{Projected Annual Profit}}{(1 + \text{ROI})^{n}} \right] - \text{Vehicle Cost}$$

The variables and constraints are the same as Case (1).

The solution procedure is the same as Case (1). Unfortunately, Excel did not permit the ROI to be optimized directly. To get around this problem, the discounted profit (above equation) was maximized first. Then the ROI was increased manually until the break-even point coincided with the life of the vehicle.

## 9.5 Optimization Results & Discussion

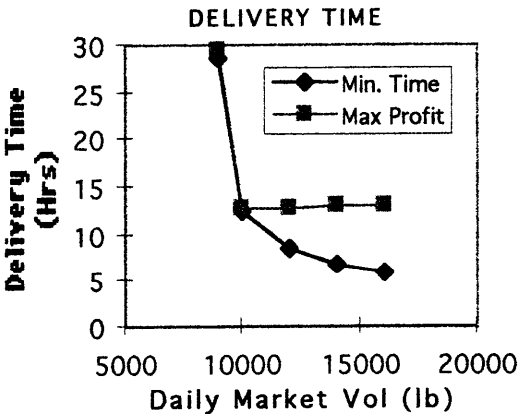
After experimenting with the model, it became clear that the market volume was a major factor in the business case. The business case for 20% ROI cannot close unless there is more than 10,000 lbs per day. The greater the market demand, the greater the revenue. The greater the revenue, the faster the vehicle and/or the greater the number of flights per day. The results shown in Figures 9-9 to 9-14 are plotted against the daily market volume. The optimum configuration for Minimum Time and Maximum ROI is clearly different.

Case (1): Minimize Delivery Time

As mentioned before, the delivery time (Fig. 9-9) was shorter as demand increased. This was achieved by having a faster vehicle (Fig. 9-11) and more departures a day (Fig. 9-12). To close the business case at least 10,000 lbs daily market volume (Fig. 9-13) was needed, with two Mach 3 vehicles operating a total of three flights a day. Door-to-door delivery time for such an operation was 12.5 hours, with a price of $32/lb. For six-hour delivery, the optimum solution was five Mach 4 vehicles flying a total of nine times a day. The price for this service was $71/lb.

Case (2): Maximizing Profit

The optimization showed that the most profitable Fast Package business was not one that maximizes the flight speed. In fact the optimal speed was nearly constant at Mach 3 (Fig. 9-11). Number of flights and fleet size were also constant at 3 and 2 respectively (Figures 9-12 & 9-13). Delivery time was 12.5 hours, and the price was $32/lb.



**9-9: Optimum Delivery Time**

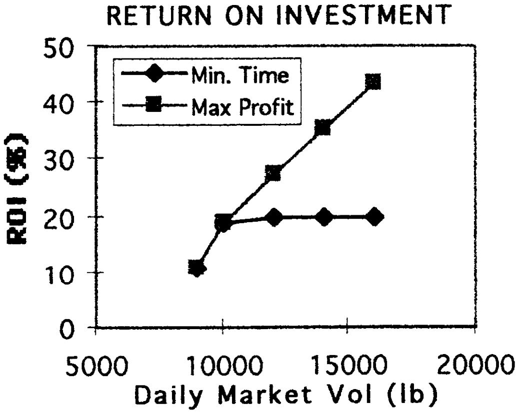


**Fig. 9-10: Optimum ROI**

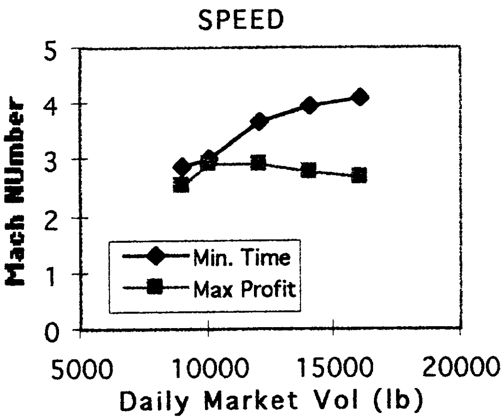


**Fig. 9-11: Optimum Speed**

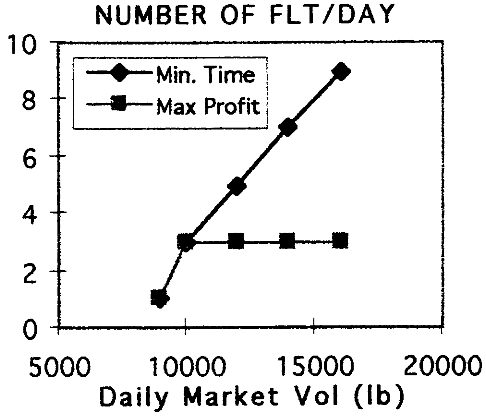


**Fig. 9-12: Optimum Flighs/Day**

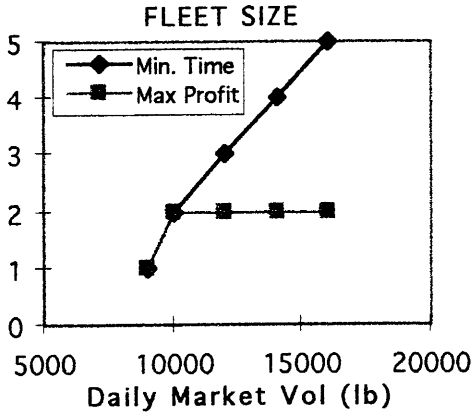


**Fig. 9-13: Optimum Fleet Size**

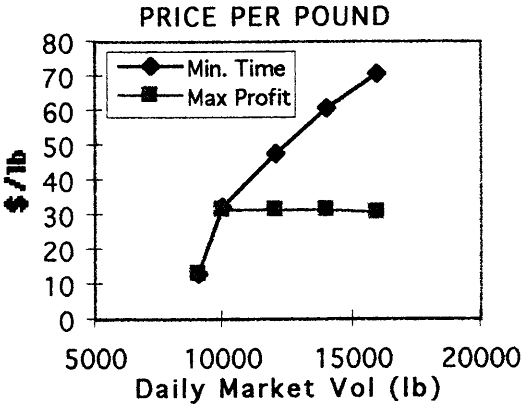
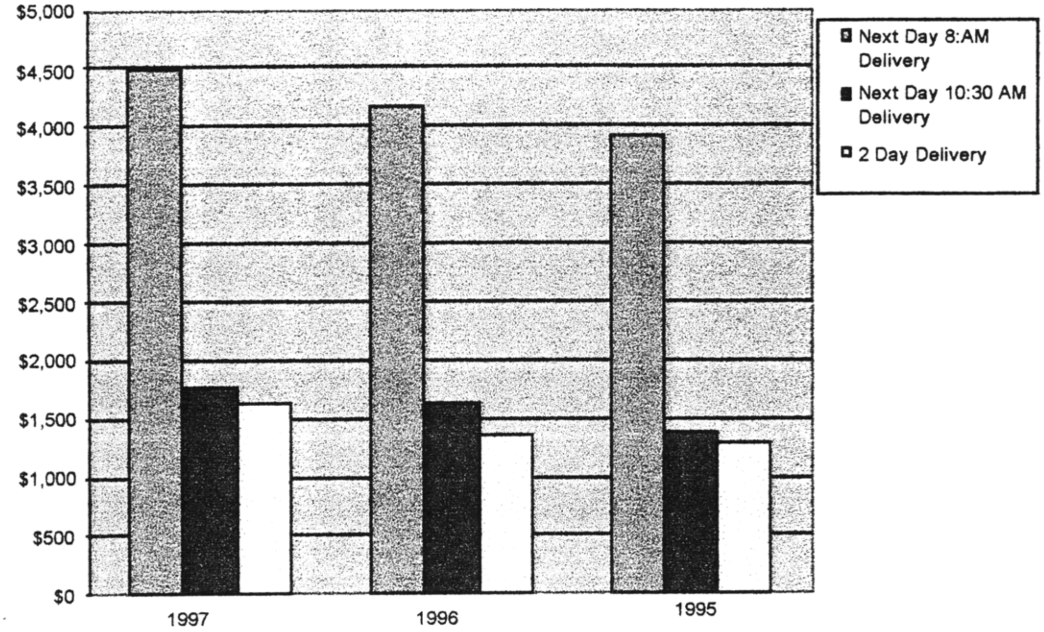


**Fig. 9-14: Optimum Price**

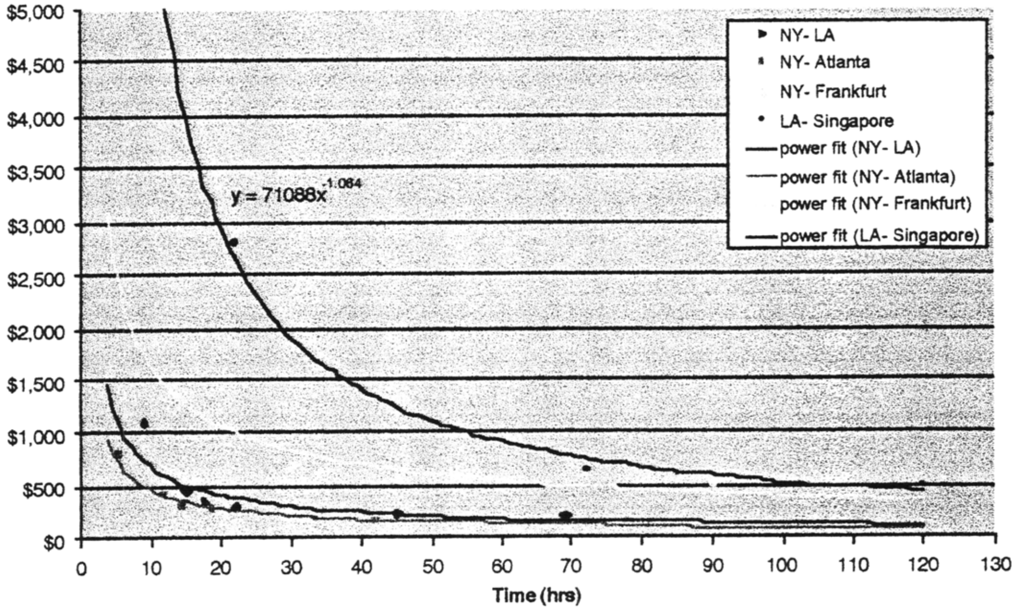
## 9.6 Optimization Summary

The optimum flight speed, number of flights, and fleet size were determined for a range of projected market volume for Fast Package. The results showed that there exists a minimum market demand in order to close the business case. Within the limits of the cost model, the minimum daily market volume was 10,000 lbs. The results also showed that the design would be different if profit was to be maximized, as opposed to minimizing delivery time. For the maximum profit case, the optimum was two Mach 3 vehicles operating a total of three flights a day. For faster delivery time, the optimum speed was dependent on the daily market volume. For a market of 16,000 lbs, 6 hour door-to-door delivery time was possible over a 9000 mile range. This service would be provided by five Mach 4 vehicles operating a total of nine flights a day.



Fed Ex Annual Revenue for Various Services

source: Federal Express 1997 Annual Report



Cost vs. Time for 150 lbs

source: http://www.fedex.com, http://www.flifo.com

Fig. 9-15. Price vs. Time

# 10. CONCLUSION

The system issues for Fast Package Delivery were better understood through the work of this thesis.

Fast Package was approached in two ways: a Scheduled Service, and an On-Demand Service. High-Speed Civil Transport was found to be suitable for the Scheduled Service, while a new Mach 6 scramjet would be better suited to the On-Demand Service.

For the Scheduled Service, current sorting schedule limits the usefulness of going beyond Mach 2.5, while higher flight speeds will always improve the delivery time for the On-Demand Service. Although the 28-hour door-to-door delivery time for the Scheduled Service did not meet the initial goal of four-hour door-to-door delivery time, it was easier to close its business case because of the higher volume of packages carried. The door-to-door delivery time for the scramjet was 5.3 hours and costs $410,000 a flight.

The markets for Scheduled Service and On-Demand Service are distinct from each other. Scheduled Service has high volume but at a low price of around $15/lb because overall delivery process is slow. On-Demand Service justifies a high price of $200-1000 per pound, but the amount of cargo carried is much smaller. A common error found in previous works is that On-Demand pricing was applied to the Scheduled volume. If the correct price and volume is used, many of proposed systems will not be profitable doing Fast Package.

The Fast Package concepts were largely driven by the need for high reliability. The key system requirement in both cases was self-diagnostic capability, which stemmed from the need for reliability and low maintenance-hours. Other key drivers to the concepts were noise regulations and integration with airport facilities. These requirements make space systems an unlikely choice for Fast Package.

Preliminary cost estimation for the Mach 6 vehicle was difficult because there is no precedent for such a vehicle. Because of the airplane-like reliability and cycle life required for Fast Package Delivery, current estimates were made using an airplane cost model. Comparing with published cost for RLVs under development, the airplane model appears to give higher cost estimates.

The two concepts were designed to the two extreme modes of operation (one scheduled flight a day, and on-demand). Using the project cost and sizing models, it was shown that a Mach 3 vehicle operating twice a day will give the best return on investment (ROI). For a ROI of 20%, a minimum of 10,000 lbs of packages per day is needed.

Based on this study, an important conclusion is that there would significant non-recurring cost for a dedicated Fast Package flight vehicle. Estimates show that at least 600 units will be necessary to reduce the non-recurring cost per vehicle to acceptable levels. A more feasible approach would be to adopt a high-speed passenger aircraft for Fast Package Delivery, such as the proposed USAF Military Space Plane.

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