R-1075-NASA
October 1972

Effects of A V/STOL Commuter Transportation System on Road Congestion In The San Francisco Bay Area

T. F. Kirkwood

A Report prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Rand
SANTA MONICA, CA. 90406

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PREFACE

This report is one of a four-volume study analyzing the socioeconomic and environmental effects of an intraurban air transportation system on the San Francisco Bay Area. The study was sponsored by the National Aeronautics and Space Administration, Ames Research Center, under contract NAS2-6480.

The Rand work is based on an earlier study for NASA by the Boeing Company, which determined the hardware and economic requirements for a vertical or short takeoff and landing aircraft (V/STOL) commuter transportation system to serve the nine-county San Francisco Bay Area in 1975-1985 and 1985-1995.[1] Rand's charter was to investigate the indirect or secondary benefits or disadvantages of such a system on the community it would serve.

This volume describes the impact that a V/STOL system might have both on highway congestion in the San Francisco Bay Area and on parking requirements downtown.

In addition to the summary volume, the other reports in this series discuss in detail the specific effects of the V/STOL system envisaged by the Boeing study: distribution of primary costs and benefits, and long-run effects on residence and commuting. Together, the four volumes provide a comprehensive view, for transportation planners and policymakers, of the likely consequences of the installation of a V/STOL commuter system. Specifically, they should aid NASA's R&D policy decisions about aircraft with the ultra-short-range mission.

The complete series includes the following reports:

1. R-1074-NASA, *External Impacts of an Intraurban Air Transportation System in the San Francisco Bay Area—Summary Report,* by J. Y. Lu, J. R. Gebman, T. F. Kirkwood, P. T. McClure, and J. P. Stucker.
2. R-1075-NASA, *Effects of a V/STOL Commuter Transportation System on Road Congestion in the San Francisco Bay Area,* by T. F. Kirkwood.
3. R-1076-NASA, *Distribution of Primary Benefits and Costs of Intraurban Air Transportation in the San Francisco Bay Area,* by J. P. Stucker.

[1] The Boeing Company, *Study of Aircraft in Intraurban Transportation Systems: San Francisco Bay Area,* Seattle, Washington, September 1971.

4. R-1077-NASA, *Long-run Effects of an Intraurban Air Transportation System on Residential Location and Commuting in the San Francisco Bay Area,* by J. P. Stucker.

SUMMARY

This report examines the impact that a V/STOL (vertical or short takeoff and landing) commuter transportation system might have both on highway congestion in the San Francisco Bay Area and on parking requirements downtown. The specific systems considered are a "1980" system using a 50-passenger helicopter and a "1990" system using a 50-passenger vehicle with a tilt rotor design. It is estimated by Boeing that these systems will transport 67,231 passengers per day by 1980 and 131,250 passengers per day by 1990. The 1990 system consists of 26 V/STOL ports of which ten handle over 10,000 passengers a day each, while the largest port (downtown San Francisco) handles over 35,000.

While no attempt is made in this study to validate the Boeing demand figures, it should be recognized that our estimates of savings in freeway construction costs and parking requirements are strongly dependent on these figures.

It can be reasonably expected that by 1980 and 1990 considerable extension of the Bay Area freeway and highway systems may be necessary to alleviate potential future congestion, even if there were improved rail commuter service, upgraded bus service, and expansion of BART (Bay Area Rapid Transit) to its full capacity. Such extension might have to include a new Bay Bridge, a bypass for the Caldecott Tunnel, and an additional freeway along the waterfront on both sides of the Bay. The implementation of a V/STOL system would reduce the amount of expansion required by diverting some commuters from automobile travel.

The conclusions of the study point out that the implementation of a V/STOL system would divert a substantial amount of automobile traffic from the Bay Bridge —perhaps half the present bridge capacity could be diverted by 1990. It is indicated that the potential savings in freeway expansion costs could amount to $256 million by 1980 and $510 million by 1990. Should the demand differ from that estimated by Boeing, these savings would vary in approximate proportion to the demand. The cost of implementing the V/STOL system, however, would not vary in proportion to the demand—a system designed to handle one-half the Boeing demand would cost more than one-half the cost of the Boeing system, one designed for twice the Boeing demand would cost less than twice the Boeing cost.

When the V/STOL system is in operation, some highway and road construction in the neighborhood of the V/STOL ports will be required if congestion is to be

avoided, but the amount would be small compared with the saving in freeway expansion that the system would allow. The heavy rush-hour flow to the downtown San Francisco V/STOL port may also tax the capacity of BART in that neighborhood.

Finally, the V/STOL system would free from 35 to 62 acres of off-street parking areas in downtown San Francisco, which could then be used for other purposes. (Again, this saving is dependent on the demand estimates.) The study finds that commercial uses for this freed area could be found which could result in less daily traffic in downtown San Francisco than would be the case if the V/STOL system were not implemented.

ACKNOWLEDGMENTS

The author wishes to acknowledge the help of Barbara Y. Kitashima, who built the model for determining the distribution of traffic over the road net, and J. C. Davidson and G. E. Peck, who supplied information on the cost of freeway and bridge construction. The author also would like to thank G. E. Peck, L. P. Holliday, and L. G. Chesler for their advice and comments which resulted in significant improvements in the study.

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I. INTRODUCTION

Several vertical or short takeoff and landing (V/STOL) systems intended to serve the San Francisco Bay Area are described in a study done for NASA by the Boeing Company [1]. The specific systems analyzed are those that could be in full service by 1980 and by 1990, and airplanes having both vertical takeoff capability and short takeoff capability are considered. Based on estimates of the costs, fares, and service times, Boeing's analysis indicates that these systems might attract from 67,231 passengers a day in 1980 to 131,250 in 1990. This commuter-type demand is visualized as comprising round trips that are completed in the same day. The traffic is highly peaked in the morning and evening rush hours, but is assumed to be symmetrical (i.e., at any given moment there are equal numbers of passengers going in each direction) except for the traffic going to downtown San Francisco, which is almost entirely directed into the city in the morning and out of it in the evening.

The basic demand analysis in the Boeing study did not consider the effect of Bay Area Rapid Transit (BART). Since this report is based on Boeing's demand estimates, our results should be interpreted as applying to the situation that would exist if BART did not service a significant number of those passengers who would consider using the V/STOL system, if it were implemented.

It is not the purpose of this report to validate estimates of the amount or nature of the demand made in the Boeing study. Instead, we have investigated the effects on several aspects of surface congestion that a system having the demand defined by Boeing might have.

The one basic assumption made in our study and in Boeing's is that the commuters who use the V/STOL system would travel between the same origins and destinations by private auto (one person per auto) if the V/STOL system did not exist.

Our study considers the effects of the implementation of a V/STOL system on auto congestion in the following areas:

- The main freeway and highway systems in the Bay Area.
- The road system in the neighborhood of the V/STOL ports.
- The downtown San Francisco parking areas.

II. CONGESTION ON THE MAIN FREEWAY AND HIGHWAY SYSTEMS

The V/STOL systems discussed in this report are assumed to be operational between 1980 and 1990. It can reasonably be expected that by that time the existing freeway and highway systems will have been considerably extended. For example, the future traffic levels estimated in the Bay Area Transportation Study Commission report [2] indicate that even if commuter rail service is improved, bus service is upgraded, and BART is expanded to its full capacity, the freeway system will still have to be greatly expanded to avoid congestion.

Boeing's demand estimates and the Commission's future traffic-level estimates are both based on the assumption that future Bay Area commuting will remain heavily oriented toward San Francisco; however, if regional growth (possibly affected by policy decisions against expanding the freeway system or critical bridges) results in a shift of business away from the San Francisco area, the commuting patterns may not be the same as those studied here, and the effect of V/STOL on congestion may well be different. Such a change in growth pattern may offer opportunities for V/STOL systems, especially to affluent commuters who choose to live in preferred locations up to, say 50 miles from their offices. But the design of these systems will necessarily differ from those studied by Boeing.

Estimates of future traffic levels may be somewhat uncertain, since they depend on a number of assumptions regarding the rate and nature of regional growth. Estimates of the most likely location of choke points in the freeway and highway systems, however, may be considerably more reliable. This is particularly true in the San Francisco Bay Area, where both the geography and the dependence on bridges strongly constrain the direction of future growth and thus make the location of likely choke points fairly clear.

The Transportation Study Commission's report identifies the following key links as likely choke points:

- The Bay Bridge.
- The Golden Gate Bridge.
- The Caldecott Tunnel.
- The Bay Shore Freeway just south of San Francisco.

- The East Bay Freeway south of the Oakland end of the Bay Bridge.
- The North Berkeley Freeway.

Figure 1, which shows the existing freeway and highway systems in the Bay Area, clearly indicates that these links are likely to be heavy traffic carriers, regardless of assumptions about future growth, as long as there is a heavy flow of commuters into and out of downtown San Francisco and Oakland. According to the Commission's analysis, a number of improvements will have to be made if these links are to be able to handle future anticipated traffic. Improvements foreseen by the Commission include a new Bay Bridge, a bypass for the Caldecott Tunnel, and an additional freeway along the waterfront on both sides of the Bay.

This report does not attempt to predict the absolute level of future traffic. It does assume, however, that the freeway system will have to be expanded, but that the presence of a V/STOL system may reduce the amount of expansion required. The number of lanes freed on each link in the road system by the use of V/STOL and the reduction in miles of freeway lanes that would need to be constructed before 1980 and 1990 are estimated by assuming that if the V/STOL system did not exist, the commuters would use their autos to make the same number of trips between origins and destinations near the V/STOL ports. Since the exact locations of the origins and destinations are not known (and such data probably would be meaningless for estimating exact origins and destinations in the future), there is some uncertainty about traffic volume on the streets in the immediate neighborhood of the origins and destinations. However, this uncertainty would not be expected to affect the estimate of traffic on the major freeways.

Figure 2 shows the locations of the V/STOL ports that were considered in the Boeing system. The Boeing study considered systems using both STOL and V/STOL aircraft and had slightly different locations for some of the ports. However, these differences and the differences in predicted demand are small enough that there appears to be no point in considering all the aircraft types separately as far as ground congestion is concerned. Thus, only two systems are considered, a 1980 system using a 50-passenger helicopter and a 1990 system using a 50-passenger vehicle with a tilt rotor design.

The demand for these systems, as estimated by Boeing is

Year	*Passengers/Day*
1980	67,231
1990	131,250

These figures represent the total number of passengers traveling in both directions per day. Total demand is also broken down into the daily demand between each pair of V/STOL ports,[2] and we have used these data as the basis for our estimates of traffic distribution.

The Boeing report also includes three curves that show how the demand varies throughout the day. One curve shows traffic flow into downtown San Francisco (very

[2] See Ref. 1, pp. 403-412.

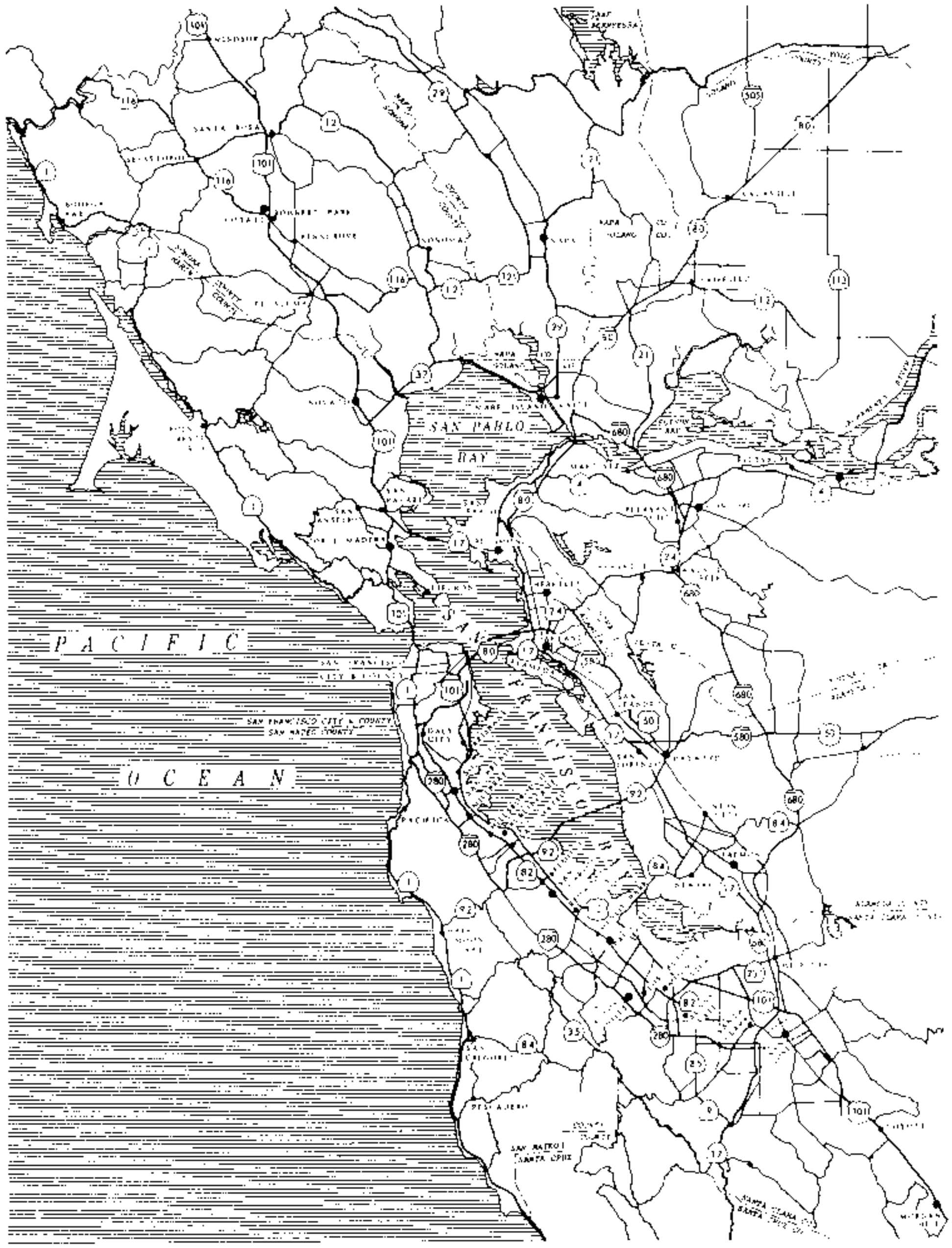

Fig. 1—Road net in the San Francisco Bay Area

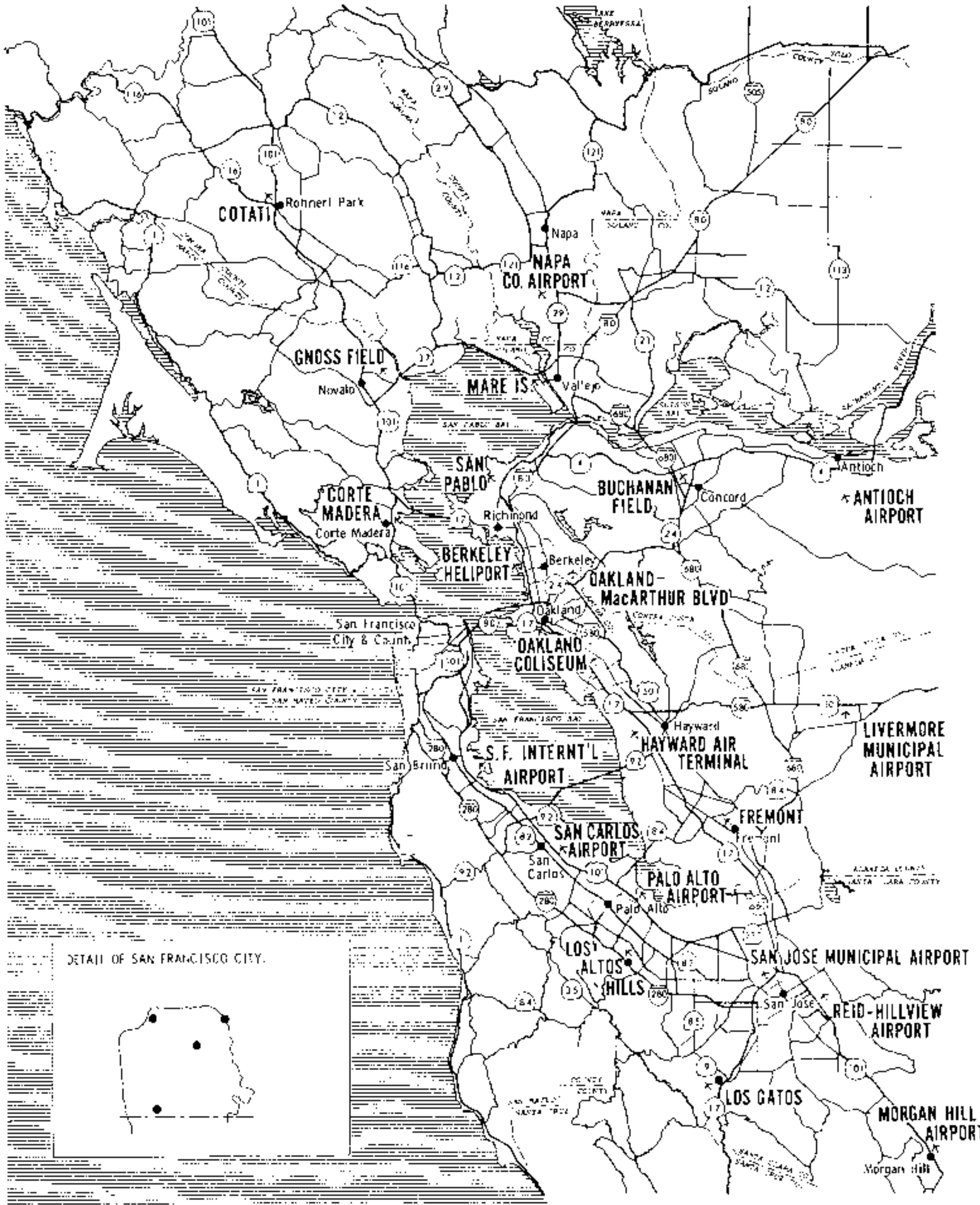

Fig. 2—Location of V/STOL ports in the San Francisco Bay Area

highly peaked during the morning rush hour); one shows the flow out of downtown San Francisco (highly peaked during the late afternoon); and another defines flow between all other V/STOL ports (more moderately peaked in both morning and evening rush hours and symmetrical in that there are approximately equal numbers of travelers going in each direction at any given time). These curves were based on household survey data obtained in the Bay Area and, although there was considerable variation between different origin-destination pairs, a representative set of curves was selected. For the purposes of our analysis, these curves were approximated by the curves shown in Fig. 3, from which it can be seen that the flow *into* downtown San Francisco is very highly peaked and asymmetric. Since the potential V/STOL passengers represented by these curves are presumably business commuters, the curves would be expected to be more higly peaked than similar ones describing the total traffic flow. The Division of Highways [3] gives the ratio of peak-hour two-way traffic over the Bay Shore Freeway to the average hourly traffic as 1.5,[3] whereas if the same ratio is calculated for areas other than downtown San Francisco, the curves in Fig. 3 indicate a ratio of 1.9 and values as high as 2.8 for the traffic going into downtown San Francisco.

A traffic distribution model was built to determine how much traffic would be removed from each link in the road system by the use of V/STOL. For this purpose, the road network was divided into numbered links (shown in Fig. 4), and the links forming the best route between each origin-destination pair were defined. In most cases, selection of the "best" route is obvious. If one route is significantly shorter than the others, it is considered "best." If two routes of about equal length are available, preference is given to the route that avoids congested areas. In a few cases, there appear to be two routes of about equal attractiveness. In these cases, it was usually assumed that half the travelers used each route.

Having defined the links for the routes between the various origin-destination pairs, and using the daily travel rates between these pairs as defined by Boeing, our model calculated the auto traffic on each link that would be required to transport the daily V/STOL passengers.[4] The model then calculated the traffic during peak hours by multiplying the daily traffic between each origin-destination pair by the appropriate peaking factor (Fig. 3) and aggregating the results by link. These results can be interpreted as representing the amount of traffic that the V/STOL system would remove from each link in the road network. The model also aggregated the peak-hour passengers by terminal; this aggregation was used in the analysis of terminal congestion described in Sec. III.

A reduction in the number of vehicles that use each link can be viewed as either reducing the congestion on the link, thereby permitting a corresponding increase in traffic speed, or as reducing the number of miles of freeway lanes that must be built in the future to accommodate the anticipated growth in traffic.

The relation between the capacity of a freeway lane and the vehicle speed has

[3] In obtaining this ratio, it was assumed that all daily traffic occurred during a 16-hour driving day.

[4] One passenger per auto was assumed.

The number of freeway lanes freed on the more critical links in the road net, as estimated by this procedure, is shown in Table 1 for both the austere case and deluxe case assumptions on lane capacity.

The manner in which the lane-mile saving would be distributed over the entire network is shown in Figs. 6 and 7. The data in these figures apply to the 1980 and 1990 demand situations and are based on the austere-case capacity assumption. It can be seen that the earliest effects of V/STOL would be to relieve the Bay Shore and East Bay Freeways and the Bay Bridge. If the V/STOL system continued to grow, it would continue to offload these links and would also begin to offload the Golden Gate Bridge, North Berkeley Freeway, and Highway 24, which passes through the Caldecott Tunnel. Possibly the most important contribution of V/STOL would be the relief of traffic on the Bay Bridge. The present bridge has 10 lanes (5 each way); therefore, if the 1990 V/STOL demand developed as assumed, the V/STOL system might free about one-half of the present bridge capacity.

The inclusion of fractional lanes in the total lane-mile calculation might be questioned, since unless there is sufficient reduction in traffic to free an entire lane, no saving in road construction can be made. Including fractional lanes, however, seems justified if one considers that, since the highway system will be steadily expanded in the future, partial freeing of a lane means that construction of a new lane can be delayed until a later date. Thus, the total lane-miles saved by a given date indicates the reduction in the freeway expansion rate.

To obtain a rough idea of the magnitude of the cost saving implied by a reduction in freeway expansion, we established some representative costs of road, tunnel, and bridge construction based on the present program of proposed Bay Area high-

Table 1

NUMBER OF LANES ON CRITICAL FREEWAY LINKS FREED BY V/STOL SYSTEM OPERATION

	Lanes Freed			
	"Deluxe" Rush-Hour Speed (47 mph)		"Austere" Rush-Hour Speed (30 mph)	
Link	1980	1990	1980	1990
Bay Bridge	4.9	8.0	2.5	4.0
Golden Gate Bridge	1.3	3.2	0.7	1.6
Caldecott Tunnel	1.2	2.6	0.6	1.3
Bay Shore Freeway	2.7	4.9	1.4	2.5
East Bay Freeway	2.1	3.5	1.1	1.6
North Berkeley Freeway	1.2	2.6	0.6	1.3

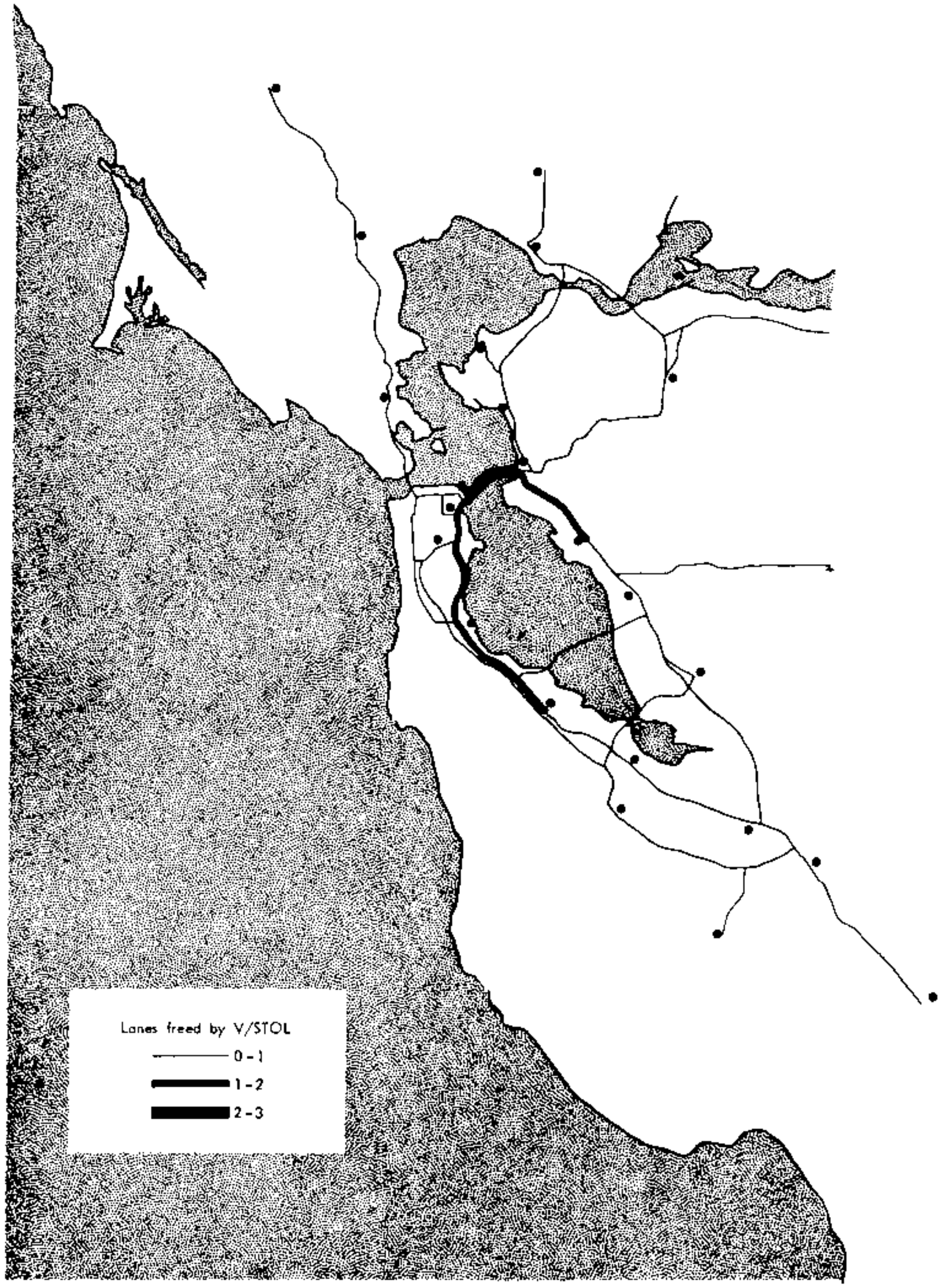

Fig. 6—Effect of V/STOL on future freeway and highway requirements: 1980 VTOL system described in the Boeing study

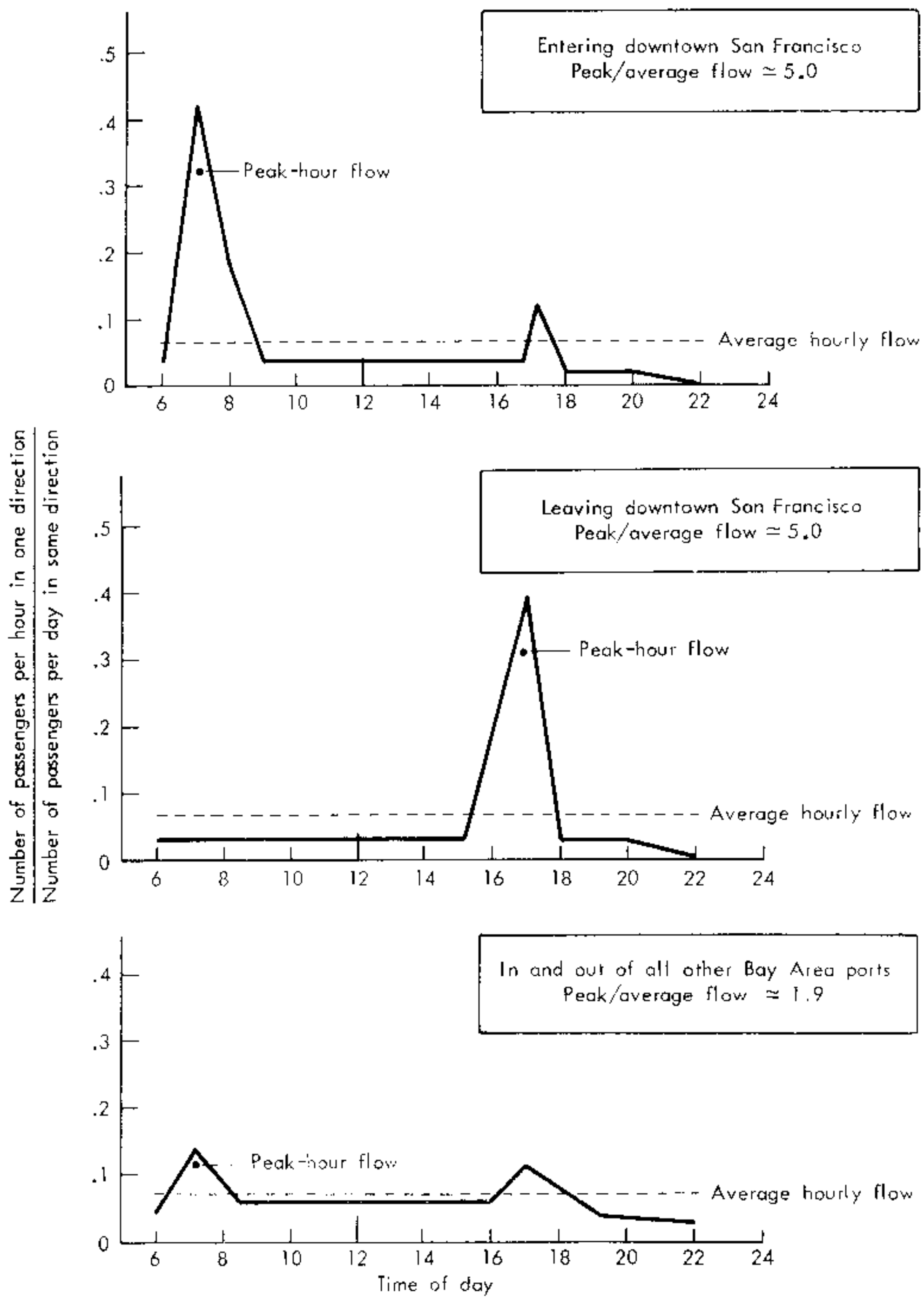

Fig. 3—V/STOL passenger demand throughout the day

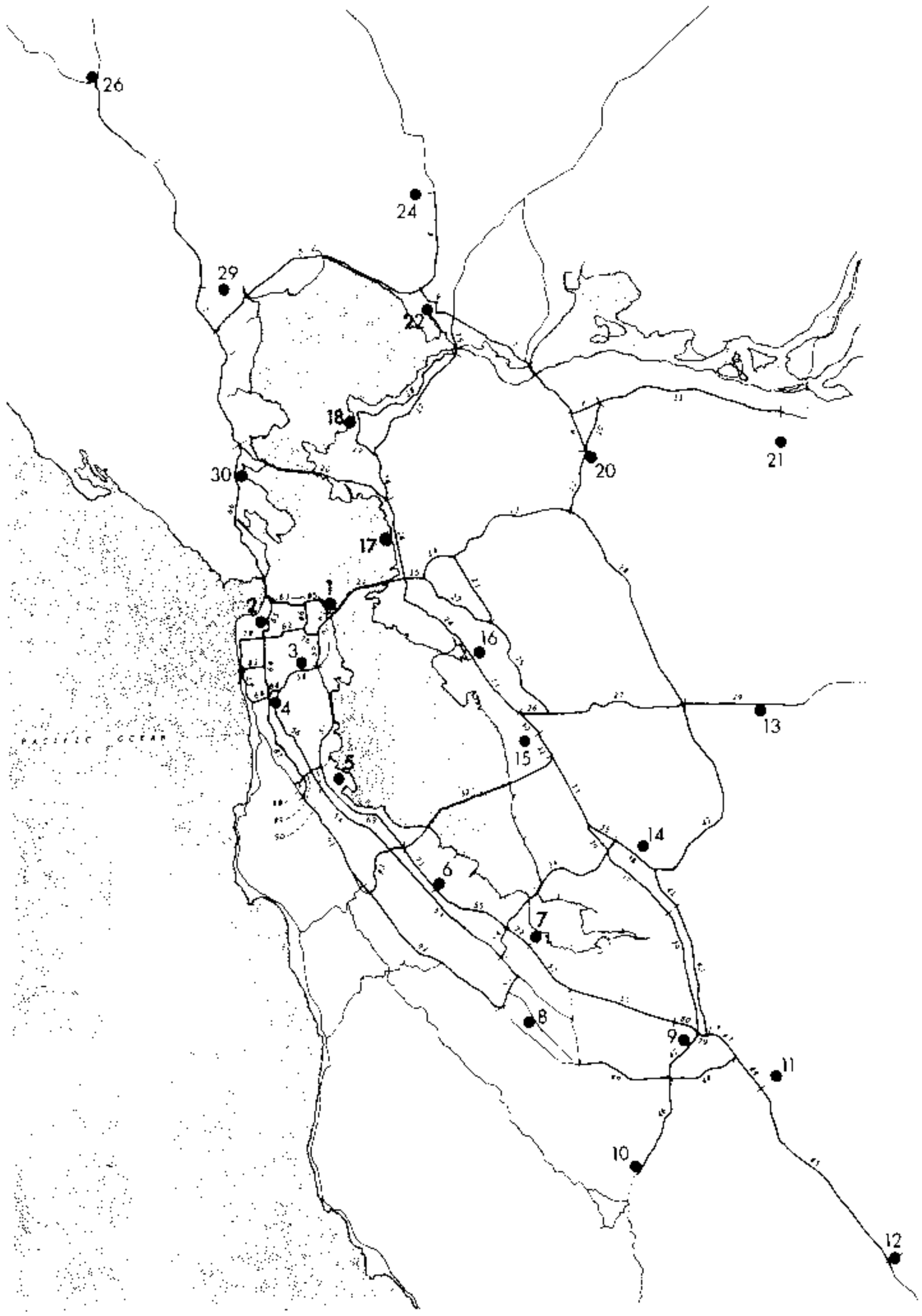

Fig. 4—Road links and V/STOL ports considered in congestion analysis

been well researched. The curve in Fig. 5 (taken from the *Traffic Engineering Handbook* [4]) is typical.

The speed estimates in Fig. 5 apply to a single lane on a four-lane freeway. Although traffic is slightly faster on the inner lanes than on the outer, and may also be faster on a six-lane freeway than on a four-lane freeway, these differences are small enough to be ignored here. Figure 5 shows that the maximum capacity of a freeway lane approaches 2000 cars an hour, but this volume is reached only when traffic is traveling at a speed of about 30 mph. If higher-speed operation is desired, and enough lanes are provided that the volume of autos is in the neighborhood of 1000 per hour, the average auto speed will be 47 mph.

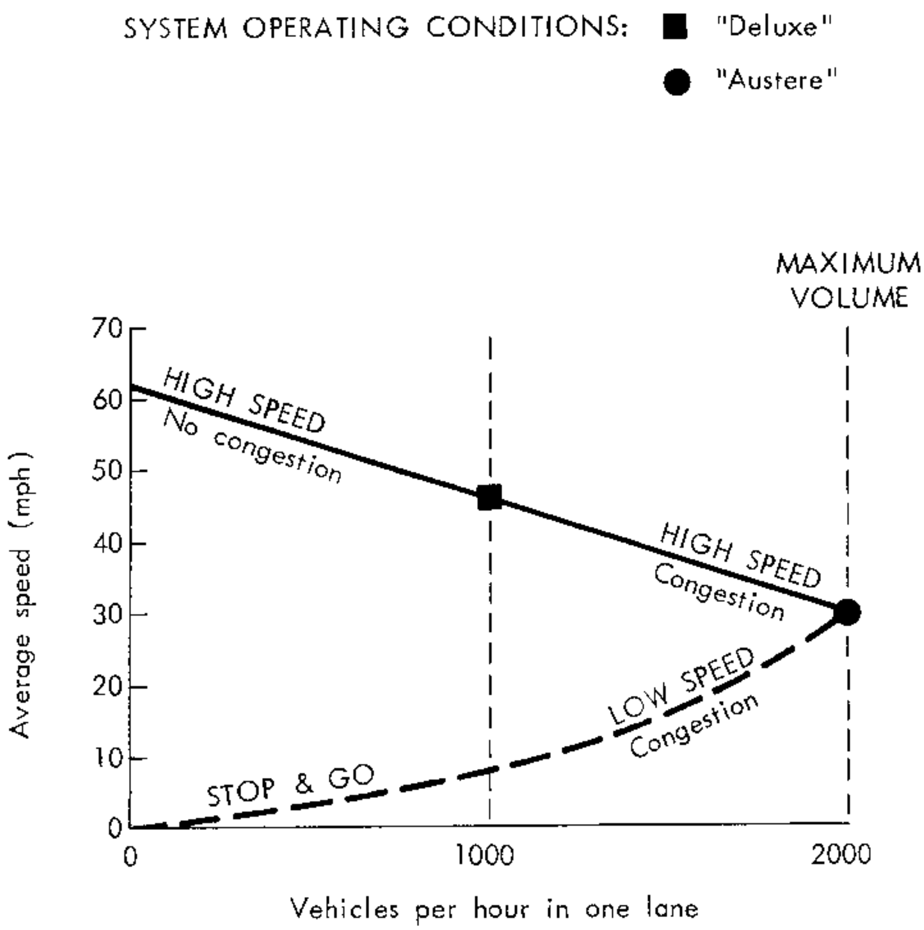

Fig. 5—Average speeds on four-lane freeways

Current congestion in the Bay Area is such that during the peak hours, lanes now operate close to their maximum capacity in the most heavily traveled direction. For example, the Bay Bridge currently operates at about 1800 vehicles per hour per lane in the most heavily traveled direction during the peak hours. The Bay Shore Freeway in San Francisco and the Caldecott Tunnel service 1950 and 1850 vehicles, respectively.[5]

Because the V/STOL traffic volume is so strongly peaked, the estimates of the number of lanes freed depends strongly on the assumptions made regarding the acceptable congestion level during the peak hour. Two cases are considered. The "austere" case, i.e., the case that results in the least future freeway construction, assumes that in the future the freeway system will be expanded so that during rush hours the freeways will operate at maximum capacity. Figure 5 indicates that this will result in an average vehicle speed of 30 mph, and that this average speed will be accompanied by some traffic instability; i.e., drivers will be forced to accelerate and decelerate at times in order to stay with the traffic. Under these conditions, the capacity of a lane will be about 2000 vehicles per hour. The austere case, then, represents a future expansion of the freeway system while maintaining about the current level of peak-hour congestion.

The "deluxe" case situation assumes that, in addition to being expanded to handle increased traffic volume in the future, the freeway system is further expanded so as to reduce congestion in the peak hours. This extended expansion will permit a peak-hour lane volume of 1000 vehicles per hour, which Fig. 5 indicates will result in an average vehicle speed of 47 mph. The lane-miles saved by using V/STOL, based on the deluxe case, represent the maximum possible saving.

The following estimate of the number of lane-miles that V/STOL would save on the Bay Bridge in 1980 illustrates the calculation procedure used.

The traffic distribution model shows that 2530 potential V/STOL passengers cross the Bay Bridge into San Francisco in the morning peak hour, and 2403 leave San Francisco by the bridge in the evening peak hour. Using the austere criteria (2000 vehicles per lane per hour), the number of lanes saved inbound is 2530/2000 = 1.26 and the number of lanes saved outbound is 2403/2000 = 1.20.

Because of the asymmetry of traffic flow in and out of San Francisco, it might be possible to reduce the number of additional lanes required in the future by dividing the highway asymmetrically during the morning and evening rush hours. This will not always be feasible. On the Bay Bridge, which uses one level for traffic in one direction and a second level for the opposite direction, the off- and on ramp configuration will probably make asymmetric operation impractical. In other cases, provision of a changeover lane with the necessary guards, curbs, and gates may be as expensive as building two ordinary lanes. In any event, this possibility has not been considered here and, in determining the lane-miles required by the potential V/STOL traffic, it is assumed that conventional lanes are used in both directions. With this assumption, the total lane construction saved on the Bay Bridge by 1980 is 1.26 + 1.20 = 2.46, or approximately 2.5 lanes.

[5] These unpublished figures were obtained from the California State Division of Highways.

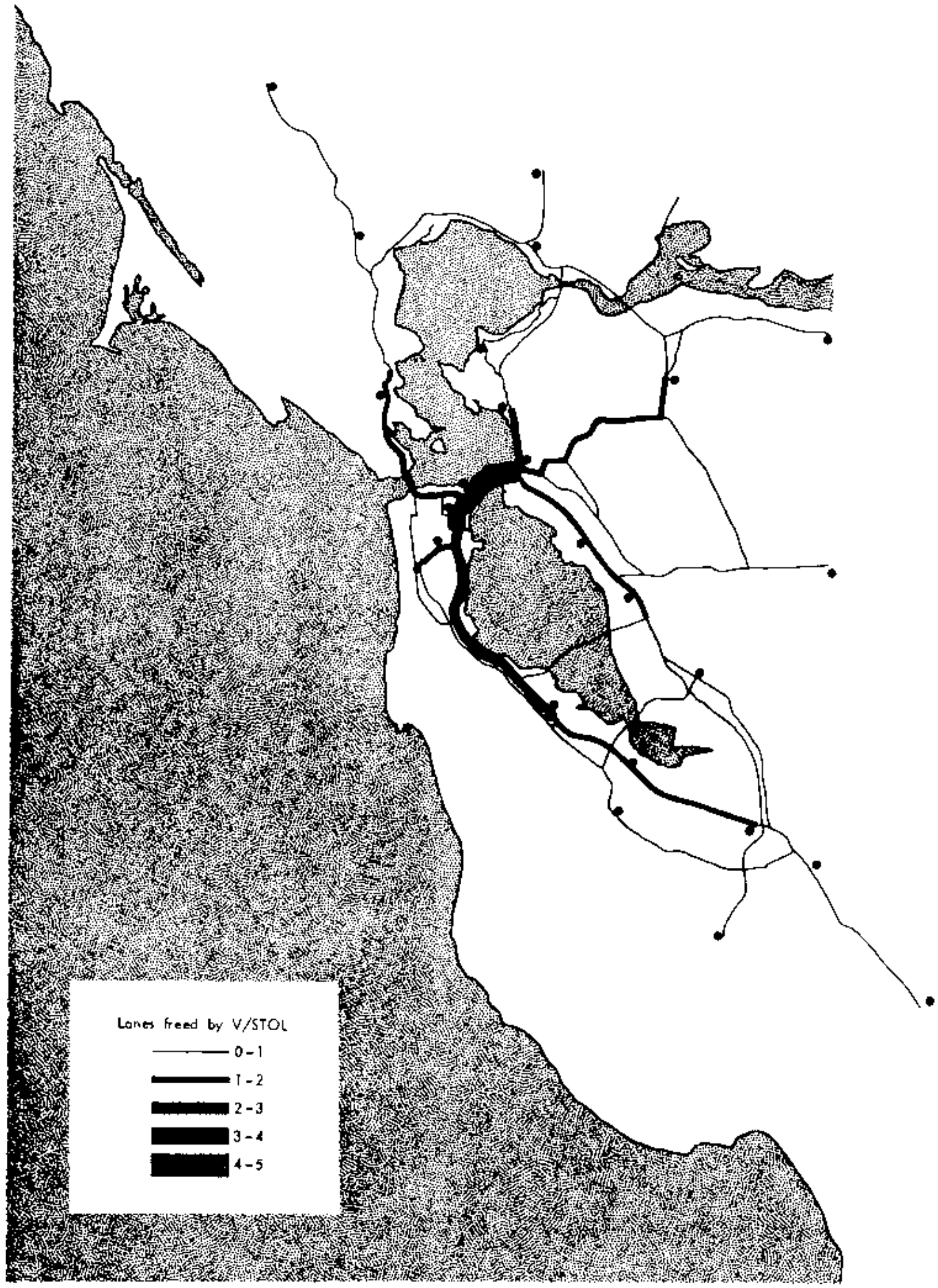

Fig. 7—Effect of V/STOL on future freeway and highway requirements: 1990 VTOL system described in the Boeing study

way construction. The costs of several proposed highway modifications are given in Table 2 on a cost-per-lane-mile basis.

Estimates of the lane-miles that could be saved by the introduction of the V/STOL system are shown in Table 3, together with associated cost savings.

It can be seen that if the austere criteria are accepted, the savings in highway expansion could be $256 million by 1980 and $510 million by 1990. Greater savings would be made, of course, if the level of service were upgraded to the deluxe level.

Table 2

LANE-MILE COSTS OF BAY AREA FREEWAY, BRIDGE, AND TUNNEL EXPANSIONS

Project	Cost per Lane-Mile
Highway Expansions	
Route 1, from junction with Route 92 to 4.6 mi north	1.2
Route 1, vicinity of Pacifica	1.4
Route 84, from junction with Route 280 to Dumbarton Bridge	1.7
Route 61, from junction with Route 92 to junction with Route 112 near San Leandro	1.3
Route 1, from junction with Route 101 to Muir Beach	1.45
Average freeway cost per lane-mile	~ 1.5
Bridge Replacements	
San Francisco - Oakland Bridge	5.3
Bencis - Martinez	5.0
Richmond - San Rafael	3.3
Dumbarton	4.5
Southern Crossing	4.0
Average bridge cost per lane-mile	~ 4.5
Tunnel Expansion	
Bore new two-lane tube for Caldecott Tunnel	5.6

Table 3

LANE-MILES OF FREEWAY AND FREEWAY EXPANSION COSTS SAVED BY V/STOL SYSTEM OPERATION

Projected Operational Date	Number of Daily Passengers	Lane-Miles Saved		Expansion Costs Saved (million $)	
		Austere	Deluxe	Austere	Deluxe
1980	67,231	128	257	256	510
1990	131,250	233	465	459	763

III. GROUND CONGESTION AT V/STOL PORTS

Congestion caused by passengers traveling to and from the V/STOL ports is somewhat more difficult to estimate than that on the main freeways and highways, because we do not know the exact locations of the passengers' origins and destinations or the routes over which they may approach the V/STOL ports. It is assumed here that the ports are sited and designed to allow access to them without overcongesting the neighboring freeways, particularly in those locations where the freeways may already be crowded. However, it seems likely that some fraction of the access traffic will travel over the freeways for at least a short distance in the neighborhood of the ports. There will be a substantial amount of traffic into some of the V/STOL ports, and it will be necessary to plan the access roads to each port carefully if congestion is to be avoided both on the freeways and on the local streets surrounding the ports.

It will also be necessary to provide parking at the ports. Many of the V/STOL travelers will be commuters who probably will be driven to and picked up from the ports and thus will not require any parking space. However, this type of passenger will double the access traffic to the ports, since he will require one trip in and one trip out of the port during both morning and evening rush hours.

A survey of intercity commuter airlines [5] indicated that about 60 percent of the passengers were driven to the airport and did not park; about 30 percent drove themselves there and parked; and the remainder used public transportation or rented cars and taxis.

The traffic distribution model described in Sec. II was used to calculate the number of passengers passing through each V/STOL port per day and during the morning and evening peak hours. Our calculations indicate that for the 1990 system, ten terminals would handle over 10,000 V/STOL passengers a day, and seven terminals would handle over 1000 V/STOL passengers departing during the morning peak hour, with a comparable but slightly smaller number of passengers arriving in the evening.

In order to examine congestion in the neighborhood of the V/STOL ports, two ports were selected for study—the downtown San Francisco terminal and the terminal at Palo Alto. The Ferry Building terminal in downtown San Francisco is a special case due to its extreme asymmetry. Palo Alto is representative of those terminals handling approximately 10,000 passengers a day without the asymmetry associated with the San Francisco terminal. The passenger traffic in these two terminals is given in Table 4.

Table 4

PASSENGER TRAFFIC IN THE SAN FRANCISCO AND PALO ALTO TERMINALS

Location of V/STOL Operation	Passengers Arriving by V/STOL During Rush Hour				Passengers Leaving by V/STOL During Rush Hour			
	Morning		Evening		Morning		Evening	
	1980	1990	1980	1990	1980	1990	1980	1990
San Francisco[a]	3237	5701	688	1211	344	606	3237	5701
Palo Alto[b]	366	612	554	942	610	1035	339	568

[a]Total passengers per day = 20,236 (1980); 35,636 (1990).

[b]Total passengers per day = 7327 (1980); 13,326 (1990).

SAN FRANCISCO

The situation in downtown San Francisco is much different from that at other sites. As indicated by the peaks in passenger flow shown in Table 4, a flux of passengers comes into the city by V/STOL in the morning rush hour and leaves in the evening rush hour. This traffic contributes little to street congestion in San Francisco, since these commuters will be on foot when they deplane and will probably use either BART or local busses, or will walk to their destinations. Those commuters who cannot reach their destinations conveniently by these methods will probably not use the V/STOL system, but will continue to commute by auto.

These commuters may present a congestion problem to BART, however. Assuming the minimum possible headway (90 sec) and stop time of 20 sec, a series of BART trains of ten cars each could move 19,500 passengers an hour over one track. The 1990 V/STOL system will bring in and take out 5700 passengers during both the morning and evening rush hours. Although BART has a potential capacity 3.5 times that required to handle the V/STOL traffic, it may be difficult to provide the number of trains necessary during the rush hour and still offer adequate service throughout the other areas serviced by BART. Thus, V/STOL may increase the cost of operating BART.

During the nonrush hours, V/STOL passengers will leave and arrive at the San Francisco terminal at a rate of about 1200 per hour. Some may drive their cars to the terminal instead of using BART. If all drove down one street, they might occupy most of a city street lane throughout the day. However, it can be expected that they will be coming from origins distributed randomly over the northwest portion of San Francisco and so will make use of a large number of streets leading toward the Ferry Building terminal. There are approximately 30 miles of streets within 1 sq mi of the Ferry Building. Assuming that the average driver spends 5 min in this square mile (at an average overall speed of about 12 mph), V/STOL passengers will add 100 autos to this area at any one moment, or about 4 autos per mile of street—two moving toward the terminal, and two moving away from it.

Considering that many passengers will not use their autos to get to the V/STOL port, it appears that the nonrush-hour traffic will not be a serious source of congestion, except possibly on the Embarcadero or on Market Street in the immediate neighborhood of the Ferry Building.

PALO ALTO

At Palo Alto, and at all the sites except San Francisco, the demand is much more symmetrical, with a more nearly equal number of passengers arriving and leaving Palo Alto throughout the day. It is assumed that one-third of the morning rush-hour travelers who leave by V/STOL will park their cars at the port for the day, and that the remainder will be driven in and picked up on their return. The travelers arriving at Palo Alto by V/STOL are assumed to use public transportation to reach their destinations. If the Palo Alto V/STOL service is to attract passengers, some form of public transportation will have to be provided for those who arrive by V/STOL and do not have their own transportation. It is assumed here that a 50-passenger shuttle bus going to downtown Palo Alto will be provided.

Based on these assumptions, it is estimated that the number of vehicles traveling to and from the Palo Alto V/STOL port in the morning rush hour in 1990 will be 1035 going to the port, and 712 returning from it. (This includes 12 shuttles carrying arriving V/STOL passengers.) If all of these vehicles were to move on the freeway system—half traveling north and half south—they would require 0.5 of a lane traveling toward the port and 0.4 of a lane traveling away from it, if a speed of 47 mph is maintained. But if all the vehicles were to approach the port on a well-signaled arterial road at a speed of 35 mph, then the number of lanes required would increase to 0.8 toward the port and 0.5 away from it. Since in the evening rush the direction of flow over the roads would be reversed (due to those passengers who parked their cars at the port during the day), whereas the traffic volume would remain much the same, it will be necessary to provide for the larger lane requirement in both directions. Thus, a total of 1.0 additional freeway lane, or 1.6 arterial lanes, would be needed to handle the rush-hour traffic. This is serious enough to require that the approaches to each V/STOL site be carefully planned, and probably a decision will have to be made as to whether it would be more desirable to bring the V/STOL access traffic over the freeway system or to keep it on the local arterial system.

Not all of this additional requirement should be associated with the use of V/STOL, however. A similar need would exist if the commuters were to drive directly to their destinations by auto, except that in the latter case, the additional lanes would be needed for freeway access rather than for V/STOL port access. The difference between the two cases will be zero if access roads are expanded to handle peak-hour traffic in both directions. If access roads make use of movable dividers to reduce the expansion required, the V/STOL system will require more access-road construction than the freeway system, owing to the need to accommodate the return trips home of the "deliver and pick-up" vehicles. Even in this case, if it is assumed that access traffic will diffuse over the road net within a mile and a half of the port or freeway, the ten V/STOL terminals that will handle over 10,000 passengers a day in 1990 will require only 16 more lane-miles of access-road construction than the freeway system. If the 16 lane-miles of access-road construction is compared with the freeway lane-mile saving through the use of V/STOL (between 233 and 465 lane-miles for the 1990 system), it can be seen that the road requirements for access traffic will be small compared with the saving in freeway lane-miles that V/STOL could bring about.

In summary, the examination of congestion in the neighborhood of the V/STOL ports indicates that the passenger flow through the ports will be sufficient to require careful planning of the access-road system if congestion is to be avoided, but that the amount of incremental road construction required will be small compared with the saving in future freeway construction associated with the use of V/STOL.

IV. PARKING IN DOWNTOWN SAN FRANCISCO

The V/STOL system described in this report will deliver 10,118 passengers per day into downtown San Francisco in 1980 and 17,500 passengers per day in 1990. If instead of using V/STOL these people drive their autos, they will need to park them during the day. The number of cars parked throughout the day can be found by subtracting the demand curves of Fig. 3 for passengers going out of downtown San Francisco from those given for the passengers coming into the area. The remainder will be parked in downtown San Francisco. Figure 8 shows that during most of the day, the number of autos parked in the downtown area equals about 51 percent of the daily incoming passengers. This number approximately represents the autos arriving in the morning rush hour and parking throughout the day. While autos continue to arrive (at a much lower rate) during the remainder of the day, they are balanced by an equal number leaving, so that the number parked remains constant.

The number of parking spaces required to accommodate the potential V/STOL passengers, then, is 5160 for the 1980 system and 8950 for the 1990 system. Since most of these autos park all day, they will probably be in parking lots rather than on the street. The *Traffic Engineering Handbook* [4] estimates that an area of 300 sq ft is required by a parked car when adequate aisles and waste space are allowed for. This would imply that the 1980 V/STOL system would free 1.5×10^6 sq ft (35 acres) of downtown parking space for other uses. The 1990 system will free 2.7×10^6 sq ft, or 62 acres.

No attempt is made in this report to estimate the effect of freeing this amount of space on the economy of San Francisco, or on the Bay Area as a whole, other than to note that at $2.50 a working day, the V/STOL passengers in the 1980 system will pay $\$2.5 \times 10^6$ a year in parking fees, whereas those in the 1990 system will pay $\$4.5 \times 10^6$. The introduction of V/STOL would remove this source of income from downtown San Francisco, but the use of this freed parking space for other commercial purposes might offset the loss.

Although the economic effect of these changes is beyond the scope of this study, it is possible to make some estimate of their effect on street congestion in downtown San Francisco. The *Traffic Engineering Handbook* describes a regression analysis that was used to estimate the daily-trip attraction to the central business district (CBD) as a result of using the freed parking space for other commercial purposes.

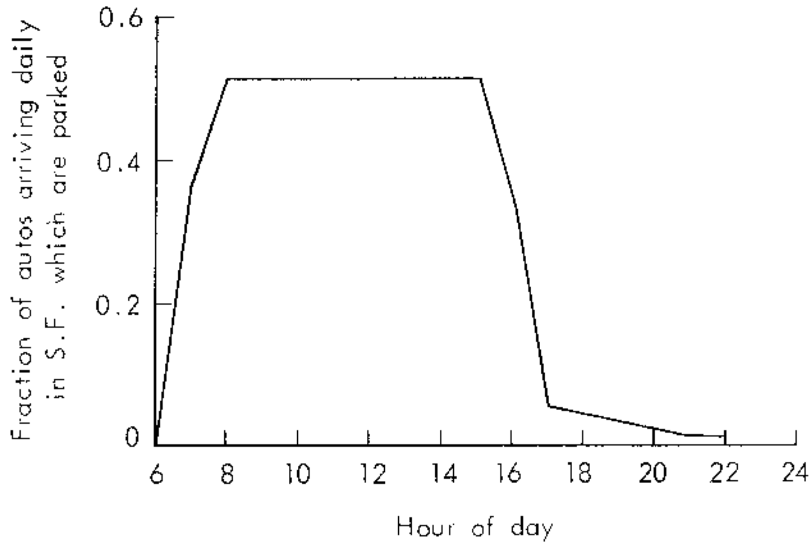

Fig. 8—Parking in downtown San Francisco

Seven major cities were considered in the study. Although San Francisco was not included, the results for the cities considered were sufficiently similar that an approximate equation was found which can be assumed to represent other cities. The equation is

$$Y = 14X_1 + 5X_2 + X_3 - 1800,$$

where Y = the daily number of person-destinations in the CBD from within the city,
X_1 = retail area (in thousands of square feet),
X_2 = service area (in thousands of square feet),
X_3 = manufacturing area (in thousands of square feet).

Using this equation, we estimated the number of autos per day drawn to the CBD by the use of the freed parking space for various commercial enterprises. The results are given in Table 5. In each case enough of the freed space was assigned to parking to accommodate the people attracted to the downtown area. The parking area required was calculated by assuming that people drawn by the additional retail and service establishments would park for an average of 1.5 hours in a 10-hour day and would ride with 1.5 passengers per auto. People drawn by the additional manufacturing and warehousing industry (presumably workers) are assumed to park all day and to ride with 1.0 passenger per auto.

Table 5

NUMBER OF AUTOS ATTRACTED DAILY TO DOWNTOWN SAN FRANCISCO BY COMMERCIAL USES OF FREED SPACE

Use of Freed Space	Number of Automobiles 1980	1990
Parking for potential V/STOL passengers	10,118	17,818
Retail	10,100	17,600
Service	4,430	7,730
Manufacturing or warehousing	1,180	2,100

If the area freed by the use of V/STOL is converted to retail stores, the total number of autos per day drawn to the CBD will remain about the same as it would be if the V/STOL system were not implemented and its potential passengers drove their cars to the CBD. However, street congestion will be improved during peak hours, since the traffic caused by retail customers will not be as highly peaked as that due to the commuters; most of the stores will not open until after the morning commuter rush, and the customers may try to avoid the evening rush.

If the freed space is used for service, there will be an appreciable reduction in the total number of autos coming into the CBD and, in addition, a more random distribution of traffic, which will tend to reduce the commuter peak-hour rush.

Using the freed space for manufacturing and warehousing will result in the greatest reduction in the daily number of autos coming into the CBD, but much of this traffic (workers driving to and from work) may occur during the rush hours. Also, the number of heavy trucks coming into the downtown area may increase.

V. CONCLUSIONS AND DISCUSSION

The conclusions given in this study are strongly dependent on the demand estimates generated in the Boeing study and on the assumption of that study that BART is not available or does not handle a significant number of passengers. As a result, our estimates of the reductions in congestion due to the implementation of a V/STOL system probably represent an upper bound for the real situation.

The passenger traffic diverted to V/STOL represents only a small portion of daily personal trips into the Bay Area (the Boeing study indicates 1 percent). However, because the commuter traffic is so strongly peaked and tends to be concentrated on a few freeway links, it requires a significant amount of highway capacity. V/STOL's most important impact on highway congestion may be to divert future traffic from the Bay Bridge. Our estimates indicate that, by 1990, V/STOL might divert about one-half the present traffic volume from the Bridge capacity—enough to significantly delay the need for a new bridge. Conceivably, if the future growth of the region is centered less on San Francisco than was assumed in estimating the future traffic in the *Bay Area Transportation Report* [2], it might even eliminate the need for an additional bridge.

The estimates made in our study indicate that the saving in future freeway expansion due to the use of the V/STOL system could amount to $256 million by 1980 and to $510 million by 1990.

The V/STOL system will require some highway and road construction in the neighborhood of the V/STOL ports if road congestion is to be avoided, but the amount of road construction required would be small compared with the saving in future freeway construction.

Finally, in downtown San Francisco, the V/STOL systems would free from 35 to 62 acres of off-street parking space that can be put to commercial uses. If this space is used for retail stores, the total number of autos entering downtown San Francisco per day will be about the same as if the V/STOL system had not been developed, but congestion would be eased during the commuter rush hours and increased during the middle of the day. Use of this space for service or manufacturing purposes will result in a reduction of the total number of autos per day in the downtown area. Since the downtown street system probably cannot be expanded significantly in the future, the anticipated growth of the region will probably result in increasing congestion unless steps can be taken to prevent it. The introduction of V/STOL, together with rezoning to encourage service and manufacturing, might be one such step, but it would have to be compared with other possible solutions for reducing downtown congestion before it is taken.

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