# TRANSPORTATION PROBLEMS FACED AFTER BIG EARTHQUAKES

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Civil Engineering

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April 15, 1991

Blacksburg, Virginia

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(ABSTRACT)

Transportation facilities and services provide the cornerstones to the rescue and response operations after a big earthquake. This study appraises the transportation actions taken by the authorities in the immediate aftermath of the Loma Prieta Earthquake of October 17, 1989. The failure of several transportation structures had a significant impact on rescue operations, traffic congestion and change in travel patterns in the San Francisco Bay Area. Emphasis is placed on travel demand management strategies adopted to meet the travel needs in the Bay Area and to return traffic to normalcy. The short-term and long-term impacts of closures of certain highways due to a 7.5 magnitude earthquake are also addressed in this research.

Recent predictions by the United States Geological Survey show that there is a 67 percent chance of a big earthquake of 7.5 magnitude happening in the Bay Area before the year 2020. Therefore, there is a dire need to look at the transportation problems that the Bay Area might face if the "Big One" really hits. It is also important to note that certain bridges play a major role in the cross-bay transportation. Hence, the failure of such critical links would greatly influence the mobility of the citizens in the

region. A macro-level measure referred to as "Weighted Roadway Congestion index" (RCIW) is developed to assess the severity of the closures of these links. To fulfill this objective, scenario analysis is performed for the expected closures in the San Francisco Bay Area. It is important to note that the macro-level measure developed is applicable only to urban areas. This research also aims at identifying the key network parameters, such as number of lane-miles per freeway exit and freeway network connectivity that impact roadway congestion after earthquakes.

# *Acknowledgements*

I would like to express my sincere gratitude to Professor Antoine G. Hobeika, Director of the Center for Transportation Research at Virginia Tech and Chairman of my thesis committee for his always enthusiastic and supportive attitude towards me and this research effort. Also, for providing me with the financial support throughout my involvement in this research project sponsored by the National Science Foundation (N.S.F.). Through remarkable insight into trends in the Transportation Engineering profession, he greatly influenced the structure of my program at Virginia Tech. I would like to acknowledge Dr. Richard D. Walker, for his friendship and guidance through the Master's program and for serving on my committee. In addition, I would like to thank Dr. Antonio A. Trani for being a member on my committee.

I would like to extend my special thanks to Dr. Sigon Kim who contributed to the successful completion of my research. I also thank him for his constructive comments through my research and also for advising me in structuring my thesis.

Special thanks are due to Mr. R. Sivanandan, Research Associate at the Center for Transportation Research, for his suggestions and kind help throughout my stay at the Center. All colleagues at CTR need to be thanked for their friendship and cooperation.

Nothing of this would have been possible without the moral support of my parents and brothers in India. I would like to express my gratitude to my father for encouraging me and giving me an opportunity to continue my studies, for all his moral and financial support.

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# 1.0 INTRODUCTION

## 1.1 Background of the Problem

In the San Francisco Bay region, seven damaging earthquakes of magnitude 6.5 or greater occurred during the 83 years prior to the great San Francisco earthquake of 1906. Only two damaging earthquakes have occurred in the 83 years since. However, the stress relieved by the 1906 earthquake appears to have built up again to a failure level. Thus severe earthquakes are likely to be more frequent in the next few decades than from 1906 to the present.

The San Francisco Bay Area is the fourth largest metropolitan area in the United States with about 6 million people. At 5:04 p.m. on October 17, 1989, the Bay Area was shaken by a powerful earthquake measuring 7.1 on the Richter scale. It was named the Loma Prieta earthquake after the highest topographic point adjacent to the fault zone. This magnitude 7.1 earthquake was felt from Los Angeles north to the Oregon state line, and east to western Nevada. It was the largest to occur in the San Francisco Bay Area since the great San Francisco earthquake of 1906.

The Office of Emergency Services (OES) reported that the earthquake caused[3]

- 62 deaths
- 3,757 injuries
- Damage to nearly 116,000 homes
- Property damage worth $8 billion

- Widespread disruption of transportation, utilities and communication.

Future earthquakes in California are inevitable. They present a clear and continuing danger to the population and economy. The consequences of severe earthquakes in urban areas will be extensive--too large for "business as usual." Actions must be taken to forcefully reduce the risks, vulnerability, and exposure people share. The vast majority of structures that might fail in future earthquakes exist now--bridges, buildings, industrial facilities, and utilities. Every Californian is affected by the occurrence of a major earthquake, whether that effect is expressed as direct damage, indirect loss of utilities, increased taxation, or reduced economic activity[11].

In 1980, the National Security Council estimated that a serious California earthquake has the potential to cause from $20 to 80 billion in damage and kill tens of thousands of people. In terms of today's values, total damage impacts of future quakes would be at least twice as large and would exceed $100 billion for several of their postulated earthquakes[11]. These are only the direct physical damage costs, not the myriad other costs incurred as a result of the damage. Californians are justifiably concerned and should plan for the so-called "Big Ones."

The key transportation issues after an earthquake occurs are as follows:

- Importance of transportation in Emergency Management
- Returning traffic to normalcy
- Long term impacts of disruption in transportation services.

It is important to study the problem of an earthquake occurring in the Bay Area in the future. Presently, a macro-level measure does not exist which can approximately estimate the congestion level on an area-wide basis. This helps the emergency planners if they are interested in preparing for the projected "Big One."

## 1.2 Research Objectives

The main objectives of this research which also are the main tasks of the project funded by NSF (National Science Foundation) are two fold: (1) to appraise the transportation actions taken by the authorities in the immediate aftermath of the Loma Prieta Earthquake of October 17, 1989, and (2) to develop a macro-level measure which indicates the severity of the impact due to the closure of certain critical links in the aftermath of a big earthquake and to study that measure's relationship with the network's structural parameters. This could be achieved by

- Emphasizing the travel demand management strategies adopted to meet the travel needs in the Bay Area and to return traffic to normalcy.
- Studying the short-term and long-term impacts of closures of certain highways due to the October 17, 1989, Loma Prieta Earthquake.
- Looking at the size and magnitude of the problem and the disastrous effect if critical bridges and freeways are closed to traffic when the "Big One" really hits.
- Developing a macro-level measure referred to as the Weighted Roadway Congestion Index (RCIW) and then performing scenario analysis for the Bay Area to assess the severity of the closure of the links.
- Identifying the key network parameters, such as number of freeway exits per lane mile, that impact roadway congestion after earthquakes.

All the landlocked areas in the predicted "Big One" scenario will also be identified for the San Francisco Bay Area.

The following are some of the issues that will also be focused on in this research:

- Stress the importance of transportation in the immediate aftermath of any earthquake.
- Review the transportation actions taken by the authorities in the immediate aftermath of the Loma Prieta earthquake to facilitate emergency response, rescue, and evacuation operations.

## 1.3 Outline of the Remaining Chapters

Chapter two deals with the literature review of the transportation actions taken in the aftermath of the Loma Prieta earthquake of 1989. This also includes effects on the highway system, earthquake response effort and travel behavior. The second section of the literature review concerns the previous research conducted in the areas related to Roadway Congestion and also the structural measures of network.

Chapter three deals with the evaluation of travel demand management strategies employed in the Loma Prieta aftermath. Another portion of the third chapter deals with the impacts of the Loma Prieta earthquake. The impacts were both long-term and short-term and were mainly due to the closure of certain highways and bridges.

Chapter four presents an interesting issue, i.e., What if the "Big One" really hits? Addressed here will be the size and magnitude of the problem and the disastrous effect if critical bridges and freeways are closed when a big earthquake occurs. This also provides the reader with an insight into the problem if the "Big One" really hits the population centers of the San Francisco Bay Area. The projections for the year 2010 in terms of population, auto ownership, autos per center-line mile and number of vehicles crossing the five bridges in the Bay Area are depicted in Chapter Four.

The research methodology is briefly explained in Chapter Five, i.e., how the macro-level measure was developed to assess the severity of the problem due to the closure of certain critical links. Also the methodology involved in the scenario analysis done for the Bay Area when a "Big One" hits is detailed in this chapter.

This chapter also deals with the analysis which was done for the earthquake-borne cities. Scenario analysis performed for three different scenarios of closures of bridges and freeways is discussed in detail in this chapter. Statistical analysis done to develop the model for the macro-level Weighted Roadway Congestion Index is also dealt with in this chapter. The results obtained from regression analysis and correlation analysis with the Weighted Roadway Congestion Index as the dependent variable and various other network's structural measures as independent variables are discussed at length in this chapter.

Conclusions and recommendations of the research are presented in Chapter Six.

# 2.0 LITERATURE REVIEW

## 2.1 Introduction

The Loma Prieta earthquake was the nation's first prime-time earthquake. It occurred during the opening ceremonies of the third game of the World Series that was about to be played at Candlestick Park. Media coverage was intense from the very start, with live television focusing on the fires in the Marina District of San Francisco, on damage to bridges, and on search and rescue operations being broadcast to the nation well before local communities knew what had happened.

The most serious immediate effects were collapsed buildings, highways, and bridges; fires; loss of electric power; ruptured water and gas lines; and earth slides. Two of the most dramatic impacts of the earthquake were the failure of the Cypress Viaduct and collapse of the link span of the San Francisco-Oakland Bay Bridge, both about 60 miles from the epicenter[4].

## 2.2 Effects on the Highway System

The major damage was to the State highway system, while local roads and streets, although not unscathed, received relatively minor damage. The major highway service disruptions were in the cities of San Francisco and Oakland. The failure of the main bridge between the two cities was the major event of the quake. Within 48 hours, over 1,500 bridges were inspected for damage. Of these bridges, 74 had minor damage, 23 had major damage and 13 were closed within a short time. Of the 13 bridges, one was reopened after 5 hours, and 2 others within 2 days. Forty-one people died in the Cypress collapse, and one died on the Bay Bridge in a traffic accident moments after the earthquake. Fairly or not, the lasting legacy of the Loma Prieta earthquake probably will be the damage sustained by highway bridges[4].

Following the earthquake, 10 counties were proclaimed State and Federal disaster areas: Alameda, Contra Costa, Marin, Monterey, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, and Solano. The damage data for all the 10 counties affected as reported by the Office of Emergency Services (OES) are shown in Table 1[3].

A description of the significant highway failures and the measures taken to restore service follows:

### 2.2.1 Route 1

Twin 800-ft. bridges on a freeway section of Rte 1 failed at Struve Slough which is between Monterey and Santa Cruz.

Replacement bridges were quickly designed, constructed and opened to traffic within three and a half months. In the interim, a detour over local roads provided adequate service.

### 2.2.2 San Francisco Freeways

The failures on the freeway system consisted mainly of severe damage to structural columns. The damage to columns necessitated traffic closures on three major routes: Rte I-101 near Market to the end of a Viaduct structure near Franklin Street, Rte I-280 from Rte.101 north, and the Embarcadero Viaduct (Rte.480), which is a major traffic

**Table 1. Damage data for 10 counties in Loma Prieta earthquake**

| County | Dead | Injured | People Displaced |
|---|---|---|---|
| Alameda | 41 | 481 | 1,002 |
| Contra Costa | 0 | 22 | 0 |
| Marin | 0 | 0 | 5 |
| Monterey | 1 | 14 | 54 |
| San Benito | 0 | 110 | 412 |
| San Francisco | 13 | 700 | 0 |
| San Mateo | 0 | 451 | 0 |
| Santa Clara | 1 | 1,305 | 50 |
| Santa Cruz | 6 | 671 | 6,377 |
| Solano | 0 | 3 | 0 |
| TOTAL | 62 | 3,757 | 7,900 |

Source: Office of Emergency Services

distributor/ collector between the San Francisco Bay Bridge and Central San Francisco, Chinatown and the Fisherman's Wharf areas. Portions of these closures were soon restored to service. The location of the damaged San Francisco freeway viaducts are shown in Figure 1[3].

### *2.2.3 Cypress Viaduct on I-880*

The northern portion of this mile-and-a half long three-level structure collapsed. In all the rescue and removal operations, contractors and state personnel worked from 6 a.m. until 10 p.m. seven days a week until the area was cleaned up. The composite aerial photograph of the Cypress Viaduct showing the extent of the collapse is shown in Figure 2[3].

### *2.2.4 The San Francisco - Oakland Bay Bridge*

Automotive use stopped with the failure of two 50-foot closure deck spans. The repair proceeded around the clock, and the bridge was open for full service in one month. Figure 3 shows the upper and lower closure spans which fell when bolts attaching the east-truss span were severed.

## 2.3 Cross-Bay Transportation

San Francisco stretches some 65 miles from Alviso in the south to its northern boundary at the Richmond-San Rafael Bridge in the north. Beyond this bridge, the stretch of water becomes San Pablo Bay, which ends at the Carquinez Bridge near Vallejo. Besides the Richmond-San Rafael Bridge, San Francisco Bay is crossed by three other bridges: The San Francisco-Oakland Bay Bridge, the San Mateo Bridge, and the

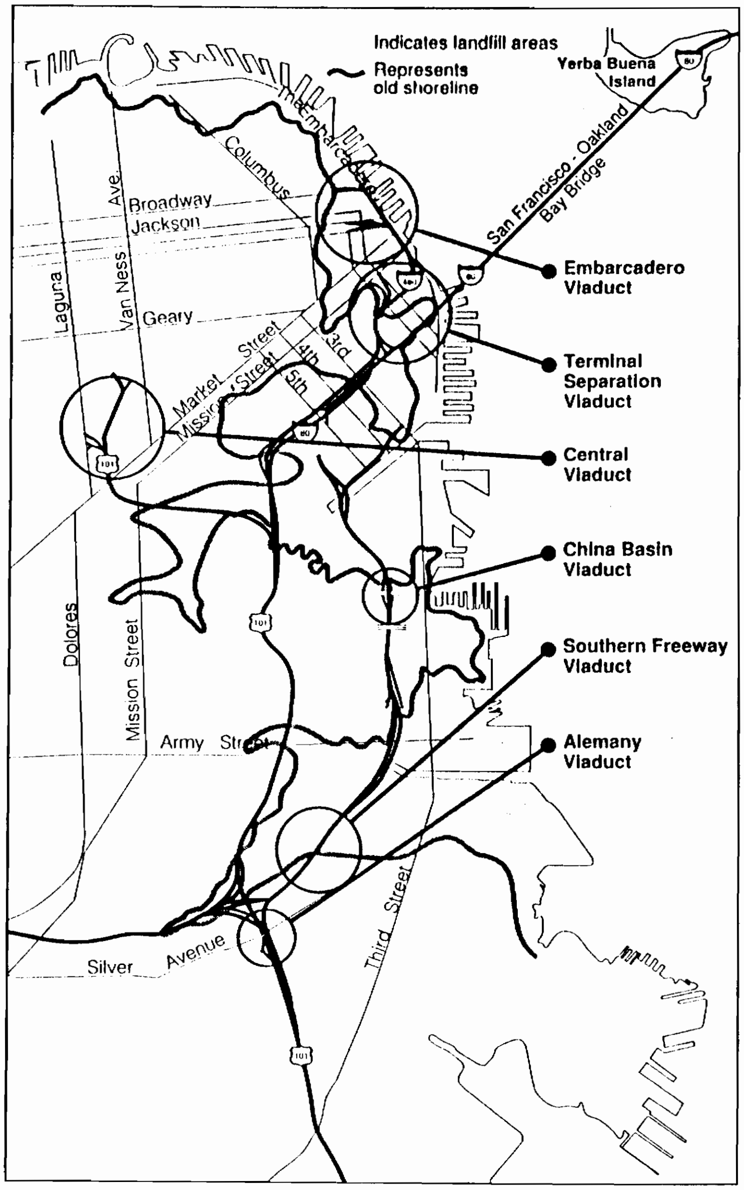



**Figure 1. Location of the damaged San Francisco Freeway Viaducts**

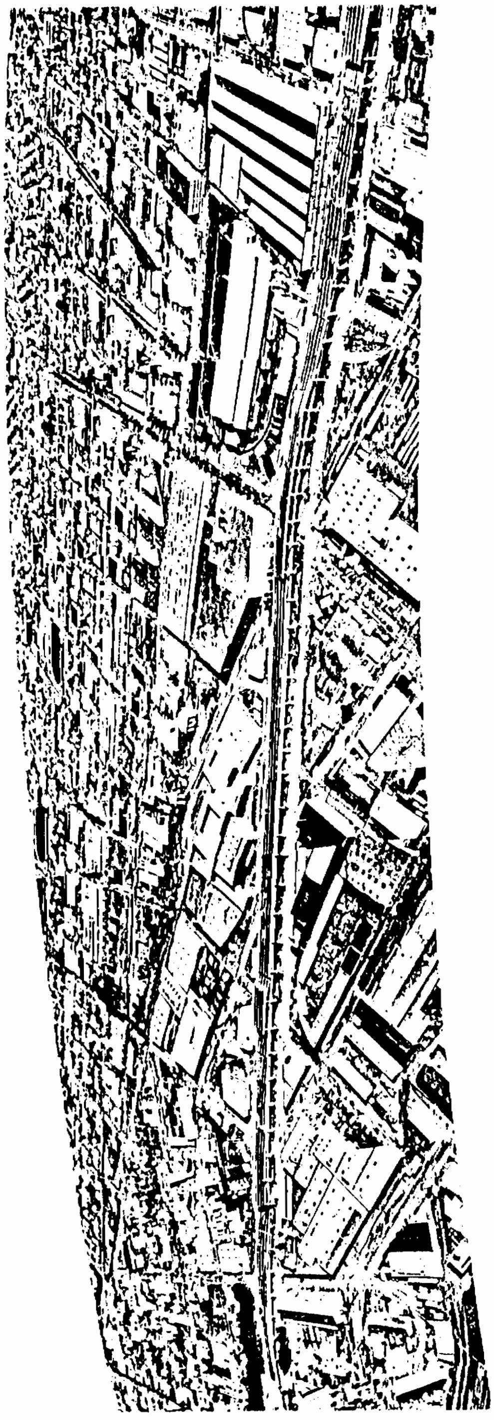


**Figure 2. Composite aerial photograph of the Cypress Viaduct**

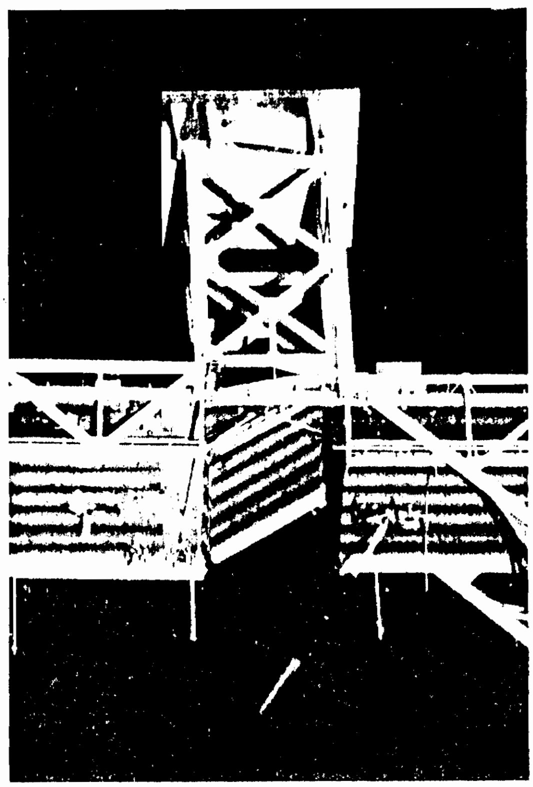


**Figure 3. Failure of the Bay Bridge upper and lower closure spans**

Dumbarton Bridge. The Bay exits to the Pacific Ocean under a fifth bridge--the Golden Gate. In addition, the Bay is traversed by the Bay Area Rapid Transit (BART) Trans-Bay Tube between Oakland and San Francisco. All these details are shown in Figure 4. The critical connections between San Francisco and its eastern and northern neighbors are the Golden Gate and Bay Bridges, and the BART Trans-Bay Tube[3].

## 2.4 Immediate Response

As with CalTrans, public transit agencies responded with all available resources. Fortunately, the BART system was designed to withstand 8.0+ magnitude earthquakes. Within about 9 hours of the earthquake, the BART system was completely reopened. No passengers were trapped in trains, and no evacuations were necessary. Because electrical power was knocked out for all of San Francisco, emergency backup lighting was needed in BART trains and stations within the city. Limited propulsion power was fed through the Transbay Tube from the East Bay to allow all San Francisco trains to be moved safely into stations for off-loading. For several hours, service at two downtown San Francisco BART stations was disrupted due not to BART, but to fears of gas leaks in nearby office buildings[4].

San Francisco Muni service was greatly disrupted by the loss of power. The Muni Metro light rail system, the electric trolley system, and the cable cars all came to a halt. With the Bay Bridge closed and BART closed initially for safety inspections, thousands of commuters were stranded in downtown San Francisco[4].

As nearly all Bay Area residents remained glued to their televisions and radios

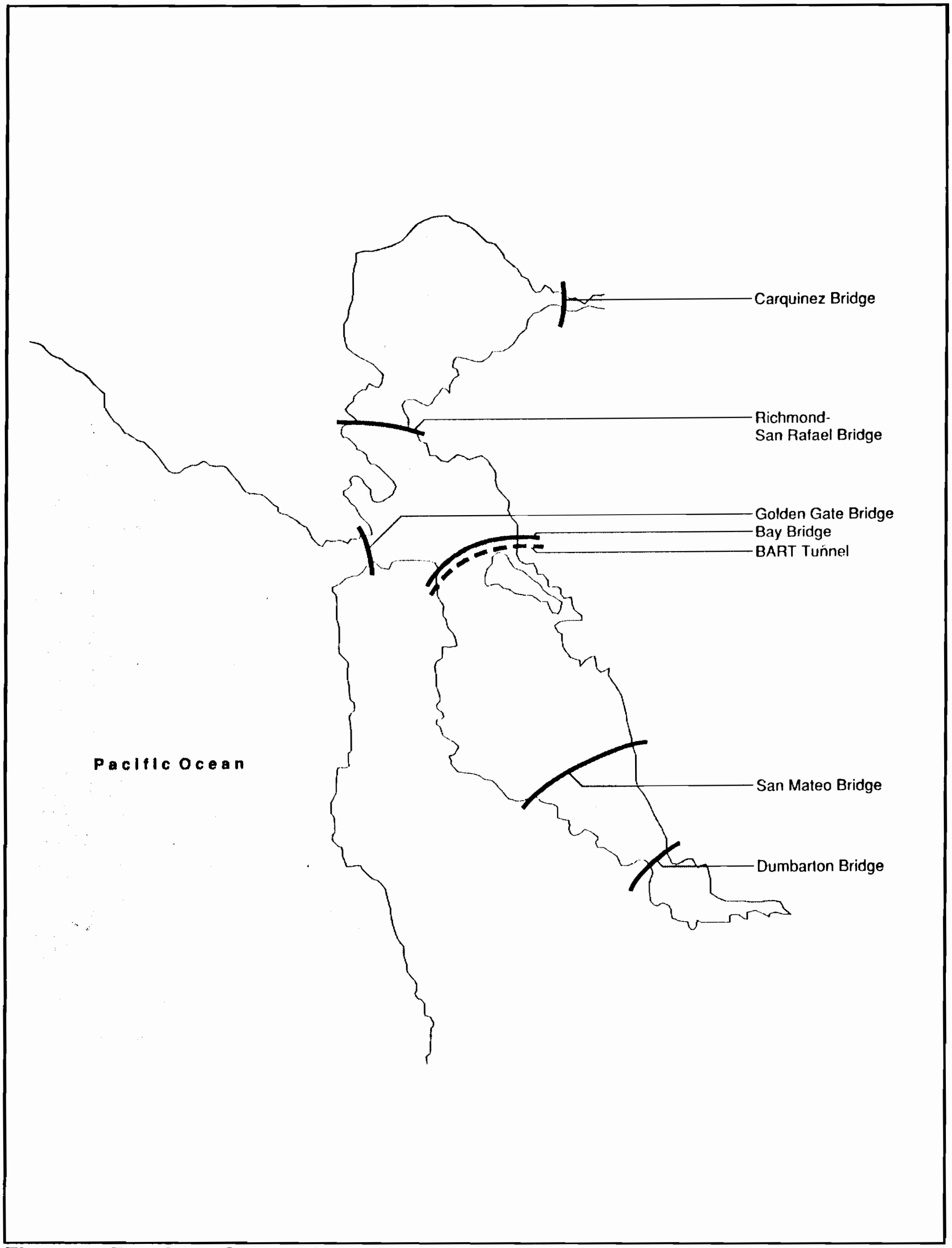



**Figure 4. Bay Area Connections**

throughout the night, they learned the full scope of the assessed damage to their systems and realized there was relatively little damage to their facilities.

## 2.5 Pre-Quake Travel

The Bay Bridge corridor pre-quake travel is shown in Figure 5[4]. It shows the morning peak period mode split in April 1989. Of the 100,000+ commuters who travel Westbound toward San Francisco between 5 and 10 a.m., 66% were already in transit or carpools. This is a significant observation in terms of transit use.

## 2.6 Travel Behavior

The immediate need, of course, was to find a way across the Bay. Prior to the quake, more than 350,000 trips were made daily across the Bay Bridge. The post-earthquake transportation services were BART, CalTrain, Alameda County (AC) Transit and Ferries. The Bridge and Transit volumes of the quake week are shown in Table 2. The Bridge volumes are measured in terms of the number of vehicles whereas the Transit volumes are in terms of the number of persons commuting[9].

### *2.6.1 October 18, 1989*

The number of vehicles crossing the Richmond-San Rafael Bridge during the morning commute dipped to 6,186 compared to the pre-quake figure of 6,500. There was a similar situation in the case of the other bridges,i.e., San Mateo (from 13,500 to 9,305), Dumbarton (from 14,200 to 9,484) and Golden Gate (from 25,433 to 21,300).

Ferry service offered commuters another option for crossing the Bay. Crowley

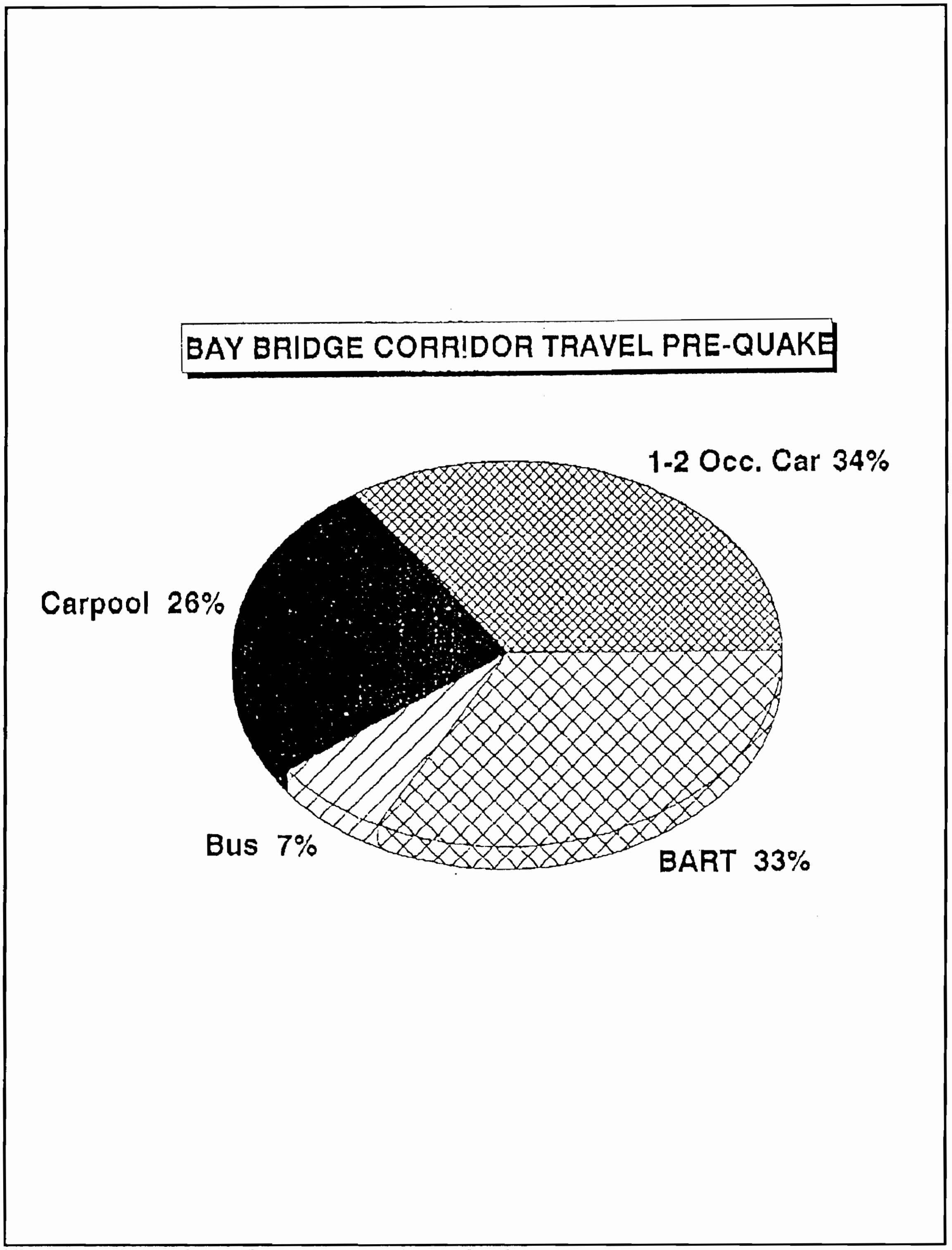



**Figure 5. Bay Bridge Corridor Travel Pre-Quake**

## Table 2. Bridge & Transit Volumes of the Earthquake Week

BRIDGE & TRANSIT VOLUMES
Before and After Earthquake

Date: 11/02/89
Time: 10:00 AM

BRIDGE VOLUMES
Morning peak period (5-10 AM)

| | Pre-Quake Average | TUES 17-Oct | WED 18-Oct | THRS 19-Oct | FRI 20-Oct | MON 23-Oct | TUES 24-Oct | WED 25-Oct | THRS 26-Oct | FRI 27-Oct | MON 30-Oct | TUES 31-Oct | WED 01-Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Richmond/S.Rafael | 6,500 | 5,479 | 6,196 | 9,152 | NA | 7,283 | 9,491 | 10,593 | 10,953 | 10,767 | 10,994 | 10,919 | 11,250 |
| San Mateo | 13,500 | 13,827 | 9,305 | 15,379 | NA | 12,383 | 15,206 | 16,994 | 17,706 | 17,702 | 19,930 | 19,736 | 19,011 |
| Dumbarton | 14,200 | 14,550 | 9,494 | 14,581 | NA | 13,520 | 12,656 | 14,040 | 14,241 | 13,981 | 14,594 | 14,732 | 14,859 |
| Golden Gate | 25,433 | 25,533 | NA | 21,399 | 19,322 | 21,585 | 25,605 | 27,514 | 28,190 | 27,538 | 29,429 | 29,700 | 28,798 |

CALTRAIN
Morning Peak Period (6:15-9:45 AM)

| | Pre-Quake Average | TUES 17-Oct | WED 18-Oct | THRS 19-Oct | FRI 20-Oct | MON 23-Oct | TUES 24-Oct | WED 25-Oct | THRS 26-Oct | FRI 27-Oct | MON 30-Oct | TUES 31-Oct | WED 01-Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| San Jose - S.F. | 3,560 | | | | | 4,200 | 4,700 | 4,537 | 4,590 | 4,193 | 4,630 | 4,630 | 4,229 |
| Sa' ns - S.Jose | ------ | | | | | 4 | 45 | 70 | 99 | 101 | 127 | 126 | 187 |

BART
Westbound Morning Peak (5-9 AM)

| | Pre-Quake Average | TUES 17-Oct | WED 18-Oct | THRS 19-Oct | FRI 20-Oct | MON 23-Oct | TUES 24-Oct | WED 25-Oct | THRS 26-Oct | FRI 27-Oct | MON 30-Oct | TUES 31-Oct | WED 01-Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 26,029 | | | | | 50,353 | 52,448 | 51,529 | 51,031 | 48,969 | 53,911 | 52,092 | 57,592 |

FERRIES
Morning Peak Period

| | Pre-Quake Average | TUES 17-Oct | WED 18-Oct | THRS 19-Oct | FRI 20-Oct | MON 23-Oct | TUES 24-Oct | WED 25-Oct | THRS 26-Oct | FRI 27-Oct | MON 30-Oct | TUES 31-Oct | WED 01-Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red & White / CI | | | | | | | | | | | | | |
| (AM Peak) | 1,154 | | | | | 3,313 | 3,109 | 3,379 | 3,817 | 3,719 | 4,279 | 4,413 | 4,557 |
| (Daily Totals) | 2,300 | 10,962 | 5,148 | 4,767 | 5,207 | 6,721 | 5,531 | 10,331 | 10,748 | 11,417 | 11,715 | 11,550 | |
| G.Gate (Saus/Lksp) | | | | | | | | | | | | | |
| (5:00-10:00 AM) | 1,492 | 1,552 | 717 | 1,550 | 2,747 | 3,525 | 2,900 | 2,475 | 2,558 | 2,459 | 3,194 | 2,897 | 2,779 |
| .ily Totals) | 4,703 | 5,199 | 3,499 | 4,915 | 5,998 | 7,339 | 6,779 | 6,365 | 6,586 | 6,961 | 9,175 | 7,433 | |

Prepared By : Caltrans - Public Transportation Branch
Ben Chuck : 557-9783. Dick Fahey : 557-9915. Chris Williams : 557-9169

Maritime's Red & White Fleet had a day's total of 5,148 compared to its pre-quake total of 2,300 per day. On October 17, the day of the earthquake, Red & White Fleet carried 10,862 people[3].

### *2.6.2 October 19, 1989*

The number of vehicles crossing the Richmond-San Rafael Bridge increased to 9,152 from 6,186. Also, in case of the San Mateo (from 9,305 to 15,379) and Dumbarton (from 14,200 to 14,561) Bridges, there was an increase in the vehicular traffic whereas in the case of Golden Gate Bridge, the number of vehicles crossing was still lower than the pre-quake levels. Red & White Fleet (Ferry Service) was used by about 4,770 people which is more than the pre-quake level.

### *2.6.3 The Week after the Quake*

In the week after the quake,i.e., from October 23-27, 1989, the number of vehicles crossing the Richmond-San Rafael Bridge was around 10,000 in the morning peak period (5-10 a.m.) which was much above the pre- quake level of 6,500. San Mateo (from 13,600 to 17,700), Dumbarton (from 14,200 to 14,500) & Golden Gate Bridges (from 25,000 to 28,140) also showed growth patterns.

CalTrain had an increase in ridership from the pre-quake level of 3,500 to 4,500. BART's Westbound Morning peak ridership increased from 26,029 to 52,448. During the first week of expanded BART service, the number of passengers carried grew from just 300,000 on Monday, October 23, to Friday's record of over 329,000--more than 50% higher than usual. Not surprisingly, the change in ridership was heaviest during rush hour, amounting to a 100% increase over pre-quake figures.

Ferry transportation, although not a major source, could yet provide service for almost double the number of commuters it used to before the quake.

Ridership on the new ferries grew daily from the first full day of the emergency services, with the figures a week later showing a near 17% increase. Total ridership on all the ferries was up by more than 27% in the same period[3].

### *2.6.4 November 13 - 17, 1989*

During the period of November 13 to November 17, the increase in the number of vehicles on all the bridges, Golden Gate, Richmond-San Rafael, Hayward and Dumbarton, still continued. In the case of BART, the change in rider level from normal was more than 100%. The Transbay total day ridership had about 124% change whereas the Transbay West bound morning peak ridership had a change of about 120%. CalTrain ridership was up by 30%. Ferry ridership grew daily from the first day of operation. There was a 150% change in ridership from pre-quake level in case of ferry service.

The post-earthquake commute summary of the week November 13 - November 17 is shown in Table 3[9].

Table 4 shows the various modes used to arrive at Ferry terminals[9].

### *2.6.5 Commute Summary of January*

The post-earthquake summary (5-10 a.m. peak trips) for the month of January is shown in Table 5. The number of vehicles crossing the Golden Gate Bridge during the morning commute dipped to a low of 23,000 compared to its pre-quake level of 25,000. In the case of other bridges, the number crossing was lower than what it was during the closure of the Bay Bridge, but it was more than the pre-quake level. There was a similar

## Table 3. Post-quake commute summary of week Nov 13-Nov 17 (Source: Caltrans)

17-Nov-89

### POST-EARTHQUAKE COMMUTE SUMMARY

| 01:58 PM (5-10 am westbound) | Before "Pre" | Fri Oct 27 | Mon Oct 30 | Tue Oct 31 | Wed Nov 1 | Thu Nov 2 | Fri Nov 3 | Mon Nov 6 | Tue Nov 7 | Wed Nov 8 | Thu Nov 9 | Fri Nov 10 | Mon Nov 13 | Tue Nov 14 | Wed Nov 15 | Thu Nov 16 | Fri Nov 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM PEAK VEHICLES | | | | | | | | | | | | | | | | | |
| Golden Gate Br. | 24,822 | 27,536 | 29,428 | 28,700 | 28,788 | 28,464 | 27,611 | 29,487 | 28,479 | 29,232 | 28,879 | 25,058 | 28,896 | 28,999 | 29,331 | 29,338 | 28,169 |
| Richmond-SR Br. | 6,500 | 10,767 | 10,994 | 10,814 | 11,250 | 11,235 | 11,232 | 11,568 | 11,830 | 11,756 | 11,435 | 10,318 | 11,530 | 11,429 | 11,601 | 11,321 | 11,609 |
| Hayward-SM Br. | 13,600 | 17,702 | 18,830 | 18,736 | 19,011 | 17,545 | 18,207 | 18,006 | 18,482 | 18,531 | 17,296 | 17,805 | 18,081 | 18,627 | 17,432 | 19,064 | 17,895 |
| Dumbarton Br. | 14,200 | 13,981 | 14,594 | 14,732 | 14,858 | 15,452 | 14,947 | 15,068 | 15,222 | 14,680 | 15,142 | 14,076 | 14,859 | 15,715 | 15,240 | 15,358 | 15,512 |
| BART | | | | | | | | | | | | | | | | | |
| Total Day | 218,286 | 329,276 | 322,898 | 335,149 | 345,641 | 346,916 | 352,896 | 338,438 | 348,164 | 347,782 | 352,585 | 320,389 | 326,313 | 345,891 | 355,131 | 357,135 | |
| 5:00-9:00am | 61,499 | 92,331 | 100,067 | 98,343 | 105,933 | 105,056 | 99,454 | 103,454 | 104,424 | 104,568 | 103,232 | 84,675 | 99,766 | 104,933 | 103,951 | 103,036 | 97,718 |
| 5:00-10:00am | 74,349 | 109,298 | 116,018 | 118,154 | 123,002 | 122,681 | 116,782 | 121,411 | 123,281 | 123,871 | 121,167 | 100,311 | 118,788 | 123,328 | 123,140 | 123,103 | 117,057 |
| Transbay Total Day | 102,152 | 207,710 | 201,914 | 212,453 | 222,105 | 222,817 | 220,168 | 218,770 | 225,009 | 224,571 | 227,664 | 207,623 | 209,913 | 223,121 | 229,460 | 228,028 | |
| % Transbay | 46.8% | 63.1% | 62.5% | 63.4% | 64.2% | 64.2% | 62.4% | 64.4% | 64.6% | 64.6% | 64.6% | 64.9% | 64.3% | 64.5% | 64.6% | 63.8% | 0.0% |
| Transbay 5-9am West. | 26,029 | 48,960 | 53,911 | 52,092 | 57,592 | 56,968 | 57,913 | 56,966 | 57,178 | 56,754 | 57,542 | 46,665 | 54696 | 58103 | 57,153 | 55,683 | |
| BART PERCENT CHANGE FROM "NORMAL" OCT. 5 | | | | | | | | | | | | | | | | | |
| Total Day | | 50.8% | 47.9% | 53.5% | 58.4% | 58.9% | 61.6% | 54.1% | 59.5% | 59.3% | 61.5% | 46.8% | 49.5% | 58.5% | 62.7% | 63.6% | 0.0% |
| 5:00-9:00am | | 50.1% | 62.7% | 59.9% | 72.3% | 70.8% | 61.8% | 68.3% | 69.8% | 70.0% | 67.9% | 37.7% | 62.2% | 70.6% | 69.0% | 67.5% | 58.9% |
| 5:00-10:00am | | 47.0% | 56.0% | 58.2% | 65.4% | 65.0% | 57.1% | 63.3% | 65.8% | 66.6% | 63.0% | 34.9% | 59.8% | 65.9% | 65.6% | 65.6% | 57.4% |
| Transbay Total Day | | 103.3% | 97.7% | 108.0% | 117.4% | 118.1% | 115.5% | 112.2% | 120.3% | 119.8% | 122.9% | 103.5% | 105.5% | 118.4% | 124.6% | 123.2% | 0.0% |
| Transbay 5-9am West. | | 88.1% | 107.1% | 100.1% | 121.3% | 118.8% | 122.5% | 118.9% | 119.7% | 118.0% | 121.1% | 79.3% | 110.1% | 123.2% | 119.6% | 113.9% | 0.0% |
| CALTRAIN (San Francisco exits) | | | | | | | | | | | | | | | | | |
| AM Peak (6-9 am) | 3,560 | 4,183 | 4,630 | 4,630 | 4,229 | 4,459 | 4,395 | NA | 4,300 | 4,158 | 4,133 | NA | 4,140 | 4,520 | 4,666 | 4,324 | 3,885 |
| %Change from 10/5 | | 17.5% | 30.1% | 30.1% | 18.8% | 25.3% | 23.5% | NA | 20.8% | 16.8% | 16.1% | 0.0% | 16.3% | 27.0% | 31.1% | 21.5% | 9.1% |
| FERRIES | | | | | | | | | | | | | | | | | |
| Golden Gate(5-10am) | 1,465 | 2,467 | 3,194 | 2,897 | 2,772 | 2,740 | 2,673 | 2,680 | 2,828 | 2,715 | 2577 | 2682 | 2621 | 2708 | 2830 | 2608 | 2558 |
| %Change from 10/5 | | 68.4% | 118.0% | 97.7% | 89.2% | 87.0% | 82.5% | 82.9% | 92.9% | 85.3% | 75.9% | 83.1% | 78.9% | 84.8% | 93.2% | 78.0% | 74.6% |
| Tiburon (7-8:30 am) | 378 | 500 | 713 | 650 | 641 | 595 | 590 | 618 | 599 | 599 | 591 | 528 | 596 | 595 | 589 | 543 | 535 |
| Vallejo exp. 6-7am) | 220 | 450 | 458 | 460 | 543 | 516 | 516 | 537 | 513 | 494 | 509 | 459 | 534 | 550 | 475 | 515 | 513 |
| %Change from 10/5 | | 104.5% | 108.2% | 109.1% | 146.8% | 134.5% | 134.5% | 144.1% | 133.2% | 124.5% | 131.4% | 108.6% | 142.7% | 150.0% | 115.9% | 134.1% | 133.2% |
| Emergency services | | | | | | | | | | | | | | | | | |
| Oakland (6-9 am) | | 1,789 | 1,765 | 1,775 | 1,804 | 1,808 | 1,617 | 2,088 | 1,980 | 1,991 | 1,932 | 1,929 | 1,752 | 1,798 | 1,808 | 1,862 | 1,932 |
| Alameda (6-8 am) | | 555 | 617 | 586 | 655 | 662 | 643 | 634 | 644 | 678 | 677 | 672 | 752 | 688 | 694 | 682 | 727 |
| Richmond (6-8 am) | | 424 | 421 | 448 | 456 | 455 | 441 | 464 | 464 | 488 | 493 | 440 | 433 | 418 | 464 | 452 | 450 |
| Berkeley (6-9 am) | | | 305 | 494 | 558 | 538 | 634 | 611 | 592 | 628 | 672 | 681 | 570 | 581 | 593 | 608 | 705 |
| Subtotal | | 2,768 | 3,108 | 3,303 | 3,473 | 3,463 | 3,335 | 3,797 | 3,680 | 3,785 | 3,774 | 3,722 | 3,507 | 3,485 | 3,559 | 3,604 | 3,814 |
| Daily % Change | | -0.5% | 12.3% | 6.3% | 5.1% | -0.3% | -3.7% | 13.9% | -3.1% | 2.9% | -0.3% | -1.4% | -5.8% | -0.6% | 2.1% | 1.3% | 5.8% |
| TOTAL FERRIES | 2,063 | 6,165 | 7,473 | 7,310 | 7,429 | 7,314 | 7,114 | 7,632 | 7,618 | 7,593 | 7,451 | 7,391 | 7,258 | 7,338 | 7,453 | 7,270 | 7,420 |
| %Change from 10/23 | | -7.5% | 11.7% | 9.3% | 11.0% | 9.3% | 6.3% | 14.1% | 13.9% | 13.5% | 11.4% | 10.5% | 8.5% | 9.7% | 11.4% | 8.7% | 10.9% |

## Table 4. Modes used to arrive at Ferry terminal (Source: Caltrans).

MODES USED TO ARRIVE AT FERRY TERMINAL
(Beginning of Trip)

JACK LONDON SQUARE - SAN FRANCISCO

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 66% |
| Carpool | 25% |
| Bus | 7% |
| Walked only | 1% |
| BART | - |
| Taxi | - |
| Bicycle | 1% |
| Other | - |
| | 100% |

BERKELEY - SAN FRANCISCO

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 65% |
| Carpool | 26% |
| Bus | 5% |
| Walked only | 1% |
| BART | - |
| Taxi | - |
| Bicycle | 3% |
| Other | - |
| | 100% |

ALAMEDA - SAN FRANCISCO

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 59% |
| Carpool | 33% |
| Bus | 6% |
| Walked only | 1% |
| BART | - |
| Taxi | - |
| Bicycle | - |
| Other | 1% |
| | 100% |

RICHMOND - SAN FRANCISCO

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 74% |
| Carpool | 20% |
| Bus | 3% |
| Walked only | 1% |
| BART | - |
| Taxi | - |
| Bicycle | - |
| Other | 2% |
| | 100% |

SAN FRANCISCO - EAST BAY (ALL PORTS)

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 25% |
| Carpool | 5% |
| Bus | 36% |
| Walked only | 11% |
| BART | 3% |
| Taxi | 3% |
| Bicycle | 6% |
| Other | 11% |
| | 100% |

TOTAL (ALL PORTS, BOTH DIRECTIONS

| MODE | PCT. OF PASSENGERS |
|---|---|
| Car (drive alone) | 62% |
| Carpool | 24% |
| Bus | 9% |
| Walked only | 1% |
| BART | 1% |
| Taxi | 1% |
| Bicycle | 1% |
| Other | 1% |
| | 100% |

## Table 5. Commute summary of peak trips of January

24-Jan-90
04:12 PM

### POST-EARTHQUAKE COMMUTE SUMMARY -- 5-10 AM PEAK TRIPS

| | Before Oct 17 | During Closure | Wed Jan 3 | Thu Jan 4 | Fri Jan 5 | Mon Jan 8 | Tue Jan 9 | Wed Jan 10 | Thu Jan 11 | Fri Jan 12 | Mon Jan 15 | Tue Jan 16 | Wed Jan 17 | Thu Jan 18 | Fri Jan 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BRIDGES** | | | | | | | | | | | | | | | |
| Total Vehicles (Peak Direction) | | | | | | | | | | | | | | | |
| Golden Gate (SB) | 24,822 | 29,223 | 23,891 | 23,999 | 23,337 | 24,141 | 24,597 | 24,493 | 24,165 | 22,954 | 18,507 | 25,161 | 24,911 | 24,774 | 23,935 |
| % Change | | 17.7% | -3.8% | -3.3% | -6.0% | -2.7% | -0.9% | -1.3% | -2.6% | -7.5% | -25.4% | 1.4% | 0.4% | -0.2% | -3.6% |
| Richmond (WB) | 6,500 | 11,450 | 6,056 | 6,157 | 6,116 | 5,983 | 6,308 | 6,360 | 5,313 | 5,947 | 5,088 | 5,722 | 6,337 | 6,345 | 6,243 |
| Hayward (WB) | 13,500 | 18,374 | 12,483 | 12,618 | 12,237 | 12,547 | 12,517 | 12,655 | 12,822 | 11,908 | 10,705 | 12,668 | 12,902 | 13,949 | 12763 |
| Dumbarton (WB) | 14,200 | 16,757 | 13,072 | 13,197 | 15,066 | 15,537 | 15,838 | 15,829 | 15,684 | 15,504 | 12,515 | 15,606 | 15480 | 16,417 | 15,632 |
| 3-Bridge Sum | 34,300 | 46,592 | 31,611 | 31,972 | 33,419 | 34,067 | 34,663 | 34,844 | 33,819 | 33,359 | 28,308 | 33,996 | 34,719 | 36,711 | 34,638 |
| % Change | | 35.8% | -7.8% | -6.8% | -2.6% | -0.7% | 1.1% | 1.6% | -1.4% | -2.7% | -17.5% | -0.9% | 1.2% | 7.0% | 1.0% |
| Bay Bridge (WB) | 41,190 | | 32,356 | 32,849 | 34,300 | 33,554 | 33,177 | 34,218 | 34,659 | 33,158 | 28,732 | 33,696 | 34,891 | 35,445 | 34,705 |
| (NOTE. Bay Bridge data exclude carpool lanes since 12-22-89) | | | | | | | | | | | | | | | |
| **BART** | | | | | | | | | | | | | | | |
| Total Passengers | | | | | | | | | | | | | | | |
| 5-10 AM Peak Tot. | 74,349 | 123,190 | 69,726 | 78,366 | 76,644 | 79,276 | 81,438 | 81,178 | 80,916 | 77,255 | 47,768 | 81,707 | 83,439 | 84,458 | 80,827 |
| % Change | | 65.7% | -6.2% | 5.4% | 3.1% | 6.6% | 9.5% | 9.2% | 8.8% | 3.9% | -35.8% | 9.9% | 12.2% | 13.6% | 8.7% |
| WB Transbay Only | 31,468 | 67,507 | 36,904 | 34,504 | 34,879 | 46,398 | 37,556 | 36,977 | 37,193 | 35,741 | 23,639 | 38,018 | 36,179 | 37,920 | 35,260 |
| % Change | | 114.5% | 17.3% | 9.6% | 10.8% | 47.4% | 19.3% | 17.5% | 18.2% | 13.6% | -24.9% | 20.8% | 15.0% | 20.5% | 12.1% |
| **CALTRAIN** | | | | | | | | | | | | | | | |
| San Francisco Exits | | | | | | | | | | | | | | | |
| 6-9AM Passengers | 3560 | 4,503 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| % Change | | 26.5% | | | | | | | | | | | | | |
| **FERRIES** | | | | | | | | | | | | | | | |
| Total Passengers | | | | | | | | | | | | | | | |
| Existing Ferries | | | | | | | | | | | | | | | |
| Golden Gate | 1,465 | 2,715 | 1,669 | 1,661 | 1,607 | 1,575 | 1,646 | 1,625 | 1,618 | 1,565 | 1,334 | 1,656 | 1,734 | 1,591 | 1,545 |
| Tiburon | 400 | 576 | 459 | 422 | 389 | 406 | 371 | 356 | 347 | 285 | 279 | 358 | 372 | 355 | 277 |
| Vallejo | 220 | 513 | 344 | 349 | 362 | 391 | 374 | 275 | 285 | 272 | 188 | 275 | 251 | 263 | 255 |
| Sum-Existing | 2,085 | 3,804 | 2,472 | 2,432 | 2,358 | 2,372 | 2,391 | 2,256 | 2,250 | 2,122 | 1,861 | 2,289 | 2,357 | 2,209 | 2,077 |
| % Change | | 82.4% | 18.6% | 16.6% | 13.1% | 13.8% | 14.7% | 8.2% | 7.9% | 1.8% | -10.7% | 9.8% | 13.0% | 5.9% | -0.4% |
| New Ferries | | | | | | | | | | | | | | | |
| Oakland | | 1,823 | 142 | 134 | 135 | 135 | 164 | 187 | 123 | 68 | 61 | 102 | 110 | 113 | 99 |
| Alameda | | 688 | 217 | 199 | 191 | 203 | 175 | 205 | 201 | 198 | 135 | 183 | 241 | 182 | 186 |
| Richmond | | 445 | 77 | 54 | 86 | 82 | 88 | 84 | 86 | 99 | 51 | 70 | 77 | 81 | 75 |
| Berkeley | | 594 | 45 | 43 | 64 | 50 | 36 | 48 | 41 | 42 | 37 | 54 | 48 | 46 | 41 |
| Sum-New | | 3,549 | 481 | 430 | 476 | 470 | 463 | 522 | 451 | 407 | 284 | 409 | 474 | 422 | 401 |
| % Change(10/23) | | 84.0% | -75.1% | -77.7% | -75.3% | -75.6% | -76.0% | -72.9% | -76.6% | -78.9% | -85.3% | -78.8% | -75.4% | -78.1% | -79.2% |
| All Ferries | 2,085 | 7,354 | 2,953 | 2,862 | 2,834 | 2,842 | 2,854 | 2,778 | 2,701 | 2,529 | 2,145 | 2,698 | 2,831 | 2,631 | 2,478 |
| % Change | | 252.7% | 41.6% | 37.3% | 35.9% | 36.3% | 36.9% | 33.2% | 29.5% | 21.3% | 2.9% | 29.4% | 35.8% | 26.2% | 18.8% |

During Closure=Average of midweek days immediately before Bay Bridge re-opening situation in the case of BART and Ferry service, also.

Table 6 gives the detailed post-earthquake commute summary--Daily trips for the month of January[9].

## 2.7 Bridge & Road Information: Status of Closures

### *2.7.1 East Bay*

- I-880 (Nimitz Freeway) was closed indefinitely between downtown Oakland and the Bay Bridge.
- I-80 was closed between Gilman Street in Berkeley and I-980 in Oakland. I-80 West Grand on-ramp was closed.
- I-580: CalTrans has completed the stretch of 580 in Richmond that leads to the Richmond-San Rafael Bridge, thus eliminating the need for cars to use the surface streets. That led to the expediting of the trip between Marin and the East Bay.
- I-980: Both ramps were closed at 11th St.; 17th St. on-ramp was closed.
- Bay Bridge was closed for at least one month.

### *2.7.2 San Francisco*

- Embarcadero Freeway was closed
- I-280 was closed from the Rte 101 junction to Sixth St.
- The Fell Street on-ramp to Rte 101 was closed.

### *2.7.3 South Bay*

Hwy 17 was closed between Santa Cruz and San Jose.

- Total closures:

## Table 6. Commute summary of daily trips of January (Source: Caltrans).

24-Jan-90
04:12 PM

### POST-EARTHQUAKE COMMUTE SUMMARY--DAILY TRIPS

| | Before Oct 17 | During Closure | Wed Jan 3 | Thu Jan 4 | Fri Jan 5 | Mon Jan 8 | Tue Jan 9 | Wed Jan 10 | Thu Jan 11 | Fri Jan 12 | Mon Jan 15 | Tue Jan 16 | Wed Jan 17 | Thu Jan 18 | Fri Jan 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BRIDGES** | | | | | | | | | | | | | | | |
| Total Vehicles (Two-Way) | | | | | | | | | | | | | | | |
| Golden Gate | 123,754 | 150,927 | 113,586 | 115,098 | 117,394 | 107,868 | 113,902 | 114,272 | 115,774 | 111,700 | 110,892 | 114,290 | 117,234 | 117,814 | 120,576 |
| % Change | | | -8.2% | -7.0% | -5.1% | -12.8% | -8.0% | -7.7% | -6.4% | -9.7% | -10.4% | -7.6% | -5.2% | -4.8% | -2.6% |
| Richmond | 44,000 | 79,173 | 46,220 | 46,996 | 45,724 | 44,624 | 46,626 | 43,590 | 46,214 | 46,928 | 44,500 | 44,220 | 47,552 | 48,500 | 50,538 |
| Hayward | 65,000 | 109,791 | 65,310 | 72,668 | 73,226 | 69,210 | 69,474 | 72,916 | 72,526 | 71,340 | 68,800 | 70,368 | 73,708 | 75,212 | 77,500 |
| Dumbarton | 41,500 | 67,139 | 46,994 | 48,356 | 58,332 | 56,046 | 57,966 | 57,958 | 57,914 | 58,134 | 51,388 | 57,002 | 57,548 | 58,238 | 60,202 |
| 3-Bridge Sum | 150,500 | 256,152 | 158,524 | 168,020 | 177,282 | 169,880 | 174,066 | 174,464 | 176,654 | 176,402 | 164,738 | 171,588 | 178,808 | 182,000 | 188,293 |
| % Change | | 70.2% | 5.3% | 11.6% | 17.8% | 12.9% | 15.7% | 15.9% | 17.4% | 17.2% | 9.5% | 14.0% | 18.8% | 20.9% | 25.1% |
| Bay Bridge | 243,116 | | 207,848 | 211,470 | 222,716 | 201,120 | 208,216 | 214,522 | 216,618 | 215,052 | 207,348 | 211,740 | 217,702 | 222,276 | 232,342 |
| (NOTE: Bay Bridge data exclude carpool lanes since 12-22-89) | | | | | | | | | | | | | | | |
| **BART** | | | | | | | | | | | | | | | |
| Total Passengers | | | | | | | | | | | | | | | |
| Total Day | 218,286 | 352,719 | 224,166 | 228,922 | 228,433 | 222,337 | 227,382 | 231,509 | 228,722 | 220,467 | 164,054 | 234,814 | 243,404 | 241,960 | 238,228 |
| % Change | | 61.6% | 2.7% | 4.9% | 4.6% | 1.9% | 4.2% | 6.1% | 4.8% | 1.0% | -24.8% | 7.6% | 11.5% | 10.8% | 9.1% |
| Transbay Only | 102,152 | 226,876 | 114,232 | 116,327 | 114,549 | 112,055 | 114,622 | 115,649 | 115,072 | 111,166 | 80,459 | 111,464 | 116,126 | 118,295 | 114,026 |
| % Change | | 122.1% | 11.8% | 13.9% | 12.1% | 9.7% | 12.2% | 13.2% | 12.6% | 8.8% | -21.2% | 9.1% | 13.7% | 15.8% | 11.6% |
| Non-Transbay | 116,134 | 125,843 | 109,934 | 112,595 | 113,884 | 110,282 | 112,760 | 115,860 | 113,650 | 109,301 | 83,595 | 123,350 | 127,278 | 123,665 | 124,202 |
| % Change | | 8.4% | -5.3% | -3.0% | -1.9% | -5.0% | -2.9% | -0.2% | -2.1% | -5.9% | -28.0% | 6.2% | 9.6% | 6.5% | 6.9% |
| **FERRIES** | | | | | | | | | | | | | | | |
| Total Passengers | | | | | | | | | | | | | | | |
| Existing Ferries | | | | | | | | | | | | | | | |
| Golden Gate | 5,010 | 7,573 | 4,808 | 4,589 | 4,796 | 4,068 | 4,441 | 4,318 | 4,200 | 3,810 | 4,449 | 4,163 | 4,621 | 4,597 | 4,251 |
| Tiburon Commute | 800 | 1,294 | 940 | 861 | 840 | 815 | 841 | 672 | 696 | 605 | 534 | 748 | 785 | 715 | 656 |
| Vallejo Commute | 440 | 1,045 | 789 | 712 | 742 | 774 | 776 | 643 | 580 | 573 | 530 | 526 | 523 | 535 | 552 |
| T/V Midday | | 569 | 565 | 422 | 487 | 268 | 392 | 312 | 429 | 161 | 612 | 403 | 423 | 460 | 323 |
| Sum-Existing | 6,250 | 10,481 | 7,102 | 6,584 | 6,865 | 5,925 | 6,450 | 5,945 | 5,905 | 5,149 | 6,125 | 5,840 | 6,352 | 6,307 | 5,792 |
| % Change | | 67.7% | 13.6% | 5.3% | 9.8% | -5.2% | 3.2% | -4.9% | -5.5% | -17.6% | -2.0% | -6.6% | 1.6% | 0.9% | -7.3% |
| New Ferries | | | | | | | | | | | | | | | |
| Oakland Commute | | 4,148 | 142 | 621 | 408 | 354 | 495 | 370 | 291 | 241 | 567 | 258 | 345 | 312 | 400 |
| Alameda Commute | | 1,418 | 440 | 622 | 415 | 369 | 449 | 424 | 451 | 415 | 351 | 467 | 501 | 388 | 507 |
| Richmond Commute | | 948 | 156 | 131 | 179 | 175 | 172 | 164 | 177 | 224 | 111 | 135 | 169 | 164 | 153 |
| Berkeley Commute | | 1,436 | 110 | 92 | 158 | 119 | 116 | 104 | 93 | 101 | 104 | 87 | 144 | 131 | 141 |
| Midday | | 2,627 | 451 | 500 | 536 | 273 | 375 | 265 | 330 | 189 | 1,148 | 244 | 361 | 361 | 425 |
| Sum-New | | 10,575 | 1,299 | 1,966 | 1,696 | 1,290 | 1,607 | 1,327 | 1,342 | 1,170 | 2,281 | 1,191 | 1,520 | 1,356 | 1,626 |
| % Change(10/23) | | 167.1% | -67.2% | -50.3% | -57.2% | -67.4% | -59.4% | -66.5% | -66.1% | -70.4% | -42.4% | -63.9% | -61.6% | -65.7% | -58.9% |
| All Ferries | 6,250 | 21,057 | 8,401 | 8,550 | 8,561 | 7,215 | 8,057 | 7,272 | 7,247 | 6,319 | 8,406 | 7,031 | 7,872 | 7,663 | 7,418 |
| % Change | | 236.9% | 34.4% | 36.8% | 37.0% | 15.4% | 28.9% | 16.4% | 16.0% | 1.1% | 34.5% | 12.5% | 26.0% | 22.6% | 18.7% |

During Closure=Average of midweek days immediately before Bay Bridge re-opening

1. Bay Bridge
2. Embarcadero Freeway
3. Rte 280 Freeway--North of Rte 101
4. Rte 880 Freeway--Rte 980 to Bay Bridge

- Controlled traffic

  Rte 17--Scotts Valley to Rte 9

- Pre-Earthquake Westbound travel Demands (a.m. Peak)

  Trans-Bay: 80,000 person trips

  Rte 17: 10,000 person trips

Figure 6 shows in detail the closures and other facilities in the form of a map[9].

## 2.8 Travel Trends

Figure 7 shows the change in morning peak transbay modes before, during, and after the Bridge closure. During the closure, there was a 10 - 15% reduction in total transbay person trips. The auto trips shown were estimated from the change in travel on the bridges to the north and south of the Bay Bridge. It appears that discretionary transbay trip making all but ceased. After the reopening, total person trips approached previous levels, but there has been a significant reduction in carpool use. This may be due to the fact that congestion on the approaches to the Bridge was so bad that the travel time advantage of the toll-free carpool lane through the toll plaza has significantly been reduced[4].

Figure 8 shows the Bay-Bridge traffic from October 1989 - February 1990. It shows

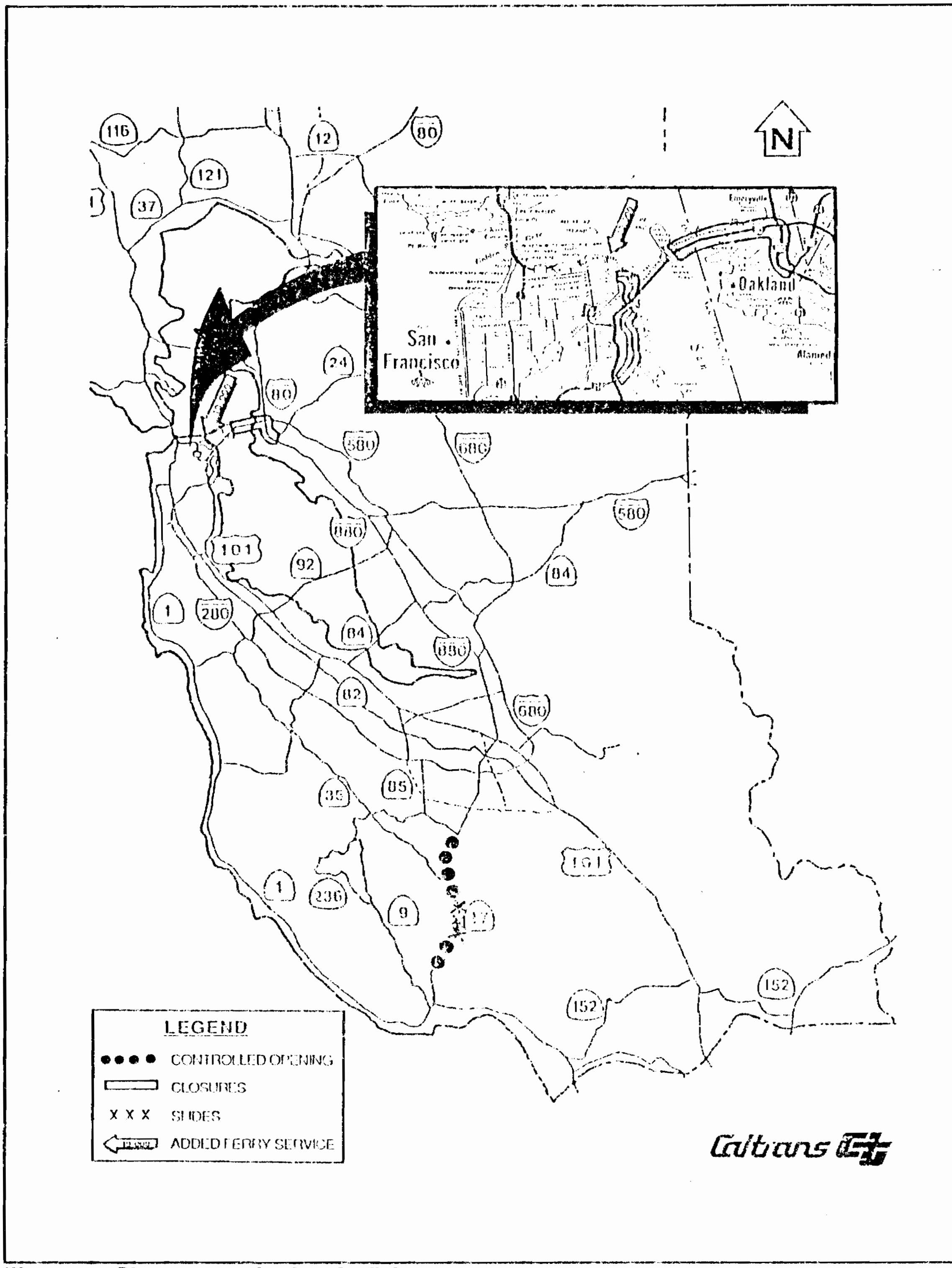



Figure 6. Closures and other facilities

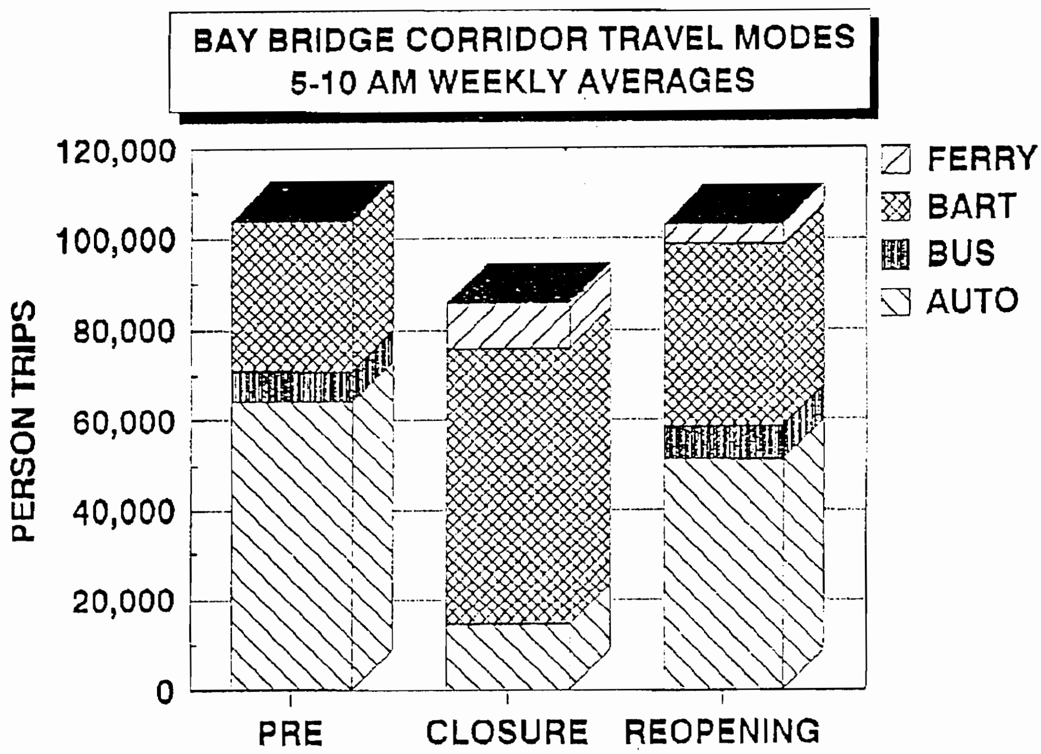



Figure 7. Change in Morning Peak Transbay Modes

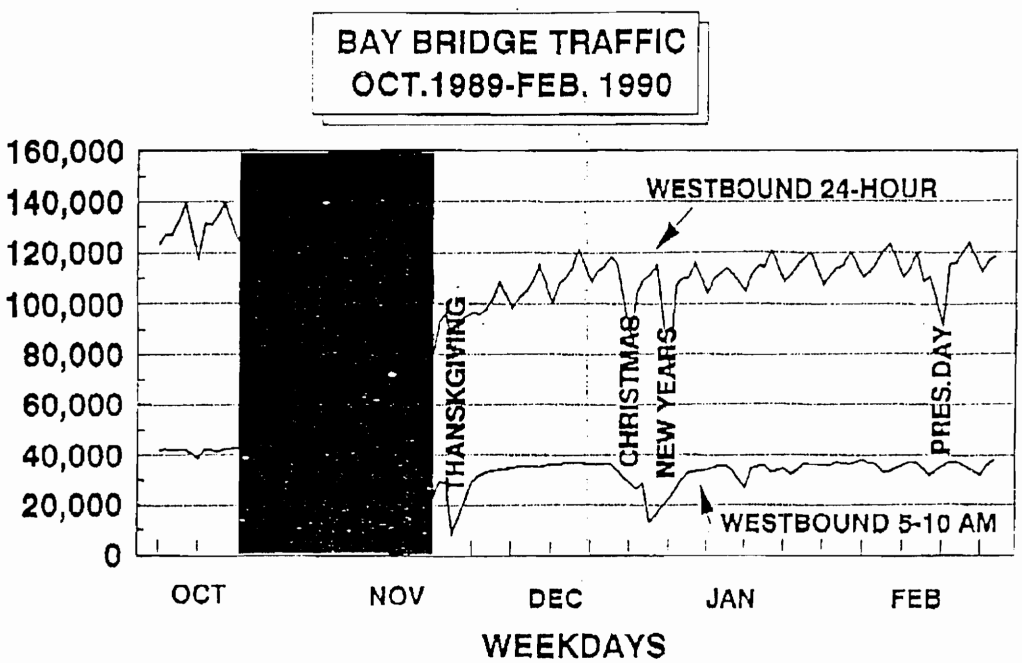



Figure 8. Bay Bridge Traffic (Oct.1989-Feb.1990)

that both the 24-hour and peak-period vehicle volumes have slowly returned to near pre-quake levels but that significant numbers of people are no longer driving[4]. Figure 9 shows that BART, which experienced record-setting patronage during the four weeks the Bridge was closed, has retained a substantial number of its weekday patrons. BART reached a peak of over 350,000 persons per day during the closure. With the reopening of the bridge, all BART night service was discontinued, and patronage backed off, although the upward trend has continued. The usual annual fall-off November - January did not occur (January is marked by "J" in the chart), and BART continued to carry 10-15% more daily patrons than before the earthquake[4].

Based on the above literature review, the travel demand management strategies employed in the aftermath of the Loma Prieta Earthquake and also the impacts (both the short-term and long term) will be discussed in the next chapter. The latter part of the literature review involves collection of information about earlier research in the fields of congestion in major urban cities, network's structural elements and so on.

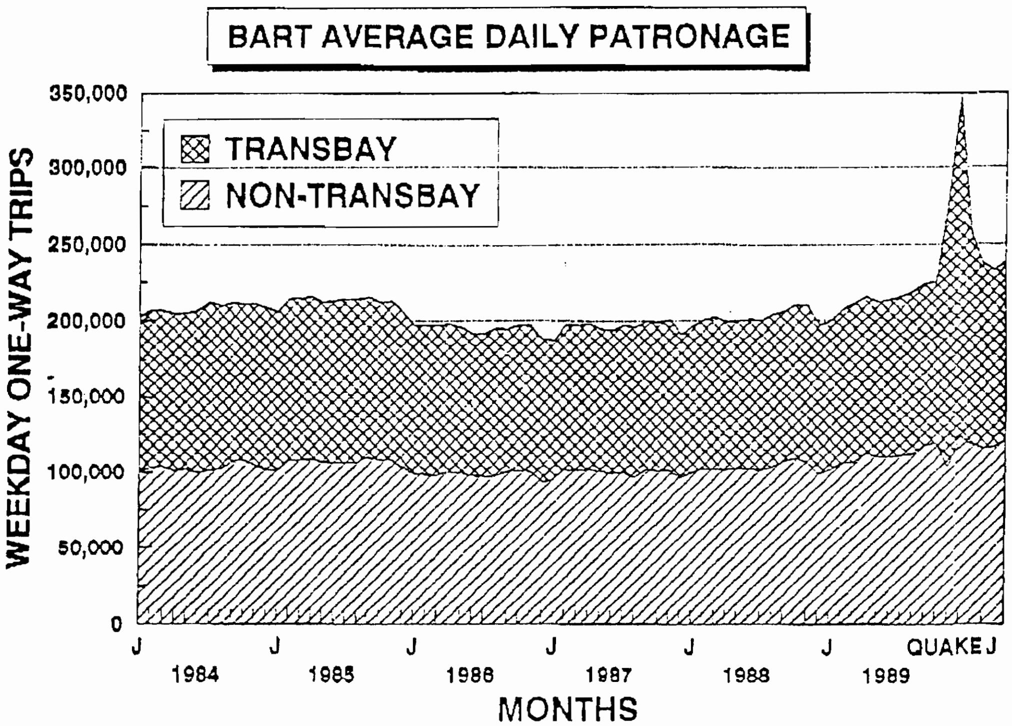



Figure 9. BART Average Daily Patronage

## 2.9 Roadway Congestion

Roadway system congestion has increased over the past decade in most large U.S. urban areas as transportation facility construction and expansion did not keep pace with the growth of travel demands. According to the Research Report "Roadway Congestion in major urban areas 1982 to 1987", published by James W. Hanks, Jr. and Timothy J. Lomax, roadway congestion can be expressed in the form of a value termed Roadway Congestion Index.

## 2.10 Roadway Congestion Index (RCI)

The RCI value for each urban area was developed by combining the Daily Vehicle Miles of Travel (DVMT) per lane-mile data for each roadway type in a ratio defined by the amount of daily vehicle-miles of travel. The way DVMT per lane-mile values were combined to calculate the urban area congestion index is shown in the form of an equation. RCI values greater than 1.0 indicate undesirable mobility levels within the urban area[22].

$$R.C.I. = \frac{VMTF/Ln\text{-}Mi * VMTF + VMTA/Ln\text{-}Mi * VMTA}{13,000 * VMTF + 5,000 * VMTA} \qquad (2.1)$$

where,

VMTF = Vehicle Miles of Travel on Freeway

VMTA = Vehicle Miles of Travel on Principal Arterial

## 2.11 Measures of Transportation Network Mobility

The second section of the literature review is about the measures of transportation network analysis.

### *2.11.1 Direct Accessibility*

Inverse of corrected time between pair of nodes which have direct connection.

### *2.11.2 Nodal Accessibility*

Sum of inverses of shortest paths (expressed in time) from particular node to all others.

### *2.11.3 Network Accessibility*

Sum of inverses of shortest paths between all pairs of nodes in the network.

### *2.11.4 Network Connectivity*

Ratio of network accessibility to a sum of direct accessibilities in the network.

### *2.11.5 Nodal Connectivity*

Ratio of nodal accessibility to sum of direct accessibilities for the node.

## 2.12 Accessibility

### *2.12.1 Definition*

Accessibility cannot be satisfactorily used as a sum of shortest paths expressed in distance or time between all nodes because distant nodes produce higher values and provide illogical results. A better approach would be to sum the time or distance inverses. In this way, shorter distances would influence more the accessibility value whereas longer distances would have insignificant effect. This approach is used in gravity model of trip distribution, which has been widely used with satisfactory results. Thus, network accessibility is defined as a sum of inverses of all shortest paths between nodes in the network.

$$NA = \sum_{i=1}^{v(v-1)} \frac{1}{t_i} \qquad (2.2)$$

where v is the number of nodes.

For a particular node, nodal accessibility is defined as a sum of inverses of shortest paths from this node to all others.

$$NOA = \sum_{i=1}^{v-1} \left(\frac{1}{t_i}\right) \qquad (2.3)$$

### *2.12.2 Relation between accessibility and the character of node*

In order to relate accessibility to the character of the node, definition of "access to the city" is introduced. It is defined as a product of nodal accessibility and ring capacity, which is simply the sum of capacities of routes approaching the city measured at the border of the city or at an arbitrarily fixed range outside the city.

AC = NA * RC

where AC = Access to city

RC = Ring Capacity

NA = Nodal Accessibility

The idea of "access to city" definition is based on the hypothesis that a city having lower accessibility must have greater ring capacity to accommodate its traffic.

## 2.13 Connectivity

Connectivity is defined as a ratio of the network accessibility to the sum of all direct accessibilities and it can be expressed by the following equation.

$$C = \frac{A}{\sum DA} \qquad (2.4)$$

where A = Network accessibility

DA = Direct accessibility (inverse of time for any direct connection)

Connectivity measures how many times accessibility of the network is greater than the accessibility explained by direct connections only.

# *3.0 Travel Demand Management Strategies and Impacts of the Loma Prieta Earthquake*

Returning traffic to normalcy is one of the important issues after earthquakes. It was efficiently achieved through the following transportation actions:

a) Travel Demand Management

b) Transportation Information Dissemination

c) Increase & Improvement of Transportation Supply

## 3.1 Travel Demand Management (TDM)

Facing a transportation crisis, officials implemented transportation demand management (TDM) actions that were bold, innovative and immediate. Existing services were expanded, and new services were created. An era of unprecedented cooperation was initiated between diverse transportation agencies. High-Occupancy Vehicles (HOV) were embraced as a partial solution to Bay Area traffic problems. Just two weeks earlier, Oct 2-6, Northern California participated in "California Rideshare Week," the largest single ridesharing promotion in the nation. After the earthquake, ridesharing programs played a vital role in the recovery of the Bay Area transportation system[4].

### *3.1.1 Planning for Recovery: The First Week*

Wednesday, the day after the earthquake, planning began for a region-wide meeting to evaluate emergency transportation needs. The regular monthly meeting of the region's Transit Operator Coordinating Council (TOCC) was already scheduled for

Thursday. The Metropolitan Transportation Commission (MTC, the regional transportation planning agency for the nine Bay Area counties) and CalTrans agreed that was the proper forum for focusing the transportation community on the earthquake response. Attendance was broadened to include not only the larger public transit operator members of TOCC, but also most smaller public operators, private bus and ferry operators, port authorities, and federal and state emergency response officials[4].

Figure 10 shows the calculation Caltrans did the day after the earthquake of available transit capacity[4]. It was thought that BART and the new ferries might be able to transport 10,000+ persons per half-hour. If people changed their travel to fill in the early and late shoulders of the peak, it seemed possible to continue to carry the normal load, if spread across five hours.

Since no one could really estimate how long the Bay Bridge would be out of service, planners assumed a three to six month timeframe for emergency services. TOCC focused, however, on a few immediate objectives:

1. Find out how each agency was responding and what resources they had available to provide additional transit service;
2. Put all available service on the street, and worry about funding later;
3. Put together comprehensive public information, and get it out to commuters over the weekend; and
4. Set up a monitoring system to form a basis for adjusting service in response to demand.

The key elements of the transit response were

1. adding to BART's capacity,

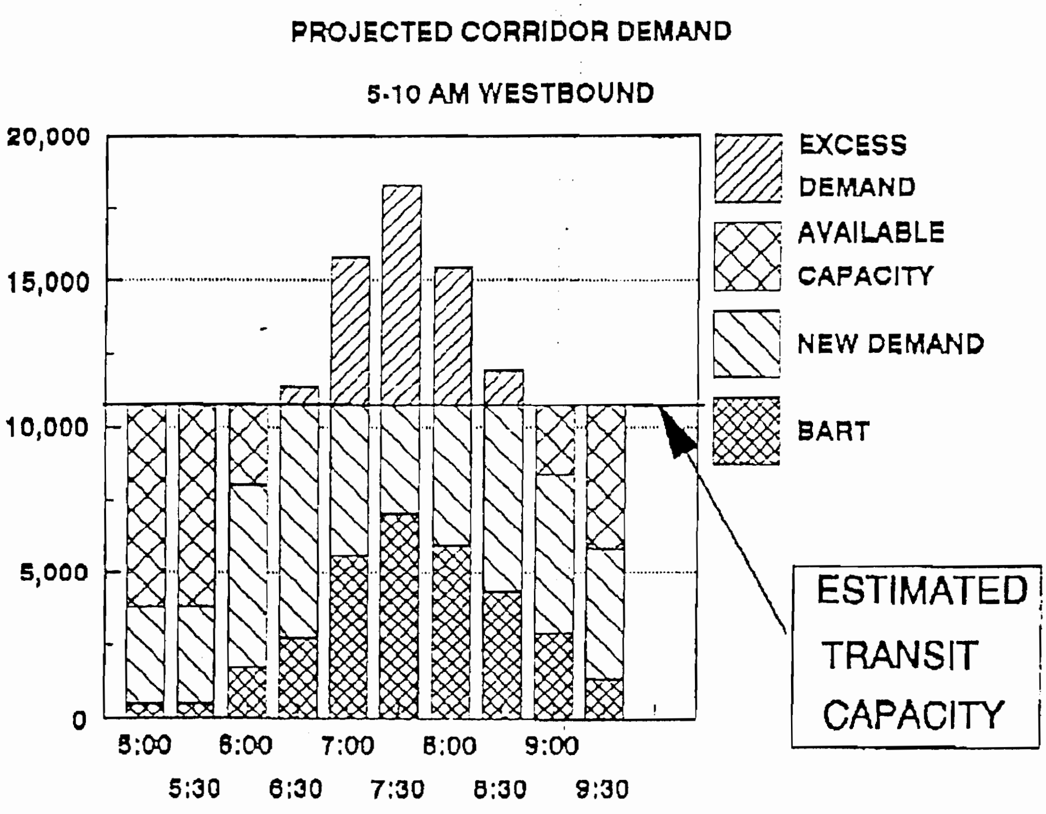



**Figure 10. Available capacity calculation**

2. promoting and supporting the new ferries,

3. providing new park and ride locations,

4. vastly increasing public information, especially to those who had never used transit, and

5. generally expanding all bus and commuter rail service in all markets as commuters adjusted to the new travel realities[4].

### 3.1.2 BART

BART has worked with local communities and businesses to secure additional parking at satellite lots. If the lots were not within walking distance of a BART station, they were served by connecting bus service to the nearest BART station. Detailed fact sheets were published, showing expanded BART service and related passenger services during the Bay Bridge closure. There were different service schedules for weekdays, for Saturdays and for Sundays. BART express Bus service areas were also listed. Richmond, South Hayward, Coliseum and Fremont (Mowry Avenue lot) had parking available normally. Parking restrictions on streets adjacent to the Concord, Lafayette, El Cerrito Plaza, and El Cerrito Del Norte stations were temporarily lifted until the Bay Bridge was back in service. Satellite Parking Lots were available in Concord, Oakland, Walnut Creek, Albany/Berkeley/El Cerrito, Pleasonton, Antloch/Pittsburgh/Murtinez and Daly City/ Colma. The connecting bus service was provided by AC Transit, San Mateo Transit(SamTrans) and Central Contra Costa Transit (County Connection). The various BART routes are shown in Figure 11. Access to BART was dramatically increased by free shuttle buses from the SamTrans Park-and-Ride lot in Colma to Daly City BART at five minute intervals during commute peaks[9].

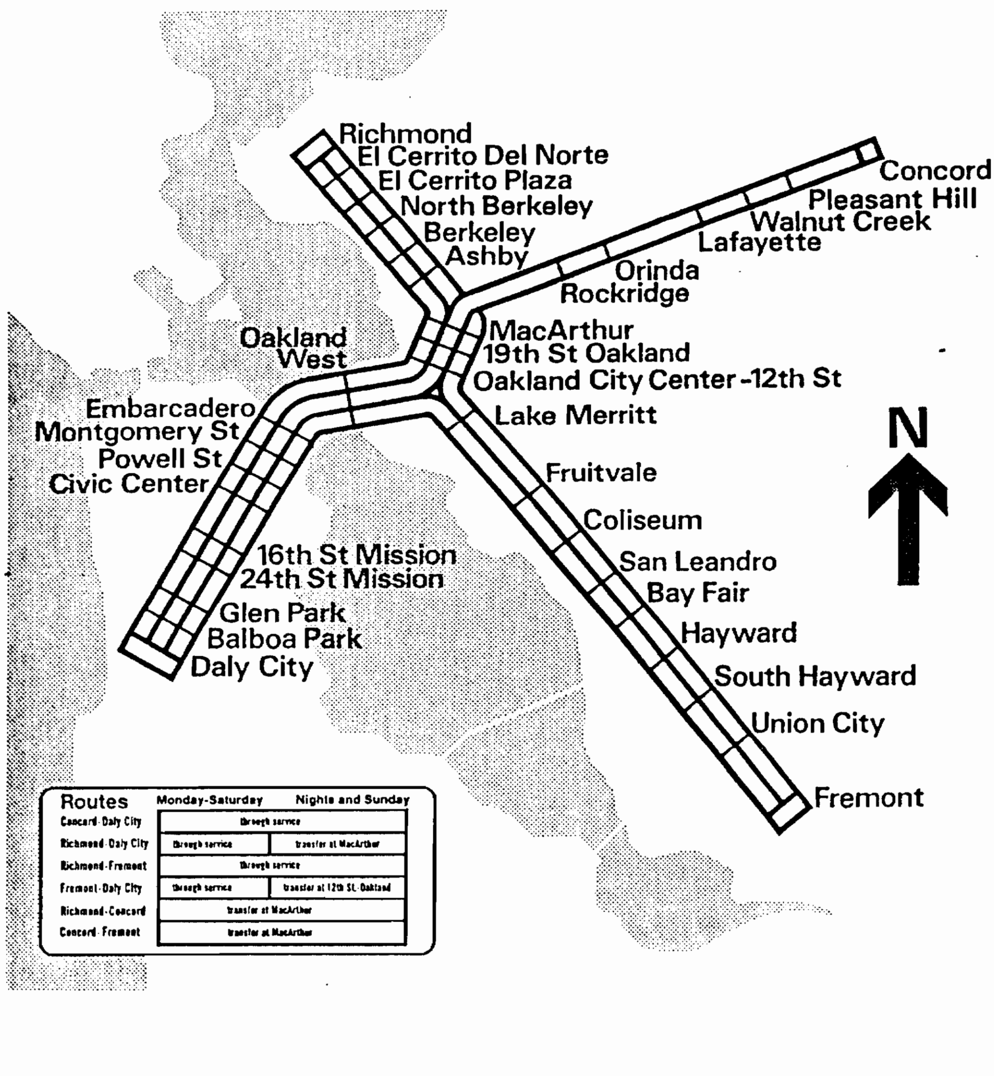



Figure 11. Various routes of BART

### *3.1.3 Transit Coordination*

#### *3.1.3.1 The County Connection: Central Contra Costa Transit Authority*

Contra Costa is one of the nine counties in the Bay Area, and the following were the Earthquake Emergency Services listed by the transit authority:

- Bus services from Concord Pavilion Park-and-Ride lot to Jack London Square were operated to meet the ferries.
- Increased Bus service to BART Port Chicago Highway Park-and-Ride lot.
- Extension of the Rte 130 - Ygnacio Valley Express.

#### *3.1.3.2 Golden Gate Bridge*

No tolls were collected on Monday and Tuesday mornings (October 23 and 24, 1989) between 5:00 a.m. and 10:00 a.m., nor on Monday evening between 3:00 p.m. and 7:00 p.m. Caltrans bridge toll tickets good on the Bay Bridge, San Mateo Bridge, Dumbarton Bridge and Richmond-San Rafael Bridge were accepted on the Golden Gate Bridge. Two of those tickets were to be presented when crossing the Golden Gate Bridge.

The Bay Area Council on October 24 instituted new policies for its own 14-person staff during the emergency. Any staff member who uses public transit would receive a ticket subsidy from the Council. The Bay Area Council is a regional business association engaged in public policy research and advocacy on a range of issues, including transportation, housing, land use, employment training, and economic development[5].

### *3.1.4 Important TDM actions*

Commuters were encouraged to participate in carpools and vanpools. Toll-free carpool lanes on the bridges operated from 5 a.m. to 10 a.m. Diamond lanes for buses, vanpools and carpools with 3+ passengers were available.

Many actions were initiated by transportation agencies to improve the Bay Area traffic flow including[7]

- elimination of bridge tolls.
- increase in existing ferry service and creation of new routes.
- establishment of new park-and-ride lots connected by shuttles to alternative transportation centers.
- establishment of commuter train service from Salinas to San Jose.
- increase in existing express buses and creation of new routes.

One of the most remarkable TDM actions was the reopening of Highway 17 to high-occupancy vehicles. When Highway 17 closed following the earthquake, the average commute time increased from 50 minutes to over two hours one-way, creating massive congestion. After a pathway was cleared, Caltrans opened Highway 17 to buses and carpools only from 5-9:00 a.m. and from 3-7:00 p.m. These HOVs were escorted in convoys by California Highway Patrol, cutting the commuter time down to a manageable hour and ten minutes.

### *3.1.5 Traffic Operations System*

Operations personnel were directly involved in numerous earthquake-response activities immediately after the earthquake. All operations and activities were coordinated by the Deputy Director of Operations and the Chiefs of the Highway Operations, Traffic Operations System, and Traffic Branches. One of the branch chiefs was at the Command Center at all times.

Although varied, the activities fall into three major areas:

1. Traffic management by the Major Incident Response Teams,
2. Development of operational improvement projects, and
3. Coordination and dissemination of roadway closure information.

In addition to these three areas, extensive data collection was undertaken to document motorist response to the closure of the Bay Bridge. The following is a brief narrative describing the activities of Highway Operations and Traffic Operations System branch personnel[9].

### *3.1.6 Major Incident Response*

In total, 21 people from other districts formed five incident response teams, in addition to District 4's three teams, for a total of eight teams available for the earthquake response effort. A variety of equipment was available, including changeable message sign (CMS) trucks, CMS trailers, highway advisory radio (HAR) trucks, fabric sign trucks, and sedans. Cellular phones were provided by District 4 to each team leader.

Incident response teams were immediately put on 12-hour shifts, 24 hours a day, to monitor both a.m. and p.m. peak periods and off-peak periods to respond to major traffic problems. In fact, the incident response team was already on the road, handling traffic management for the World Series game at Candlestick Park when the earthquake struck[9].

Traffic management activities included providing assistance to maintenance and construction during emergency repair; conducting paving and restriping activities; providing advisory CMS signage for convoys on Rte 17 near Santa Cruz; responding to bridge closures, overturned trucks and major accidents; monitoring both a.m. and p.m.

peak-period traffic conditions approaching the San Mateo-Hayward, Richmond-San Rafael, and Dumbarton Bridges; and providing advance toll-free CMS signage between the hours of 5 a.m. and 10 a.m. on these bridge approaches.

All incident response and traffic management activities were scheduled, dispatched, coordinated, and managed through the Command Center. The Command Center was also staffed 24 hours a day basically with two 12-hour shifts. Frequently, because of the difficulty of spreading the work load from the peak periods to the lighter night shifts, field and Command Center personnel were required to work up to 18+ hours per day, with maximum staffing required between 6 a.m. and 2-4 p.m.[9]

## 3.2 Transportation Information Dissemination

### *3.2.1 Coordination of Road Closures*

Highway Operations branch staff in the Command Center also coordinated all road closures for the first week after the earthquake. The responsibility of this unit was to maintain a current status of all road closures. This required close and constant communication with Radio Room, Construction, Maintenance, and Public Information staff in the Command Center. Closure reports were generally received from field personnel, either in Operations,Construction or Maintenance. In addition, commercial radio and television broadcasts were also monitored to obtain further information and also to confirm whether the media was providing the public with accurate reports.

A list of closures was updated and issued when new information about road closures or openings was reported by field personnel. The road closure updates were distributed to Command Center personnel and were FAXed to a variety of locations.

All roadway or lane closures for construction or maintenance work not directly related to earthquake recovery efforts were temporarily suspended. Moreover, all closures required approval by the Deputy District Director of Operations or by the Operations Branch Chief at the Command Center[9].

### 3.2.2 Press Briefing

After working frantically for three days to coordinate services and information, CALTRANS, MTC, and transit operators held a major press briefing on Saturday, October 21, at the San Francisco Ferry Building. Elaborate press packets were provided containing descriptions of all emergency services that would be in place on Monday morning. Maps and guides to the new services, including maps of how to get to four new East Bay Ferry terminals, were widely distributed and made available in computerized form so that they would be quickly incorporated into newspapers over the weekend[4].

### 3.2.3 Message to the public

The message to the public was as follows:

- If you don't have to travel, stay home.
- If you do have to travel, plan ahead and use public transit.
- If you can't use public transit, use carpools, but don't drive alone.
- If you're an employer, allow your employees to use flexible hours, to work nights or weekends, or to work at home[4].

The following information was released to the press. It contained a great deal of information to assist commuters in crossing from the East Bay to San Francisco.

### *3.2.4 RIDES for Bay Area Commuters*

On October 21, RIDES published INFO, a commute transportation update, which gave the special services and hours of operation. Carpool and vanpool matching services from home locations to bus, BART and ferry hubs as well as work locations were started. A special emphasis was made on filling existing vanpools and starting new vanpool groups. Additional emphasis was made on formation of carpools and vanpools for off-peak and flextime commutes, including weekends. Additionally RIDES had a toll-free hotline number from Monday, October 23, that provided commuters with up-to-date information on commute options and services. RIDES for Bay Area Commuters increased their staff from about 50 people to around 80 people. More than 2,500 phone calls were reported from Friday through Monday following the earthquake. On a normal day,they usually receive from 80-100 phone calls[6].

In the first week of the earthquake, a toll-free "800" commuter hotline was established by RIDES for Bay Area Commuters, Caltrans and MTC with information on ferries, park-and-ride lots, buses, BART, CalTrain and other commute options.

On Monday, October 23, CalTrans issued a "Bay Area Commuter Guide" with six pages of information on public transit services.

The MTC made available to the news media a computer diskette containing several maps that depict the new ferry and bus services instituted since the October 17 earthquake closed the Bay Bridge. The information was available on a Macintosh computer diskette. The Ferry terminal sites in San Francisco are shown in Figure 12[10].

Ferry Terminal Sites in San Francisco

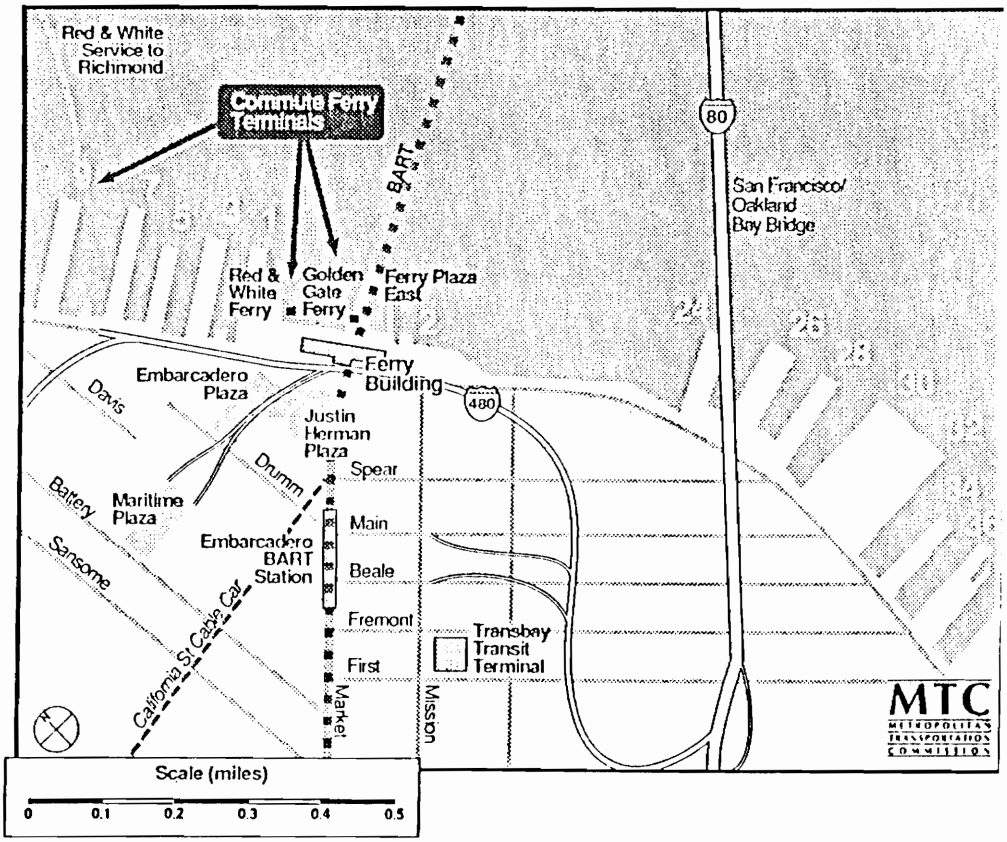



**Figure 12. Ferry Terminal Sites in San Francisco**

### 3.2.5 TOCC Meetings

To keep up with the continuing changes in demand as commuters tried alternate routes and modes, the special, expanded TOCC meetings were held weekly. Daily reports of BART, ferry, and traffic data on the other bridges were FAXed to all TOCC members and discussed at the weekly meetings. Plans for service adjustments were agreed upon at these meetings, and joint public information releases were prepared. The special TOCC meetings continued through mid-December, when it was judged that service and demand patterns had become reasonably stabilized[4].

## 3.3 Increase & Improvement of Transportation Supply

### 3.3.1 Transit Response

The Bay Area was able to marshall a substantial array of transit service alternatives because of its long-standing commitment to public transportation. The variety and depth of public transportation services already in place allowed a comprehensive and flexible system of rail, bus, and water transport, complemented by new highway HOV facilities, to be put in place virtually overnight. Without a strong local transit funding base, some degree of redundancy, expansion capacity, and widespread use of transit, such a response might not have been possible[4].

### 3.3.2 Immediate Response

Some companies put employees up for the night in nearby hotels, but most people wanted to get home, no matter how long it took. AC Transit had more than 100 buses in San Francisco for the evening commute, so it loaded them up and took off on alternative routes north and south out of San Francisco, along circuitous routes crossing other bridges or circumnavigating the Bay. AC Transit quickly rerouted its buses in the East Bay to increase service to BART stations and to the makeshift ferry terminal at the foot of Broadway in downtown Oakland. The private ferry operators, Red & White Fleet and Blue & Gold Fleet, began emergency service from San Francisco to that location immediately and continued all night until all stranded commuters had been transported.

### *3.3.3 Ferry Service from East Bay to San Francisco (And Back)*

Starting Monday, October 23, Red & White Fleet had run ferry boats to San Francisco (and back) from Richmond and Oakland in addition to its regular schedules from Vallejo, Tiburon, and Sausalito. To make the expanded service possible, Red & White Fleet had arranged to bring up four 700-passenger vehicles from Southern California to join the Bay Fleet; and Blue & Gold Fleet collaborated with them for the Oakland-San Francisco service.

### *3.3.4 AC Transit*

Concerned commuters got a helping hand with additional adjustments by AC Transit to assist San Francisco-bound riders with connections to speedy BART trains and the newly-restored option of ferries.

During the period that the Bay Bridge was out of service, "transbay" bus routes made transfer connections at East Bay BART stations and ferry terminals. For the transfer connection, BART accepted the AC Transit Transbay Monthly Pass for trips in both directions.

Bus connections to one major ferry landing--Jack London Square--were available via the Downtown Oakland Shuttle and Lines 11,33,33X,34,34X,39X and 59/76, all of which operate via Broadway, making frequent transfer connections with mainline routes and BART.

Everyone held their breath as Monday morning came. What was not expected was a major rainstorm that hit just in time for the morning commute, wreaking havoc with the new ferry service. Fortunately, many people seemed to stay home an extra day, so the much-feared gridlock did not occur.

On Monday, October 23, CalTrain ridership was up 18%, and San Mateo buses carried 15% more passengers. Ferries carried about 3,000 passengers compared to the usual hundreds of the past. The Larkspur Ferry's 6:00 a.m. run carried 572 passengers, more than triple their average of 140 passengers. BART had more than 100,000 riders over the norm of 70,000.

### 3.3.5 BART

Starting October 23, 1989, BART began 24-hour operation, seven days a week for as long as the Bridge was out of service. Capacity on both peak and non-peak hour trains was increased, and direct service on each line was extended Monday through Friday until 8 p.m. From 8 p.m. to midnight, trains were operated between Concord & Daly City and between Richmond & Fremont. Trains continued to operate after midnight every 60 minutes.

### 3.3.6 Golden Gate Bus & Ferry Services

All Golden Gate a.m. commute services were operated a half hour earlier than the normal schedule, up to 9:00 a.m. Two additional schedules were added to the Larkspur service: Larkspur to San Francisco and San Francisco to Larkspur. Two additional services were added to the Sausalito service: Sausalito to San Francisco and San Francisco to Sausalito[5].

### 3.3.7 MUNI Service for Ferry Passengers

Ferry passengers who were using East Bay and North Bay ferry services that arrived at and left from the Ferry Building had easy access to MUNI service. Since CalTrans had determined that it would be safe for pedestrians to cross under the Embarcadero Freeway north of Mission Street, ferry patrons could easily walk to their destinations or to the Muni terminals.

To further assist ferry patrons, on Monday, October 23, and Tuesday, October 24, the Municipal Railway sold October Muni Fast Passes. All the emergency and regional connecting services are depicted in Figure 13[5].

### 3.3.8 SamTrans

Transportation services were increased in West Bay. SamTrans express buses and CalTrain rail were expected to provide vital transportation links along the West Bay Corridor on Monday, when work trips resumed at full volume following the earthquake.

It was predicted that in the West Bay Corridor, Bayshore Freeway (101) and Highway 92 (San Mateo Bridge) would absorb unprecedented congestion as Bay Bridge autos and commercial vehicles inundated alternative roadways. Additional pressure was expected from the closure of the I-280 extension from Highway 101 to Third Street in San Francisco and the closure of the Embarcadero Freeway.

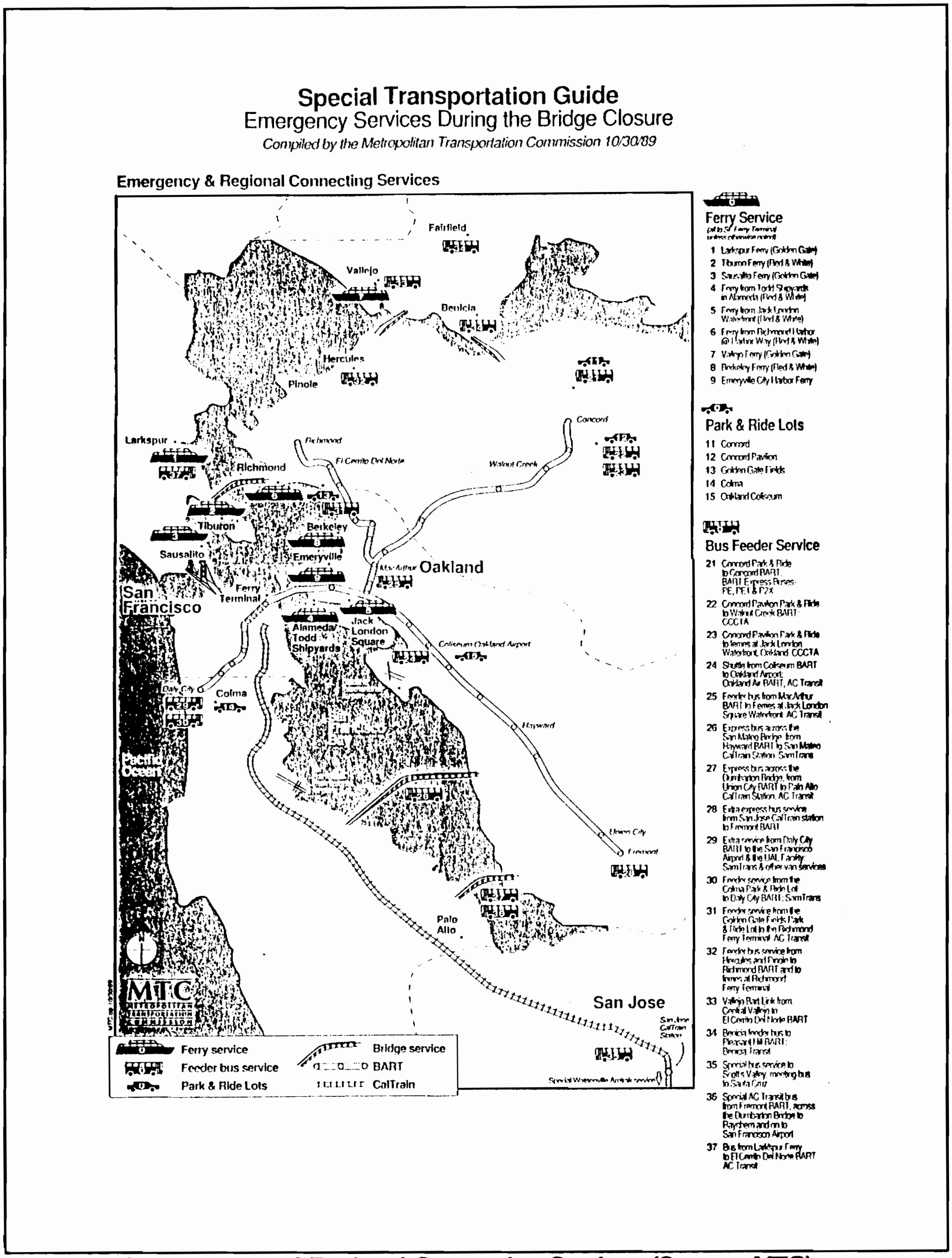



**Figure 13. Emergency and Regional Connecting Services (Source: MTC)**

On the Peninsula, CalTrain provided high-volume commute service for San Francisco-bound workers, with 13 trains departing San Jose for San Francisco between 4:50 a.m. and 9:00 a.m. SamTrans beefed up its regular commute service in three major areas:

- Added trips on Rte 5L from Palo Alto to Daly City BART via El Camino Real.
- Added service from the Hayward BART station to San Mateo via Highway 92 (San Mateo Bridge) on Rte 90E
- Added special trips on emergency Rte 3X between Daly City BART and the UAL Maintenance Base and San Francisco Airport terminals.

Access to BART was dramatically increased by free shuttle buses from the SamTrans Park-and-Ride lot in Colma to Daly City BART at five-minute intervals during commute peaks[5].

### *3.3.9 West Bound Services*

The West Bound services in place (Monday October 23, a.m. peak) were as follows:

1. Ferry Boats:

    13 Additional Boats

    10,000 trips

2. BART:

    40,000 Trips

3. Freeway improvements

    Rte 17

    Rte 880/980 Interchange--N/B

Rte 84--W. End of Dumbarton Bridge

Rte 92/280 Interchange--WB

Controlled operation

4. Additional Services developed:

3 Ferry boats (State of Washington)

Docking facilities--South San Francisco areas

The various traffic facilities are shown in detail in Figure 14.

Ferries played a very crucial role in the transbay movement. Most of the services were expanded to meet the requirements[5].

### *3.3.10 Vallejo and the North Bay*

The Vallejo Ferry was running with an additional vessel during the bridge closure. BART link service was increased. It started at 4:00 a.m. and continued until midnight.

### *3.3.11 Hercules, Pinole*

WestCAT provided feeder service to the Richmond Ferry. Ferries took people to the Ferry Building in San Francisco.

### *3.3.12 Richmond, El Cerrito*

Figure 15 shows the Ferry Terminal site-Richmond. AC Transit line L picked up passengers at Del Norte BART and elsewhere along its route, and took them to the Richmond Ferry Terminal. The terminal was located at the end of Harbor Way, near the Old Ford Plant.

Other AC Transit lines operated as usual, feeding BART stations[5].

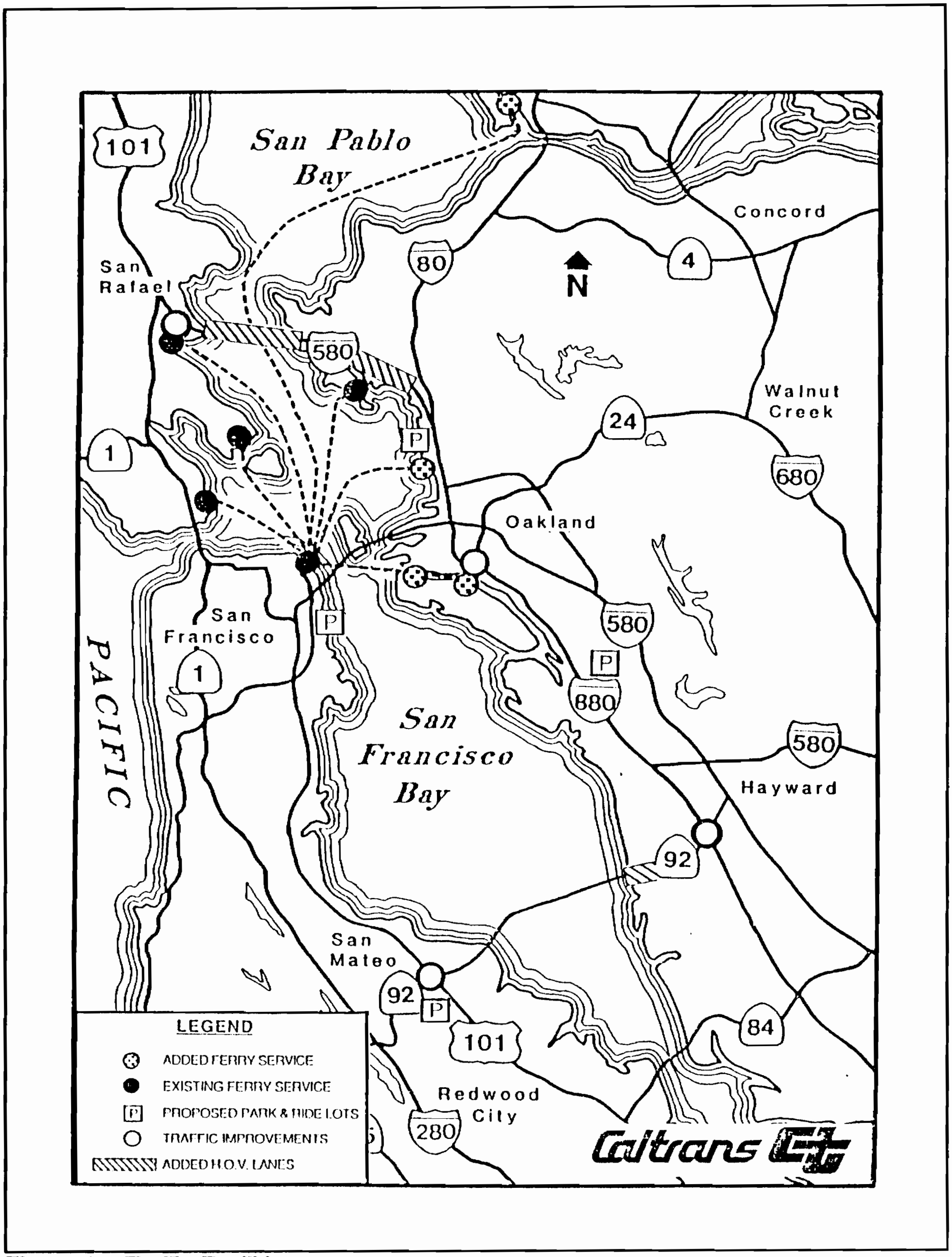



**Figure 14. Traffic Facilities**

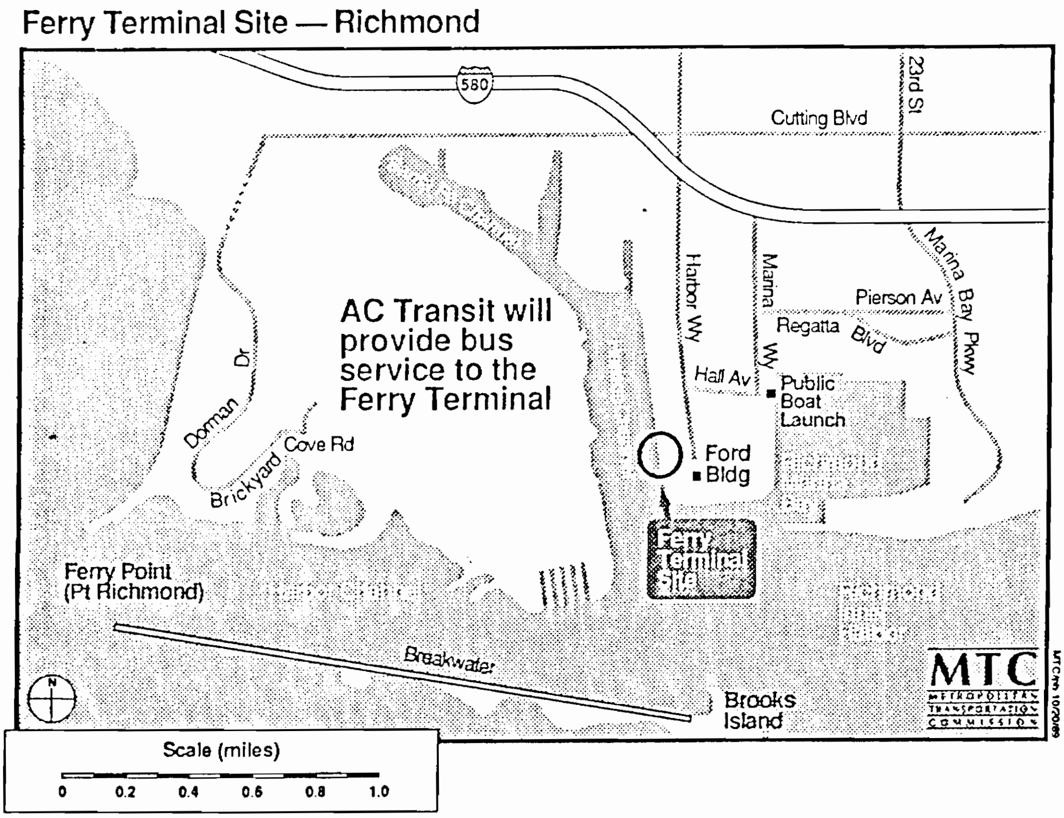



**Figure 15. Ferry Terminal Site-Richmond**

### 3.3.13 Berkeley

Ferry service from Berkeley resumed after dredging improved ferry access. Until then, residents took BART or ferries from Richmond or from Oakland. All AC Transbay lines terminated at BART stations. Other AC Transit service operated as usual.

Figure 16 shows the Regional Ferry system (Existing, Special, Enhanced service) in detail[10].

### 3.3.14 Santa Clara County

Connecting bus service to BART was increased to 24 hours a day on Rte 180. Buses ran every 15 minutes during commute hours, and every 30 minutes at other times. Routes 12 and 140 continued to serve Fremont BART.

### 3.3.15 San Mateo County

CalTrain provided extra service with 13 trains departing San Jose for San Francisco between 5 and 9:00 a.m. All riders were served.

SamTrans had additional service on Route 5L from Palo Alto to Daly City BART, plus special trips on emergency route 3X between Daly City BART and San Francisco Airport. The airport commuter provided service from Daly City BART to the airport every 15 minutes.

### 3.3.16 Marin County

Golden Gate a.m. commute services started a half-hour earlier.

### 3.3.17 Oakland

The Ferry Terminal Site-Jack London Square Front is shown in Figure 17. All AC Transit service ran as usual, except that the "transbay" buses terminated at BART stations.

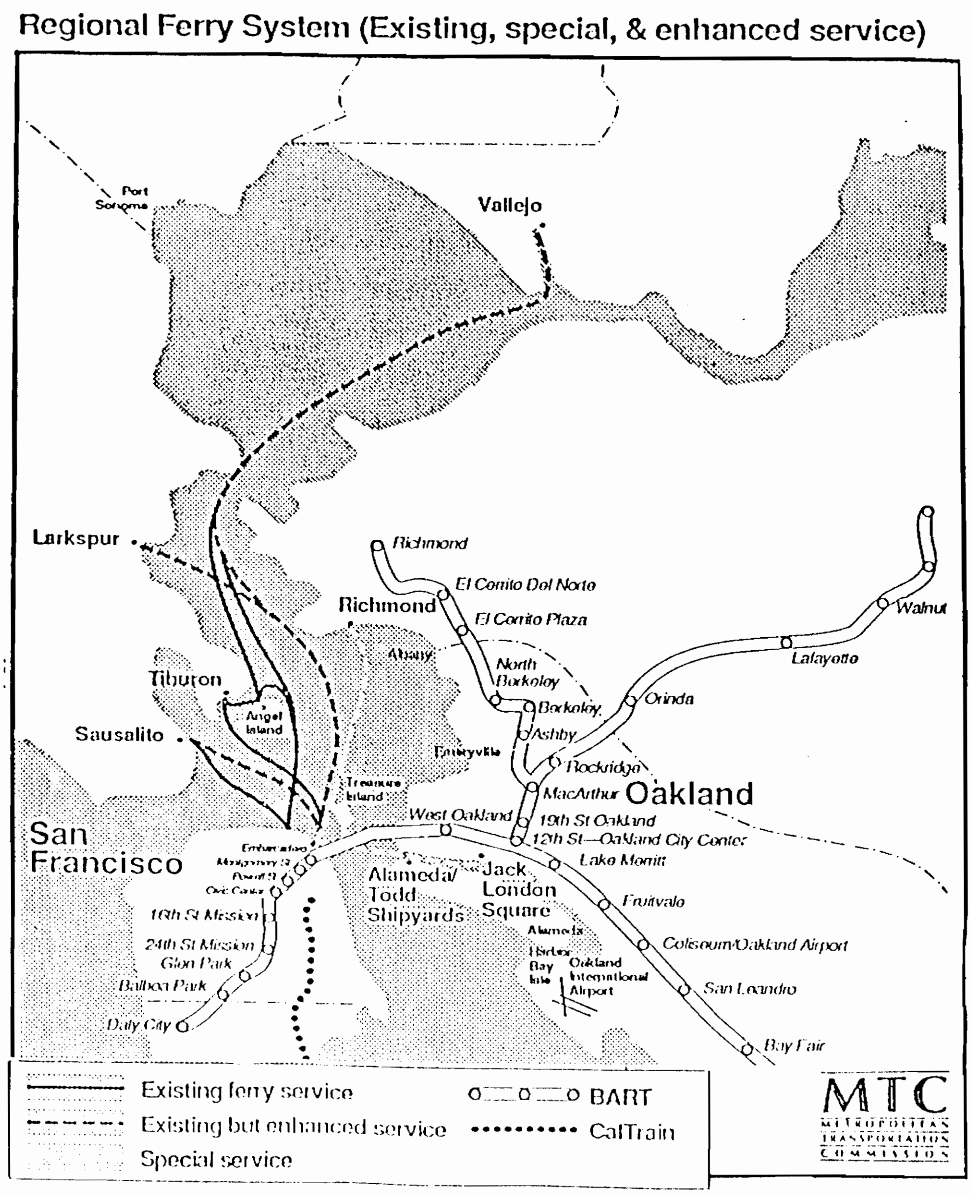



**Figure 16. Regional Ferry System**

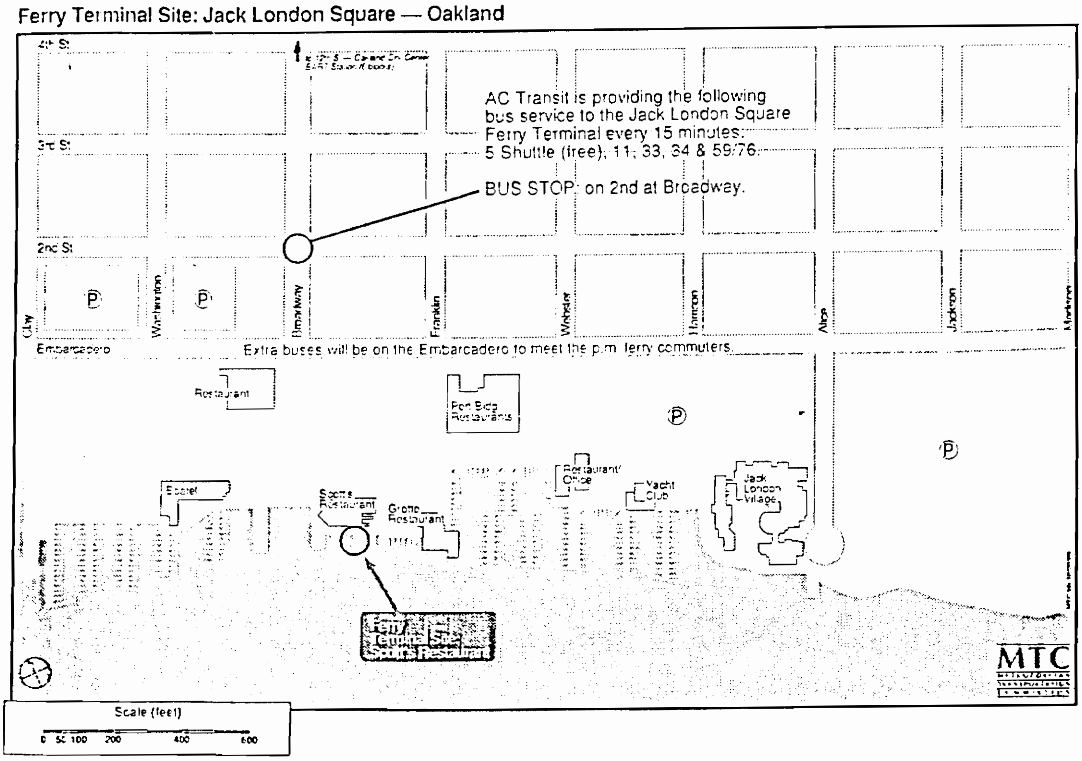



**Figure 17. Ferry Terminal Site - Jack London Square Water Front**

Also, 1400 parking spaces were available at the Jack London Waterfront area[10].

### *3.3.18 San Leandro, Hayward, Fremont*

BART was the recommended way to travel to San Francisco. All "transbay" AC Transit routes terminated at BART stations. An expanded schedule on SamTrans Rte 90E carried riders from the Hayward BART station to San Mateo from 6 a.m. to 7:45 p.m.

While BART and the ferries provided the major transbay link, other transit agencies were vital in assuring coordinated service. AC Transit, for example, redirected transbay buses and added other buses to serve five of the East Bay BART stations, as well as the new ferry terminals in Alameda, Oakland, Richmond and Berkeley. BART in turn honored transbay transfers and Fast Passes bus passengers had purchased for the month of October.

### *3.3.19 Adjustments to Post-Earthquake Transportation Services*

The month of December brought with it minor adjustments to the emergency commute transportation services put in place in the Bay Area after the October 17 earthquake. Despite the reopening of the Bay Bridge, there remained several unusable freeway links. Ferries continued to provide commute service to San Francisco from the five existing East Bay ferry terminals--Vallejo, Richmond, Berkeley, Jack London Waterfront in Oakland, and Alameda. BART discontinued its all-night service from December 3, and patrons were encouraged to use care in parking as some cities reinstated parking restrictions in neighborhoods near BART stations.

The weekday ferry patronage on all services is shown in Figure 18[4]. Before the earthquake, the only services were Golden Gate Transit's high-speed services from Marin

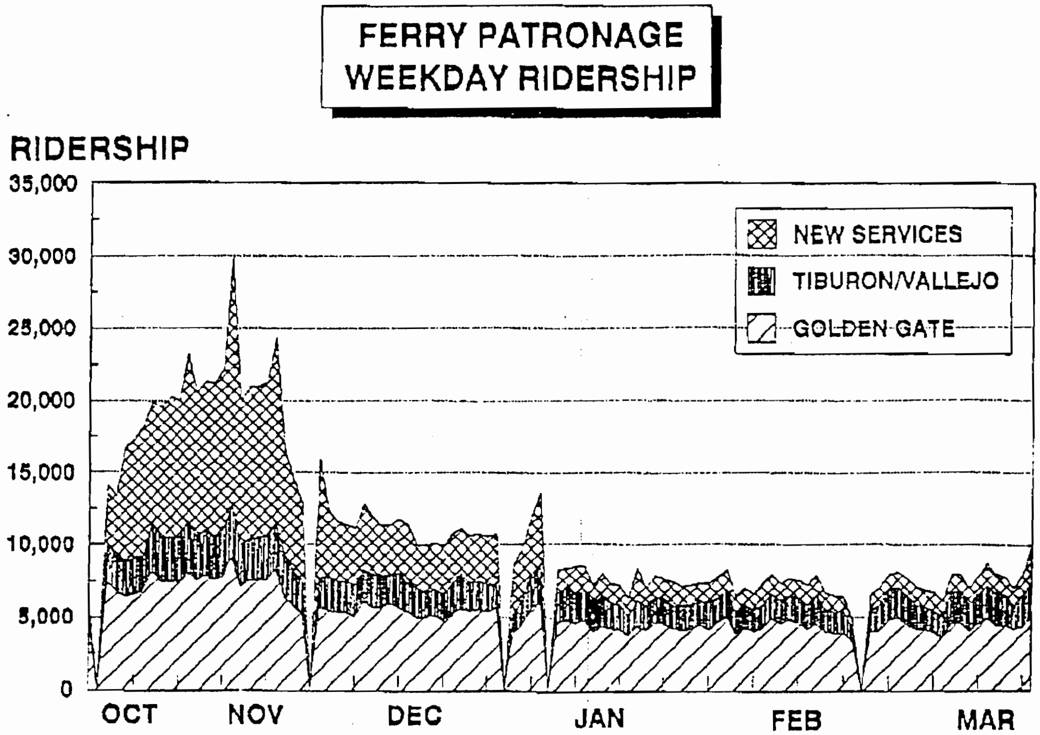



Figure 18. Week day Ferry Patronage

County and Red & White Fleet's commute service from Tiburon in Marin County and Vallejo in Solano County. Golden Gate Transit increased service during the bridge closure to accommodate people from the East Bay who took the Richmond-San Rafael Bridge to the Larkspur ferry terminal. Service was also increased on the Vallejo run to accommodate motorists who used I-80 across both the Carquinez and Bay Bridge to reach San Francisco. In addition to these existing services, CalTrans contracted with Red & White to provide new services from Richmond, Berkeley, Oakland, and Alameda to San Francisco. Before the earthquake, all existing ferries carried about 6,200 patrons per day. At the peak of the Bridge closure, old and new ferries carried nearly 30,000 patrons.

One of the spin-offs of the heightened post-earthquake coordination efforts was the institution of new transit transfers and tickets among operators. A joint ferry/bus ticket on the new services was instituted so that connecting bus transfers were included with the ferry ride. In addition, the AC/BART Plus Muni joint ticket was introduced. In November 1989, the ticket was extended to cover unlimited rides of San Francisco Muni as well. The response was dramatic, going from about 1,400 tickets to over 4,000. After the Bridge re-opening and the expected holiday period fall-off in multiple ticket sales, March sales climbed back to near record levels. Figure 19 shows in detail the AC/BART PLUS Ticket Sales[4].

## 3.4 Coordination

There are few metropolitan areas as organizationally complex as the Bay Area. Fortunately, coordination mechanisms had been in place for many years, so that

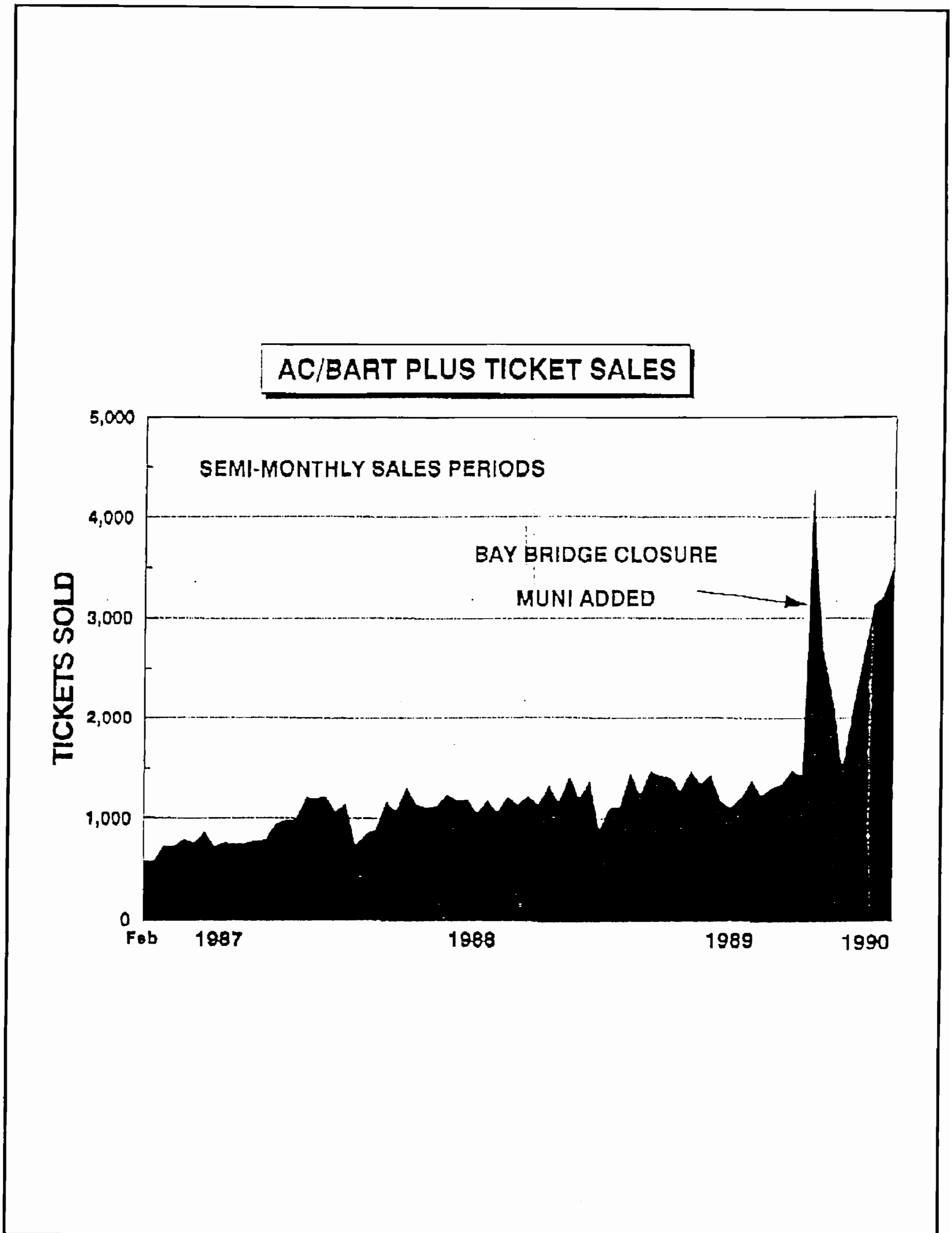



Figure 19. AC/BART PLUS Ticket Sales

operating personnel and managers of the many different agencies knew each other well and were prepared to pitch in to a joint effort without hesitation. The well-established coordination links made it unnecessary to appoint a "transportation czar" for the Bay Area[4].

## 3.5 Communication

Communicating quickly and effectively to the public was a prime reason the disastrous gridlock that had been predicted never materialized. The intra- and inter-agency communication was instrumental in providing services and responding to changing needs.

As the Bay Area set about mending the holes in its transportation network, one thing was very clear: Just as the people of the region pulled together to cope during the disaster, the transit agencies rallied to meet the area's need for mobility[4]. To wrap it up, the Bay Area transit providers' history of working together has stood them in good stead in the time of crisis.

## 3.6 Impacts of Loma Prieta Earthquake

The impacts of the Loma Prieta Earthquake were much more than the loss of life and direct damage. The Bay Bridge is the principal transportation link between San Francisco and the East Bay. It was out of service for over a month and caused substantial hardship as individuals and businesses accommodated themselves to its loss. Perhaps the key lesson learned with respect to short-term impacts was that earthquakes affecting complex social environments present special emergency response challenges[2].

## 3.7 Shift In Travel

It took just four months for the Bay Area's golden age of mass transit to lose its luster. The relatively smooth-flowing highways that emerged after the October 17 Loma Prieta quake are once more jammed. The droves of commuters who switched to ferries, trains and carpools during the cultural aftershock have returned to old ways. The crisis resolved, most of them are back behind the wheel. Traffic on the Bay Bridge which was closed for repairs for a month after the quake, has returned to pre-quake levels.

With I-280 closed due to quake-related damage, the traffic that used to sail along that route into downtown San Francisco mingled with that headed for the Bay Bridge. Together, they formed a viscous clog of cars starting at the San Francisco Airport. When the Bay Bridge was closed, Highway 101 was fine, but since the bridge went up again, 101 is a nightmare. By all accounts, Highways 880 and 17 have joined 101 in absorbing the people fleeing back to the privacy of solo commutes[8].

Although BART's daily ridership remained higher than it was before the earthquake, there was a steady decline from its post-quake peak. Before the quake, BART estimated an average daily ridership of 218,000. Immediately after, with the Bay Bridge closed and BART running for 24 hours, ridership soared to 357,000. By December 1989, it had fallen to 242,000, and by February 1990 to 233,000. Likewise, ridership in the CalTrain service that runs from San Francisco to San Jose and the ferry services throughout the Bay Area have declined from post-quake highs, but remained above pre-quake levels for quite some time.

### *3.7.1 Steady reduction*

After the quake, average daily ridership on the train jumped from its 3,560 normal to 4,503. That number has dropped steadily. Ferry use has plummeted from a post-quake high of 21,000 daily riders to about 7,300. Most of the commutes were complicated due to the demise of the Cypress Street Viaduct in Oakland, which used to take traffic directly from I-80 to I-880. Now the same cars crawl along a detour, joining existing traffic along I-580 and I-980 before intersecting I-880[8].

## 3.8 Earthquake Effects on Transbay Travel Issues

● Effects on commute to work:

- time of travel.
- route of travel.
- mode of travel.
- number of trips made; destination.

● Effects on other travel, activities -- social, recreational, personal business, work related:

- travel constraint effects.
- time constraint effects.

● Employer roles.

## 3.9 Economic Impacts

There were some important economic consequences of the failure of the Bay Bridge, I-880, and other facilities. Small businesses especially had lost patronage following the quake. Downtown retail firms had problems because of the loss of accessibility that deterred consumers during the shopping season[2].

Many localized problems would take months or longer to resolve, and some remain today. The disaster has left enough to limp along for several months.

The extent of the damage to the region's assets fortunately is a very small fraction of the region's total physical assets. Most of the region's infrastructure is intact. The earthquake lasted less than a minute, but its effects will ripple through the Bay Area economy for many months. There are winners and losers in the aftermath of the disaster[2].

## 3.10 Positive Impacts

In the post-earthquake era, some long-term positive impacts on the region are likely to include the possibility of improved land-use planning, improved resistance of structures to natural hazards such as earthquakes, and most importantly a new impetus for reducing the region's traffic congestion problems[2]. The earthquake aftermath has given the region a taste of how the traffic congestion in the Bay Area is likely to be in the future, as people in record numbers flocked to BART and the remaining bridges became jammed by the closure of the Bay Bridge. The positive learning consequences of the October 17 disaster undoubtedly will spill over into the other parts of California, as policy makers improve disaster preparedness.

## 3.11 Income & Job Losses Jolt the Region's Economy

Income and job losses are related to the physical damage and related business interruption sustained by offices, factories, warehouses, roads, bridges, highway overpasses, and lifelines such as power and gas lines, water pipelines and telecommunications facilities. The linkage between structural damage and income and job losses comes via the destruction of places where people produce goods and services and via damage to vital transportation and communication networks[2].

Clearly, the significant sources of short-term economic losses[2] in this earthquake have been the disruption of the Bay Bridge and damage to Rte 17 in Santa Cruz County. The former affected the major commute and truck transportation linkage between the East Bay and the city of San Francisco. In Santa Cruz County, highway damage disrupted the flow of traffic with the nine county Bay Area region. Many businesses were affected due to the collapse of the Cypress structure on I-880.

The income and job losses due to transportation linkage breakdowns were mainly short-term losses. They were the result of

1) People postponing shopping trips, resulting in a decline in retail sales; but, there was some regional redistribution of shopping and San Francisco sales losses were partially made up by sales increases in East Bay and other parts of the Bay region. Thus, the region as a whole did not lose many retail sales on a lasting basis[2].

2) Added Transportation costs due to longer trip times as trucks sought routes

alternate to the Bay Bridge and Highway 17; this increased the cost of doing business.

## 3.12 Fear Permeates the Economy

Another kind of economic loss was due to people's "fear" of another major earthquake. Temporarily, it prevented some people from coming to downtown shopping areas and even to work. In the aftermath of the October 17 earthquake, a significant number of people did not come back to work in downtown San Francisco for at least four to five days. That disruption of production lowered productivity for many businesses[2].

Tourism in the short run declined dramatically, putting many workers out of work for weeks, but again there was substantial recovery in the new year.

## 3.13 Opportunities Must not be Ignored

Some long-term opportunities that arose from the disaster include the following:

1) Leaders and citizens became more aware of the regional interdependence and linkages, and therefore, regional rather than narrow local solutions to issues such as transportation and disaster preparedness are likely to become more acceptable. Intra-regional divisiveness has reduced, and possibilities of more cooperation across city and country boundaries have taken an upward trend. The aftermath of the disaster provided a window of opportunity for instituting important public policy initiatives.

2) There is a good chance that significant lasting adjustments will occur in work and transportation schedules--for instance "flex time"[2]is being more widely used than before by many Bay Area businesses. Public transit is also being used in record numbers.

These developments must be encouraged on a more permanent basis[2].

3) Renewed attention will be directed to the transportation problems because of the transportation difficulties experienced in the aftermath of the quake.

## 3.14 Summary of the Impacts of Loma Prieta Earthquake

In summary, the "World Series Earthquake" of 1989 was a major but not an overwhelming natural disaster. Precise measurement of the economic impact of the quake was not possible. Aside from the physical damage, longer term income losses occurred but were not very significant[2]. Major transportation routes will require two to three years to overcome ramp and traffic diversion obstacles.

The Bay Area has enormous vitality, and it will overcome the setbacks of the Loma Prieta earthquake. The region's earthquake preparedness and post-quake damage control and emergency response have proved invaluable.

With a few major exceptions, the region's infrastructure was intact in the aftermath of the Loma Prieta Earthquake.

# *4.0 THE "BIG ONE" SCENARIO*

The Loma Prieta earthquake showed the vulnerability of a Bay crossing and other critical links in the freeway system to a relatively distant event. Future planning must recognize the likelihood and potential consequences of closer, and more powerful events on the San Andreas and Hayward faults. In particular, the possibility of a dual, or even triple failure, of Bay crossings would result in a situation for which there has been no precedent. This chapter deals with what might happen if the "Big One" really hits? The size and magnitude of the problem and the disastrous effect if critical bridges and freeways are closed when a big earthquake occurs will be addressed.

## 4.1 Hayward Fault Earthquake

Events of magnitude 7 or larger are expected at two locations in northern California, according to a report by U.S. Geological Survey, the two locations being the northern and southern segments of the Hayward fault in the East Bay. Recent predictions show that there is a 67 percent chance of a big earthquake happening in the Bay Area before the year 2020. A magnitude 7 shock on any one of these fault segments will probably cause considerably more damage than the Loma Prieta event because of their proximity to large population centers. The assumed characteristics of this earthquake are a Richter magnitude of 7.5 that results from the rupture of the entire 62-mile length of the fault from San Pablo Bay to east of San Jose. The fault traverses residential and commercial areas, posing the threat of widespread damage to buildings, utility lifelines, distribution systems and transportation routes[12]. The areas covered by the Hayward fault are shown in Figure 20.

### 4.1.1 The Area

The area encompasses populated areas of Eastern Contra Costa County and Livermore Valley on the east, most of the heavily populated greater San Jose area, and the communities north along the peninsula to and including much of San Francisco[21].

### 4.1.2 Considerable Damage

Shifting of land surface will be common, particularly on filled ground around Bay margins which might damage major structures and lifeline facilities, notably highways, rail roads, airport runways, port facilities and some utility pipelines[21].

Eight of twenty-six general acute care hospitals in Alameda and Contra Costa Counties are located within one mile of the Hayward fault. Schools located in the hills east of the fault will be functionally impaired due to disrupted utility services. The fault traverses the University of California campus at Berkeley[21].

### 4.1.3 Lifeline Corridors

The major transportation corridors that serve the East Bay Area, such as at San Pablo and Fremont, are commonly shared by various other lifeline facilities, all of which are vulnerable to major damage where they cross the fault. Simultaneous failure of several major lifelines within these restricted corridors could vastly complicate emergency response efforts[21].

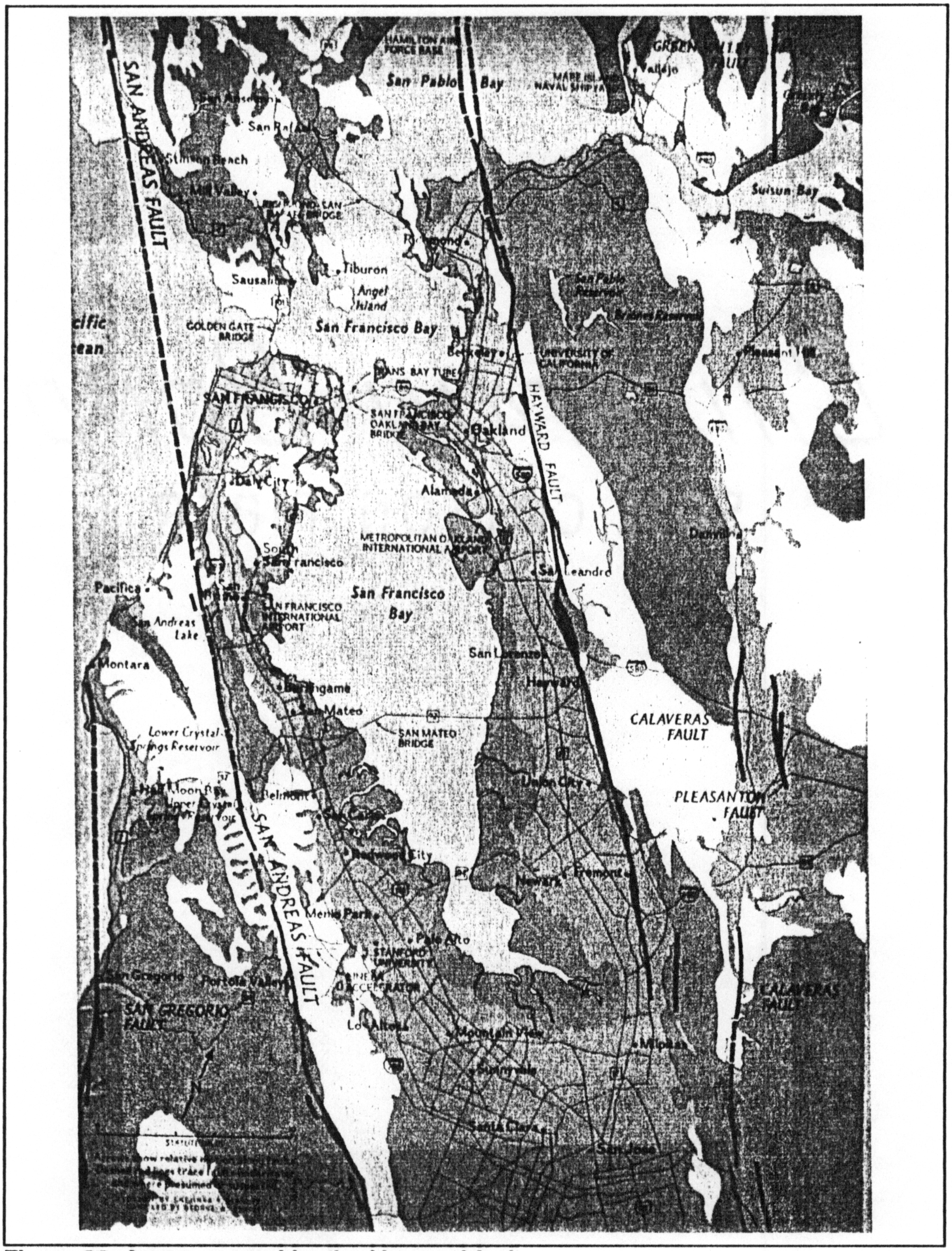



**Figure 20. Areas covered by the Hayward fault**

## 4.2 Highways

### *4.2.1 General Characteristics*

In the San Francisco Bay Area, the state highway system includes almost all of the heavy-duty traffic arteries and carries over 65 percent of the traffic volume. The major corridors for highway traffic in the East San Francisco Bay Area are as follows:

- Three major north-south routes: I-580, Rte 17, and Rte 238.
- One major access route on the north and the east: I-80.
- Five major routes to the West from the East Bay: Rte 17 (Richmond-San Rafael Bridge), I-80 (Bay Bridge), Rte 92 (Hayward-San Mateo Bridge) Rte 24 Dumbarton Bridge), and Rte 37 in the North Bay.
- Two major routes to the east from the East Bay: Rte 24 (Caldecott Tunnel) and I-580.
- I-680 provides an additional route to the east from Southern Alameda County and Santa Clara County via Mission Pass.

There are alternative surface streets which can be used to bypass most major freeways, but primary access to the West and East from the urban East Bay is limited to the San Francisco Bay crossings, the two routes through the East Bay hills to the east, and I-80[21].

## 4.3 Size of the Problem

In this section of the research, based on the U.S. Geological report that the Hayward fault earthquake might hit in the next 20 to 30 years, the size of the problem in the year 2010 is addressed. The problem is referred to in terms of the growth in the East Bay and the West Bay. The following issues of growth are identified as closely affecting the transportation system during disaster periods:

- Population
- Auto Ownership
- Autos per center-line mile
- Number of vehicles crossing the Bay.

Too often, we focus on growth as the cause of congestion, overcrowding, etc. Growth is the problem per se.

## 4.4 Population

Over the period 1990-2010, about 42 percent of the region's population growth will occur in Alameda and Santa Clara Counties[19]. The population projections are based on the Association of Bay Area Government's (ABAG's) "PROJECTIONS 90" which provided data for the base year 1980, estimates for 1985 and forecasts for the years 1990 and also 2010 for the nine-county San Francisco Bay Area. The projections represent the upper bound of the forecast range and were performed by the Regional Economic-Demographic System (REDS). REDS is an analytical and econometric model which uses a non-survey input-output (I/O) model to drive the interaction in the system. The basic equations and I/O model are updated every two years. The most recent update occurred in 1988. The population model is a Cohort-Survival model. ABAG used trend analysis to determine long-term growth forecasts for each county's population and households.

Linear exponential and geometric regression time series equations were used to predict future growth. The results of the trend equations were summed and averaged[19].

### *4.4.1 Demographic Assumptions*

To create projections for the year 2010, the demographic assumptions concern fertility, births, deaths, migration[19].

#### 4.4.1.1 Fertility and Births

Since 1980, the regional period fertility rate has been increasing. In creating Projections 90, ABAG has assumed that the regional period fertility rate will stabilize below the current level. The period fertility rates and the estimated and projected births, deaths and migration are furnished in Appendix A.

Population, auto ownership and autos per center-line mile are fairly good indicators of the growth levels in any area. If there are growth trends in terms of population and auto ownership for any area as a matter of fact, then we can conclude that the area will experience congestion problems in the future.

In the San Francisco Bay Area, the growth problem can be projected as growth in the East Bay and West Bay, respectively. The East Bay is comprised of Alameda, Contra Costa, Santa Clara and Solano Counties whereas San Francisco, San Mateo, Marin and Sonoma Counties comprise the West Bay. Both East and West Bay were considered to project the size of the problem. This was mainly because the trans-bay movement was centered around these counties, the only exception being Palo Alto city of Santa Clara County.

The population projections for the year 2010 taking 1990 as the base year are shown in the form of bar charts in Figure 21. Between 1990 and 2010, Alameda and Contra Costa Counties will absorb about 37 percent of the region's new residents. The population of these counties is projected to increase by about 21 percent, a staggering rise from 2,062,000 in 1990 to 2,489,140 in the year 2010, whereas the West Bay would experience only a 12 percent increase during the same period.

Since forecasting for 122 cities and unincorporated areas and nine counties is a complicated process, all county and sub-regional forecasts were reviewed and approved by local governments[19].

## 4.5 Auto Ownership

Basically, auto ownership is a central demographic characteristic which influences all other aspects of travel demand: trip frequency is affected by number of autos owned, as is trip distribution and choice of travel mode. Trip frequency per household is positively correlated with higher auto ownership levels. Availability of autos provides positive incentive to travel further distances to work. Availability of cars for workers in a household affects propensity to take transit, to carpool or to drive alone to work.

The increasing auto affluence of Bay Area households may, in fact, lead to higher dependency on the use of autos for all forms of work and non-work travel. Instead of the transit dependency of zero-auto households, we may be headed towards the reality of auto dependency for the two-plus autos-per-household market. Transportation planners should realize that modal alternatives to drive-alone auto usage are basically hampered by this long-range auto ownership trend.

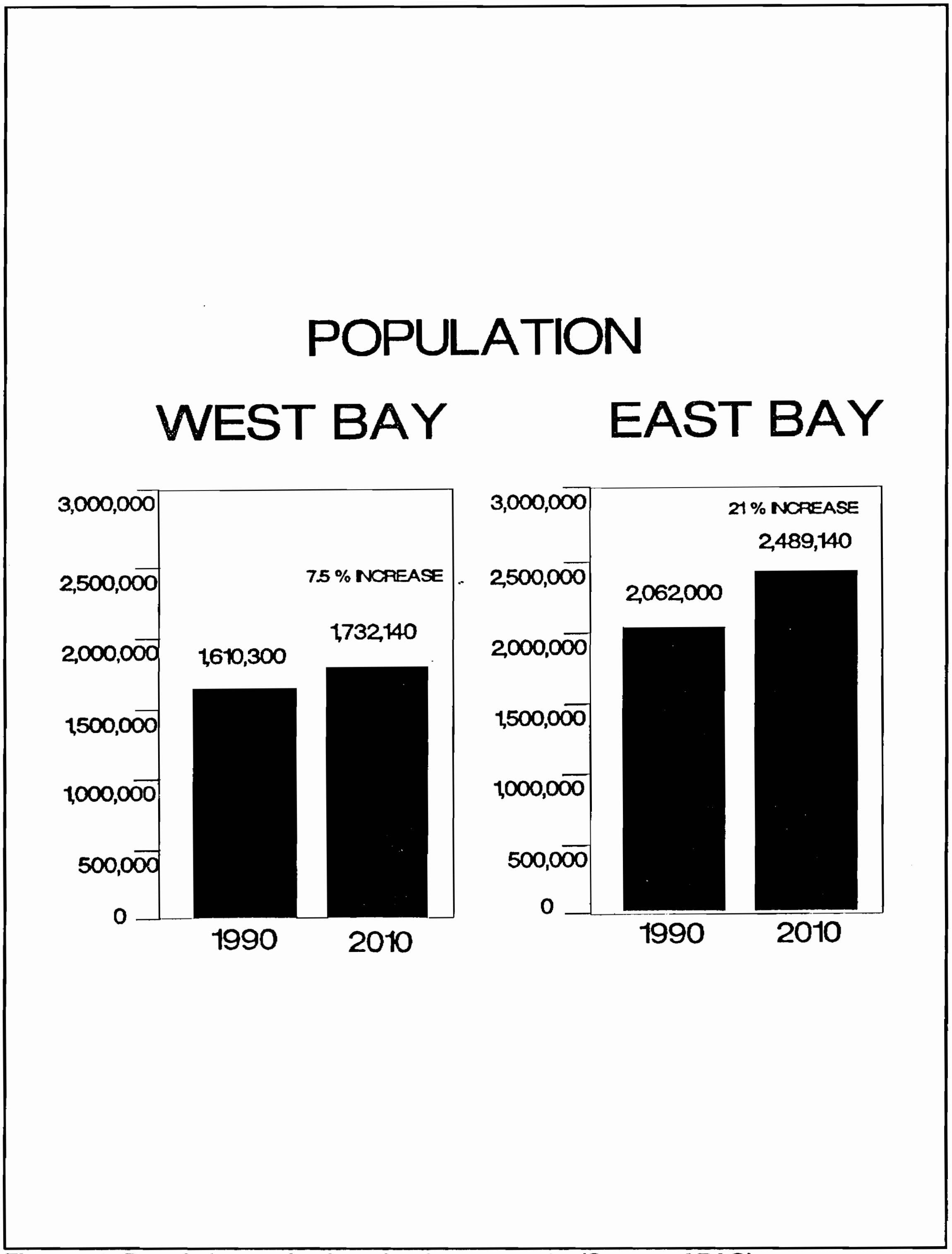



Figure 21. Population projections for the year 2010 (Source: ABAG).

Long-range travel demand forecasts are prepared to ascertain impacts of long-range transportation. The auto ownership forecasts for the year 2010 are based on ABAG's Land Use Forecasts: "Projections 87" and "Projections 90" and Metropolitan Transportation Commission's (MTC) Travel Demand Forecasting Model System: MTCFCAST-80/81[20]. Mathematical models were used in describing and quantifying behavior of Bay Area residents in terms of their commute patterns, non-work travel patterns, and propensity to use public transit relative to carpooling or driving alone. These mathematical models were empirically estimated using actual travel behavior patterns of a small heterogeneous group of Bay Area residents. Models were used to stratify households by auto ownership levels[20].

Critical "core" assumptions in the preparation of travel forecast simulations include transportation policies, land-use policies, and exogenous inputs. Transportation policies were described in terms of transit and highway routes to be simulated. Land-use policies were described as the projected location of housing units, population, and job opportunities, both at the regional and the neighborhood scale. Exogenous input assumptions include gas prices, fuel economy, transit fares and parking prices. Understanding these core input assumptions is integral to understanding the implications of the resultant travel demand forecasts[20].

Auto registration statistics compiled from State Department of Motor Vehicles (DMV) showed a 20.6 percent growth in Bay Area autos between 1980 and 1989. Bay Area population, in comparison, has grown by only 11.8 percent from 1980 to 1989. The Bay Area has gained over 680,000 new vehicles while gaining only 614,000 new people over the same period in time[20].

Long-range travel forecasts reinforce and continue the trend we have seen over the past ten years. MTC is forecasting that the vehicle population will grow to 5.3 million vehicles by the year 2010, a 34 percent increase over an estimated 1989 level of 4.0 million vehicles. The Bay Area as a whole is expecting a 21 percent increase in total population from 1989 to 2010. This yields a 10 percent increase in the number of autos per person, climbing from 0.69 autos per capita in 1989 to 0.76 autos/person by 2010.

MTC's auto ownership models stratified households by the number of autos owned, rather than directly computing a rate of autos per household. In other words, households were stratified as to whether they owned zero, one or two-plus autos. The two-plus auto households were converted into number of vehicles owned, using a constant factor (2.55 to 2.65) and summed to one-auto households to determine total auto ownership by area of residence[20]. Forecasts show that the number of zero-auto households will decline from a regional 12.3 percent of households in 1980 to just 8.7 percent by 2010. All nine Bay Area counties show a decline in total zero-auto households[20].

Auto ownership in the East Bay shows an increase of 36 percent for the projected year 2010 as compared to the 1990 value. A 10 percent growth in auto ownership is expected in the West Bay. We can expect more travel within the East Bay. The auto ownership values for both East Bay and West Bay for the base year 1990 and the projected year 2010 are shown in the form of charts in Figure 22.

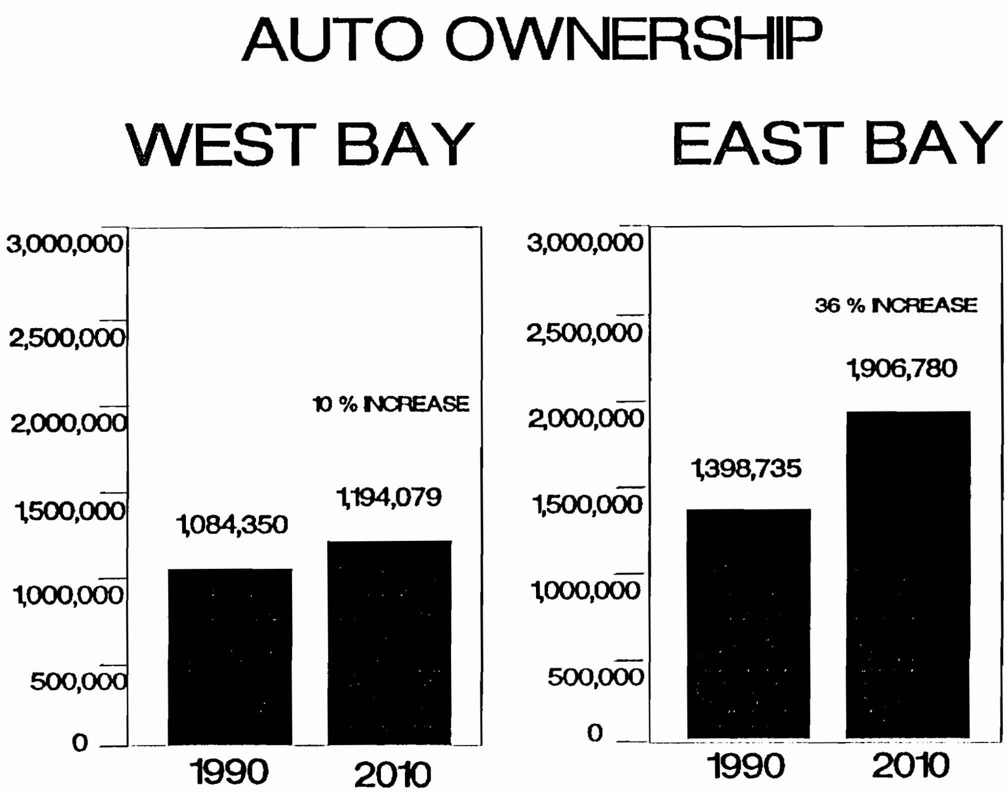



Figure 22. Auto ownership forecasts for the year 2010 (Source: MTC).

## 4.6 Autos per Center-Line Mile

To get a relative handle on the auto ownership statistics, MTC included measures of land use and transportation to identify density characteristics. One such measure is autos per center-line mile which gives an overview of the density levels in an area. San Francisco shows the highest density characteristics of any of the nine Bay Area counties. San Francisco shows over 6,225 vehicles owned per square mile in 1980 climbing to over 8,185 vehicles per square mile by 2010, more than six times as dense as the next nearest county, Alameda[20].

Vehicles owned per center-line road mileage shows a tighter distribution between counties than the per square mile indicator. For the Bay Area as a whole, a ratio of 170 vehicles owned per 1987 center-line miles (in 1980) increasing to 261 vehicles per 1987 center-line miles by 2010. Even the center-line density measure indicates that San Francisco County is "vehicle rich" with respect to road mileage. The average value of autos per center-line mile was computed for both East Bay and West Bay. East Bay shows an increase of about 35 percent by the year 2010, whereas the West Bay has only about 6 percent rise in the autos per center-line mile in the year 2010. The details are shown in Figure 23. We can predict more congestion in the East Bay as compared to the West Bay. An interesting feature to note is that by the year 2010, the autos per center-line value of both the East Bay and the West Bay is close enough to give an impression that travel trends are increasing in the East Bay.

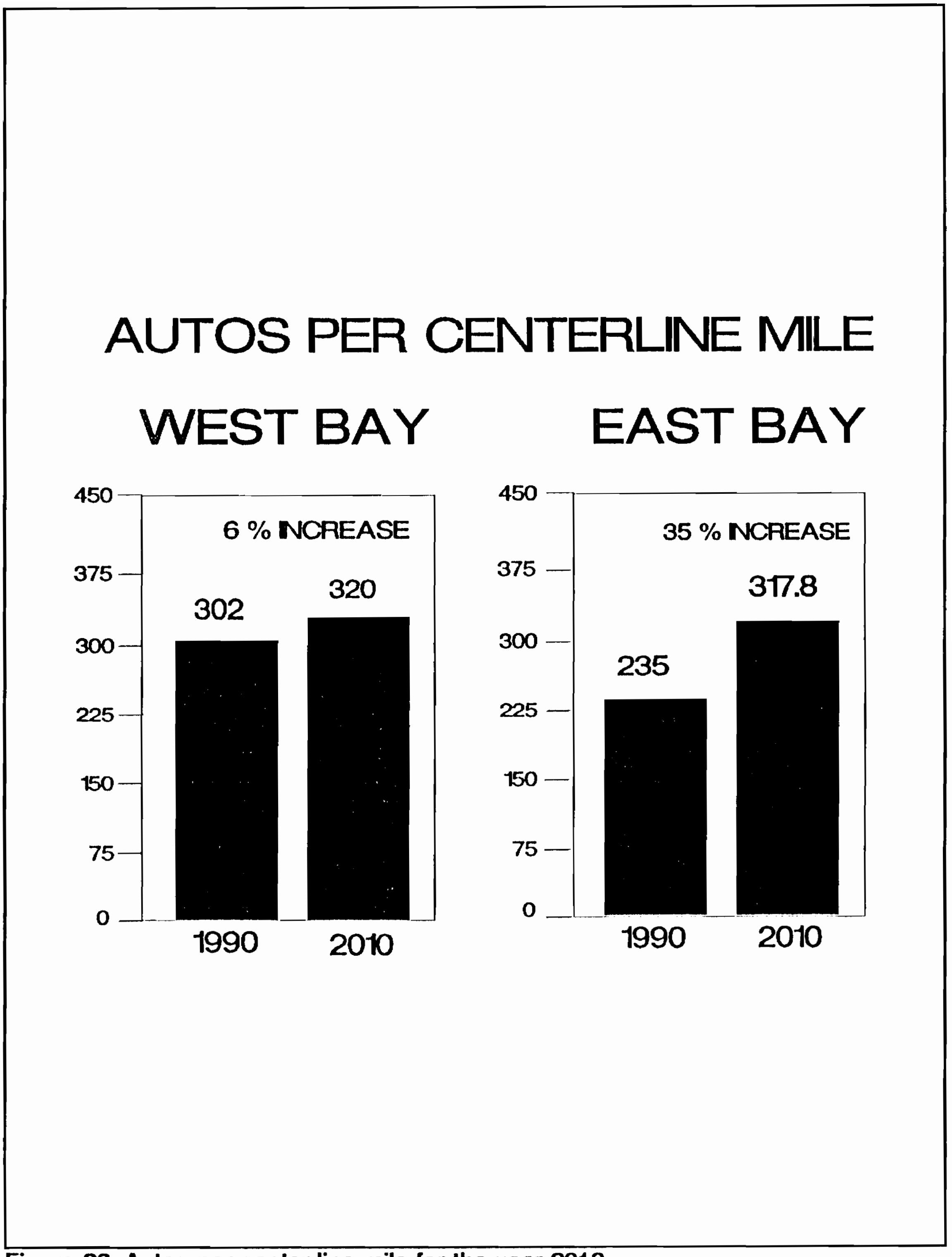


Figure 23. Autos per center-line mile for the year 2010.

## 4.7 Number of Vehicles crossing the Bay

### *4.7.1 Introduction of San Francisco Bay*

San Francisco Bay stretches some 65 miles from Alviso in the south to its northern boundary at the Richmond-San Rafael Bridge in the north. Beyond this bridge the stretch of water becomes San Pablo Bay, which ends at the Carquinez Bridge near Vallejo. Besides the Richmond-San Rafael Bridge, San Francisco Bay is crossed by three other bridges: the San Francisco-Oakland Bay Bridge, the San Mateo Bridge, and the Dumbarton Bridge. The Bay exits to the Pacific Ocean under a fifth bridge-the Golden Gate. In addition, the bay is traversed by the Bay Area Rapid Transit (BART) Trans-bay Tube between Oakland and San Francisco. The critical connections between San Francisco and its eastern and northern neighbors are those of the Golden Gate and Bay Bridges, and the BART Trans-bay Tube[3].

### *4.7.2 Importance of Bay Crossings*

The San Francisco Bay crossings form a crucial part of the entire Bay Area counties, about 20 percent of the workers are employed outside their county of residence. By the year 2010 it is estimated that this percentage will grow to slightly under 27 percent. At the same time, auto ownership, autos per center-line mile and population are expected to grow. Hence, the Bay Area highway network will continue to be crucial to the economy, but its maintenance as a swift and convenient means of travel will become increasingly difficult[3].

### *4.7.3 Before the Quake*

Before the Loma Prieta earthquake, the total number of vehicles on the five San

Francisco Bay Bridges was an average of 517,000 per weekday, together with an average of 103,000 passengers on the BART Trans-bay Tube and the ferries. The breakdown of this traffic is illustrated graphically in Figure 24. Two facts stand out: the importance of the Oakland-San Francisco link and the volume of traffic borne by the San Francisco-Oakland Bay Bridge--approximately double that of the Golden Gate Bridge and almost equal to the combined traffic carried by all four other bridges.

### *4.7.4 During Bay Bridge Closure*

When the Loma Prieta earthquake damaged the Bay Bridge, causing immediate closure of the most widely used cross-bay route, Bay Area traffic patterns were forced to change, and rapid planning had to be done to accommodate the situation. During the period of closure of the Bay Bridge, traffic was redistributed as illustrated in Figure 25. BART and the Ferries count individual fares, while the bridges count the vehicles and hence the apparent change in cross-bay totals. Total vehicles over the crossings dropped from 517,370 to 407,140 during the closure period; a significant number of people used BART or curtailed their travel.

### *4.7.5 After Bridge Reopening*

The Bay Bridge reopened for service exactly a month after the Loma Prieta earthquake had occurred. People started using the Bay Bridge as they used to before October 17th. Ferry and BART travel had returned to their normal levels. The details are as shown in Figure 26.

### *4.7.6 Travel in 2010*

The number of vehicles crossing the bridges in the Bay Area was projected for the

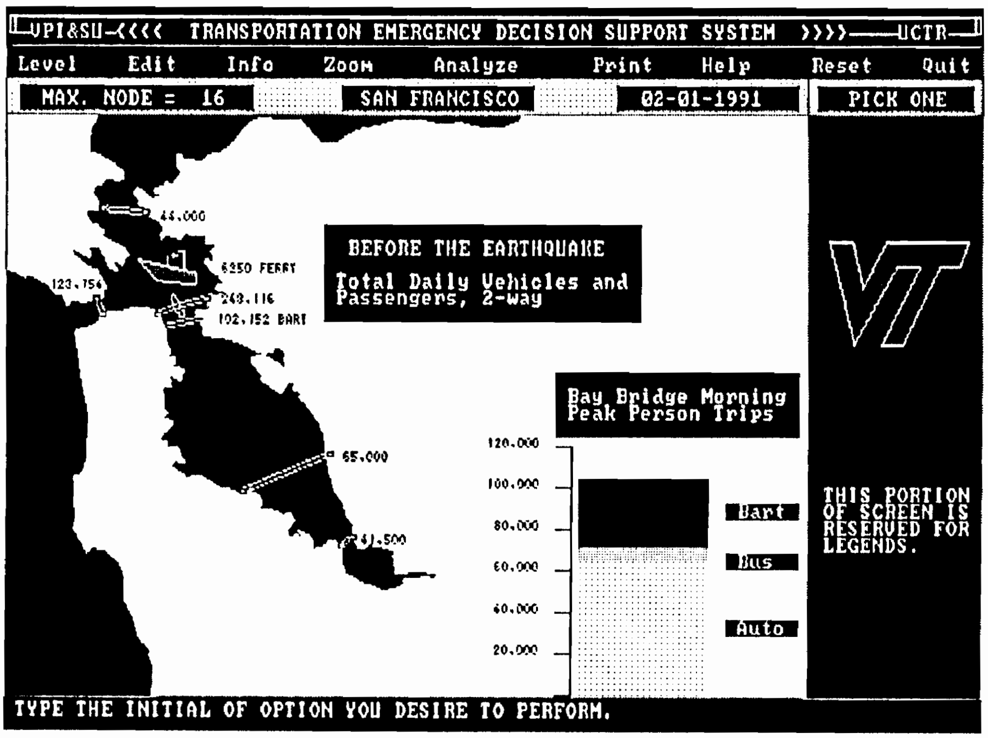



**Figure 24. Trans-bay Travel before the Loma Prieta Earthquake**

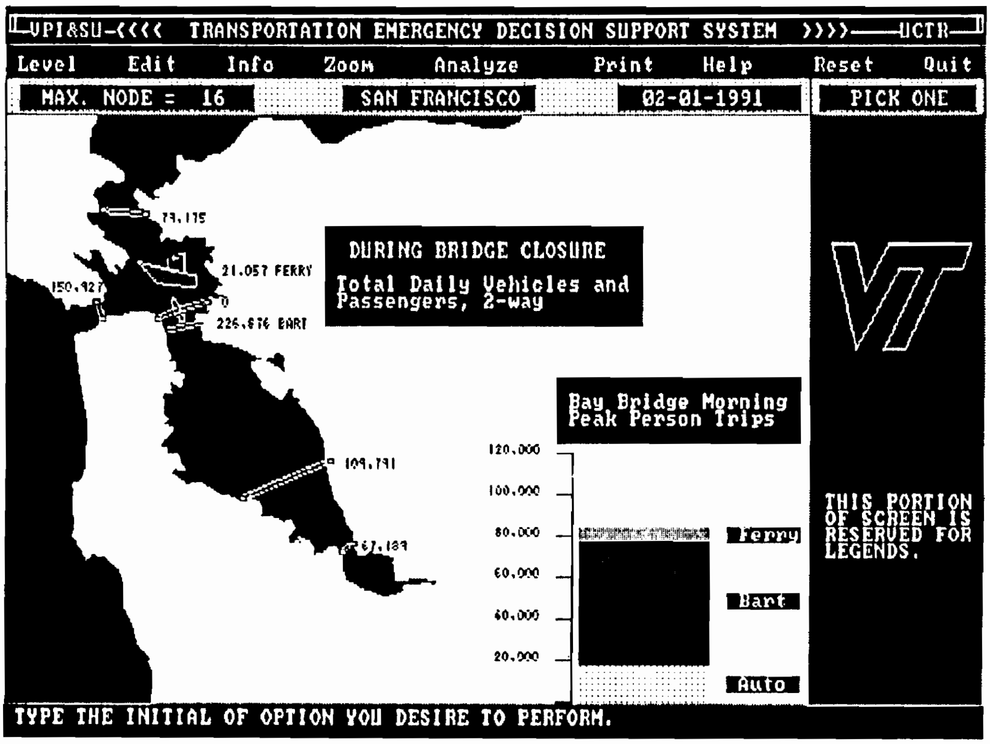



Figure 25. Trans-bay Travel during Bay Bridge Closure

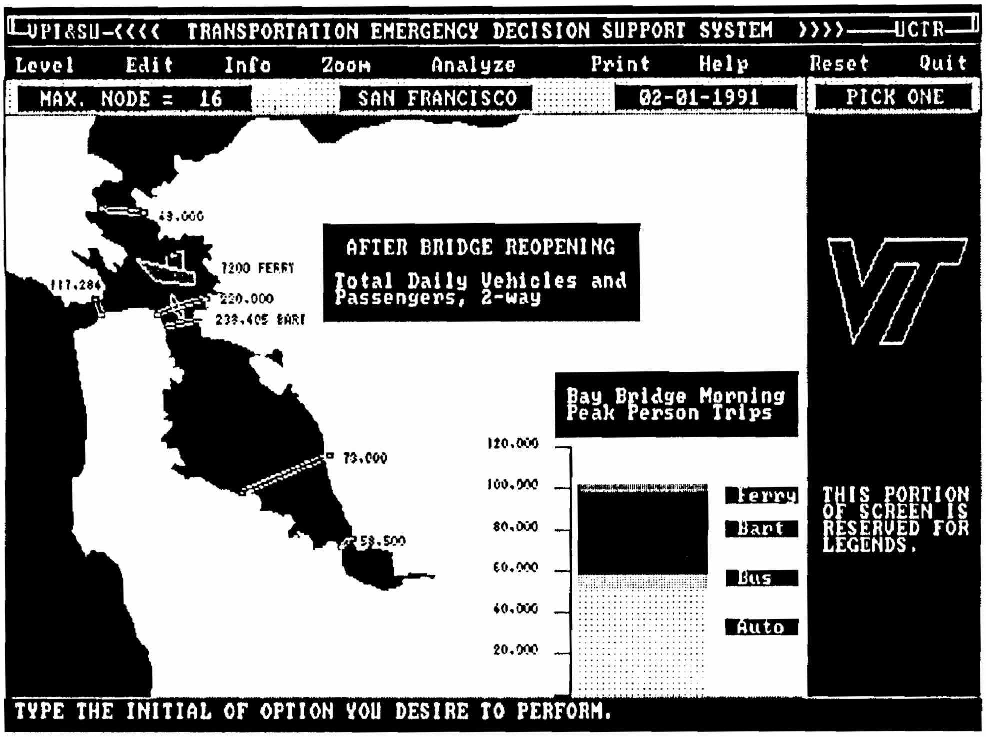



Figure 26. Trans-bay Travel After Bay Bridge Reopening

year 2010. This was done using the auto ownership growth factors for each county, and in some cases the growth factors for the city were used[20]. For example, in case of Richmond-San Rafael Bridge, the growth factors for Contra Costa County and San Rafael city were used. Since the number of vehicles across the bridges is a two-way value, the average growth factors were computed and used for the projections. The comparison between the number of vehicles crossing the Bay in the years 1990 and 2010 is shown in Table 7. Richmond-San Rafael Bridge tops the list in terms of increase in the vehicular flow with a 35 percent increase, and the increase in the number of vehicles on other bridges is also phenomenal. The total number of vehicles crossing the Bay in the years 1990 and 2010 is illustrated in Table 8.

**Table 7. Number of Vehicles Crossing the Bay.**

| Name of the Bridge | The Year 1990 | The Year 2010 (% Increase) |
|---|---|---|
| Richmond-San Rafael | 44,000 | 59,400 (+35%) |
| Bay Bridge | 243,116 | 309,244 (+27.2%) |
| Hayward-San Mateo | 65,000 | 80,000 (+23.1%) |
| Dumbarton | 41,500 | 51,000 (+23%) |
| Golden Gate | 123,754 | 146,463 (+19%) |

Table 8. Total Vehicles on all Bridges.

| The Year 1990 | The Year 2010 | % Change |
|---|---|---|
| 517,370 | 646,107 | (+ 25%) |

*All Values are estimated from MTC Travel Forecasts.

## 4.8 Overview of the Capacity of the Transportation System

It is very important to look at the capacity of the transportation system as a whole while studying the Cross-Bay travel patterns. Since the total number of vehicles crossing all five bridges is predicted for the year 2010 (as explained in earlier sections), it is possible to study the problem as such.

In the aftermath of the Loma Prieta Earthquake, traffic was returned to normalcy as commuters were using the other bridges when the Bay Bridge was closed for a month. Coupled with that, BART had run 24-hour service carrying a record number of 350,000 passengers per day. Ferry services were expanded and were run to the fullest extent possible. Here, a point which is noteworthy is that most of the ferries were brought from the neighboring states. The traffic on all the remaining four bridges was heavily congested.

Considering the Hayward fault scenario, if the "Big One" really hits and if there were to be closures of the Bay Bridge and the Hayward-San Mateo Bridge[21], the problem would be far more severe than in the case of the Loma Prieta aftermath. It is also predicted that there will be growth in the number of vehicles crossing all five bridges, as explained in earlier section. The alternative commute patterns are very much limited in the case of closure of the above-mentioned bridges. The maximum capacity of BART in the case of an emergency is 400,000 passengers per day, if operated 24 hours a day. However, BART serves only the Bay Bridge traffic, i.e., it connects mainly Oakland and San Francisco.

A ferry system could be designed with enough ferry terminal sites throughout the Bay Area, but there are not enough ferries available to meet the demand. The alternative routes are very time consuming and also not feasible in practice due to the fact that the maximum capacity of the bridges is insufficient for serving the commuters of two other bridges. The Bay Area transportation system should be designed for such worst-case scenarios in case a "Big One" hits, i.e., planning for another bridge across the Bay. This alternative may seem to be, at least initially, an expensive idea. But, for the long-term needs of the Bay Area Commuters, it would really help in the alleviation of the congestion problem and also might serve as a feasible commute alternative in the case of a disaster situation.

## 4.9 Landlocked Areas

The landlocked areas are those areas which might be affected if the "Big One" hits, basically, the damage-prone areas in the event of an earthquake. Rte 880 might suffer the worst damage. The Bay Bridge, San Mateo and Golden Gate crossings might be closed due to some damages at the approaches[21]. The statements regarding the performance of facilities are hypothetical and intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. All the major landlocked areas are illustrated in Figure 27.

## 4.10 Elevated Structures

In the event of an earthquake of higher magnitude occurring in the San Francisco Bay Area, the severity of the problem is magnified due to the extent of damage to the elevated structures. In the case of the Loma Prieta Earthquake, Cypress structure's collapse was a typical example of the collapse of an elevated structure. The extent of that damage was already dealt in the earlier chapters. All the elevated structures (freeways) are identified and are as shown in Figure 28. Incidentally, most of the elevated structures are very close to the Hayward fault.

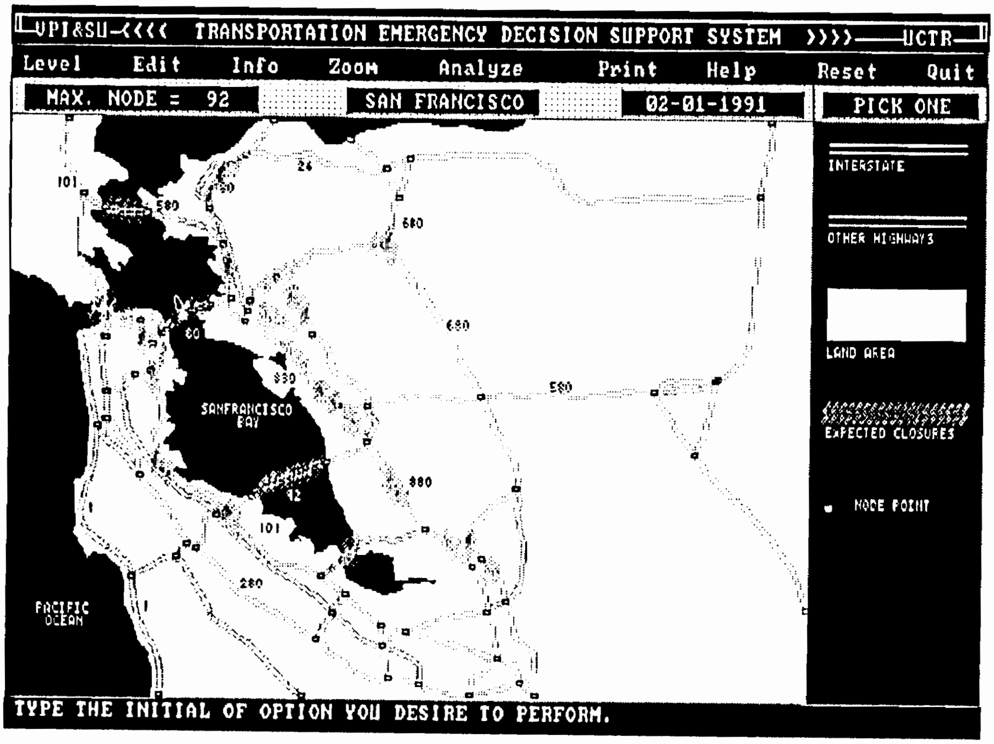



**Figure 27. Major landlocked areas in the predicted "Big One."**

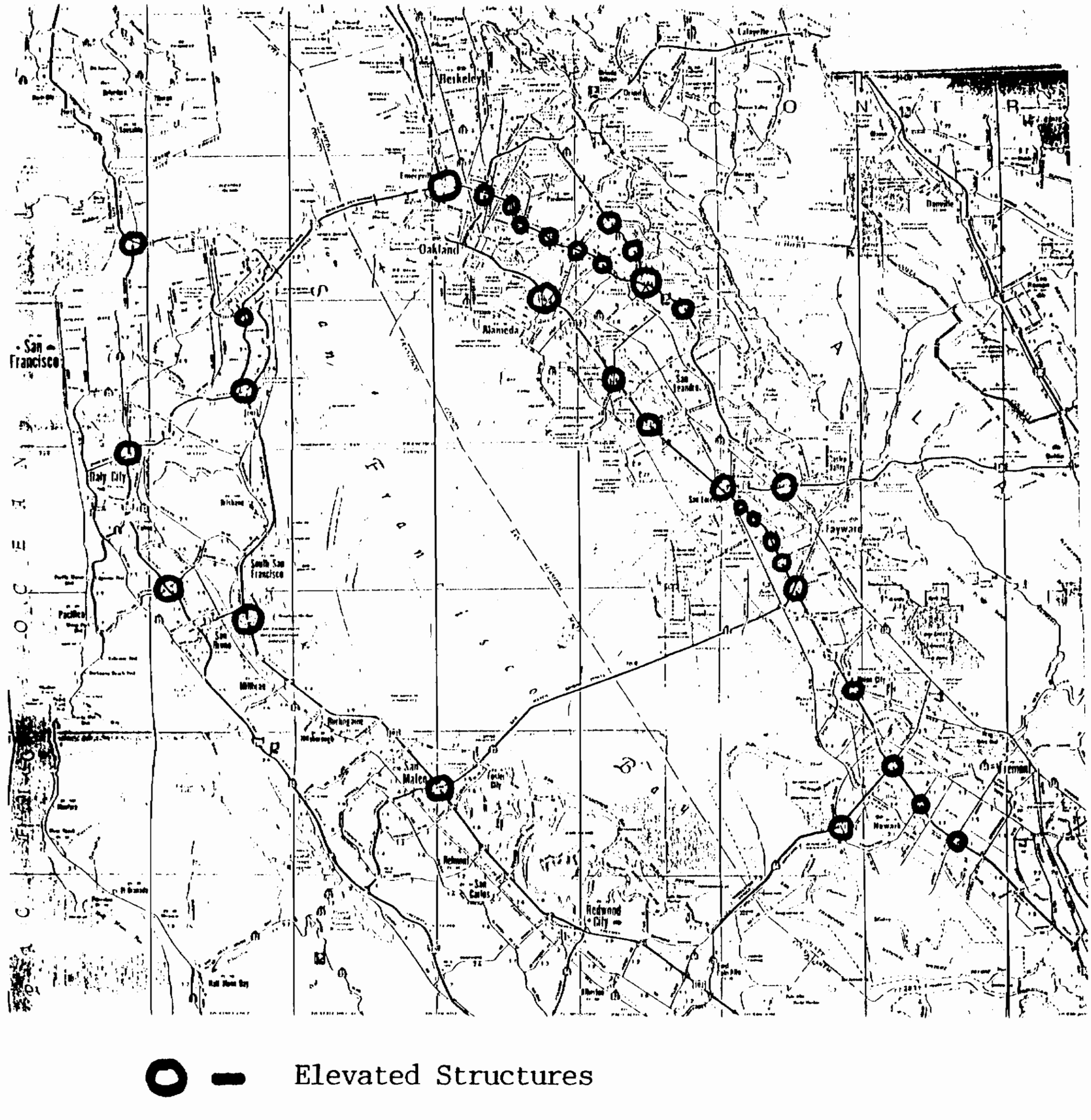



Figure 28. Elevated Structures in the Study Area.

# *5.0 RESEARCH METHODOLOGY AND ITS APPLICATIONS*

## 5.1 Introduction

The scope of this research methodology, which forms a part of the thesis is to develop a macro-level measure to approximately assess the impacts due to failure of critical links in the aftermath of big earthquakes. It is also intended to relate the network components to the overall problem of congestion due to highway failures faced by the earthquake-borne cities. The study is devoted towards developing a macro-level Weighted Roadway Congestion Index (RCIW), which is simple in structure but also capable of providing an overview of the severity of certain closures due to earthquakes. The roadway congestion index is also used to perform scenario analysis at a macro-level for the San Francisco Bay Area. All possible scenarios depicting the expected closures if a "Big One" really hits are analyzed, and the severity of the problem is addressed in terms of the RCIW. The critical factors that contribute towards the RCIW are also under the purview of this research study. This chapter provides a correlation analysis which is performed to establish the relationship between RCIW and the network's structural parameters. The results obtained from the manual analysis and also the Statistical Analysis System (SAS) are presented here.

## 5.2 Research Framework and Components

The research framework needed to accomplish the above objectives has the following steps:

- Finalizing the major urban cities to be included in the study.
- Developing a macro-level RCIW, a measure to provide an overview of the congestion level in all the major urban cities.
- Ranking the cities in order of their congestion levels based on the value of the RCIW.
- Establishing the dependence of line-haul system (such as freeways) to move vehicular traffic in earthquake-threatened cities, especially if the transportation systems fail or collapse.
- Determining the factors that have a major influence on the value of RCIW.
- Recalculating the value of RCIW due to the closure of certain critical links in the immediate aftermath of the earthquake.
- Relating the network's structural components to the RCIW.
- Analyzing the results and recommending studies to assess the impacts at a micro-level due to the failure of critical links.

Having established the framework, the next step is to conduct the research study. The following section is devoted to the way the Weighted Roadway Congestion Index was built.

## 5.3 Weighted Roadway Congestion Index (RCIW)

About 39 cities were included in the study to better represent a geographical cross-section of urban areas throughout the country[22]. The database for the study consists of various roadway measures like freeway vehicle-miles of travel, arterial vehicle-miles of travel, lane-miles of arterials and freeways and the number of lanes and volume on each link. The data for daily vehicle-miles and lane-miles of arterials and freeways for the year 1988 were based on the Texas Transportation Institute's (T.T.I) report on roadway congestion. Originally, the data were obtained from a variety of federal and state sources, like the Highway Performance Monitoring System (HPMS) database compiled by FHWA to estimate congestion on the freeway/expressway and the principal arterial street system.

The values for each system are combined into a Roadway Congestion Index used to rank mobility in each urban area on a relative scale. The following equation illustrates how the Daily Vehicle Miles of Travel per lane-mile values are combined to calculate the urban area congestion index.

$$RCIW = \frac{\frac{VMTF/Ln\text{-}Mi}{13,000} * VMTF + \frac{VMTA/Ln\text{-}Mi}{5,000} * VMTA}{VMTF + VMTA} \quad (5.1)$$

where,

VMTF is Vehicle Miles of Travel on the Freeway.

VMTA is Vehicle Miles of Travel on the Principal Arterial.

According to the studies conducted by the Texas Transportation Institute, when area-wide freeway travel volumes reach 13,000 daily vehicle miles of travel per lane-mile, congested conditions (level of service D) are predicted to occur. For principal arterial streets, the corresponding level of service is represented by a system average of 5,000 daily vehicle miles of travel per lane-mile. These values are also in general agreement with values presented in the Highway Capacity Manual. The aggregate value of the RCIW was estimated by combining the indices of both the freeway and the principal arterial streets[22].

Once the methodology for determining the RCIW was established, all the cities were ranked using a SORT procedure in Statistical Analysis System (SAS) based on their congestion levels, in order to look at the congestion problem as a whole for all urban areas in U.S.

The mobility levels in all the cities considered for the study can be compared using the ranking of the 39 cities as shown in Table 9. It can be seen from the table that Los Angeles ranks first in terms of the level of congestion and San-Francisco - Oakland cities were ranked third based on their RCIW value. These RCIW values are valid on a current basis, i.e., under normal conditions, without any closures to any links in the system. Based on the present values of RCIW, it is justified to perform scenario analysis for the San-Francisco - Oakland cities. RCIW values greater than 1.0 indicate objectionable mobility levels within the urban area. About 21 cities have RCIW values greater than 1.0 and 14 cities have Daily Vehicle Miles Travelled (DVMT) per lane-mile values of freeway, exceeding the desirable area-wide average of 13,000 DVMT per lane-mile. In the case of DVMT per lane-mile values of principal arterials, 26 cities have values exceeding the

**Table 9. Ranking of the 39 cities based on RCIW values**

| OBS | CITY | DVMTF | DVMTA | DVMTLMF | DVMTLMA | DVMTLMFA | RCIF | RCIA | RCIW |
|---|---|---|---|---|---|---|---|---|---|
| 1 | LOS_ANGE | 102140 | 78240 | 20590 | 6520 | 27110 | 1.58385 | 1.304 | 1.46246 |
| 2 | WASHINGT | 23600 | 18800 | 15850 | 8250 | 24100 | 1.21923 | 1.650 | 1.41023 |
| 3 | SANFRAN_ | 40370 | 13540 | 17360 | 6620 | 23980 | 1.33538 | 1.324 | 1.33253 |
| 4 | MIAMI | 7890 | 13740 | 13710 | 6800 | 20510 | 1.05462 | 1.360 | 1.24860 |
| 5 | CHICAGO | 31970 | 26070 | 14500 | 6940 | 21440 | 1.11538 | 1.388 | 1.23784 |
| 6 | NEW-YORK | 78010 | 49710 | 13430 | 6990 | 20420 | 1.03308 | 1.398 | 1.17511 |
| 7 | PHILADEL | 16680 | 22120 | 11910 | 6850 | 18760 | 0.91615 | 1.370 | 1.17489 |
| 8 | SEATTLE | 17190 | 8820 | 15080 | 5980 | 21060 | 1.16000 | 1.196 | 1.17221 |
| 9 | ATLANTA | 22970 | 9790 | 13920 | 6570 | 20490 | 1.07077 | 1.314 | 1.14346 |
| 10 | DETROIT | 22020 | 21670 | 13430 | 6160 | 19590 | 1.03308 | 1.232 | 1.13174 |
| 11 | HOUSTON | 27100 | 10190 | 15140 | 5150 | 20290 | 1.16462 | 1.030 | 1.12783 |
| 12 | SAN-DIEG | 25040 | 8850 | 14770 | 5460 | 20230 | 1.13615 | 1.092 | 1.12462 |
| 13 | TAMPA | 3440 | 4070 | 11860 | 6500 | 18360 | 0.91231 | 1.300 | 1.12242 |
| 14 | SACRAMEN | 8420 | 6660 | 12470 | 6340 | 18810 | 0.95923 | 1.268 | 1.09560 |
| 15 | PORTLAND | 7100 | 3280 | 13150 | 6250 | 19400 | 1.01154 | 1.250 | 1.08689 |
| 16 | BOSTON | 22720 | 12860 | 15040 | 4780 | 19820 | 1.15692 | 0.956 | 1.08430 |
| 17 | PHOENIX | 5550 | 16680 | 10670 | 5790 | 16460 | 0.82077 | 1.158 | 1.07381 |
| 18 | ST-LOUIS | 17390 | 11470 | 11710 | 6570 | 18280 | 0.90077 | 1.314 | 1.06500 |
| 19 | NASHVILL | 5250 | 5390 | 11930 | 5890 | 17820 | 0.91769 | 1.178 | 1.04956 |
| 20 | DENVER | 10490 | 10450 | 12200 | 5690 | 17890 | 0.93846 | 1.138 | 1.03804 |
| 21 | DALLAS | 22380 | 8150 | 13360 | 4810 | 18170 | 1.02769 | 0.962 | 1.01016 |
| 22 | AUSTIN | 5220 | 2070 | 12430 | 4920 | 17350 | 0.95615 | 0.984 | 0.96406 |
| 23 | CLEVELAN | 12670 | 5010 | 12800 | 4510 | 17310 | 0.98462 | 0.902 | 0.96120 |
| 24 | PITTSBUR | 7380 | 10630 | 7770 | 6020 | 13790 | 0.59769 | 1.204 | 0.95555 |
| 25 | BALTIMOR | 13920 | 9160 | 11500 | 5260 | 16760 | 0.88462 | 1.052 | 0.95105 |
| 26 | MILWAUKE | 7140 | 4730 | 12200 | 4770 | 16970 | 0.93846 | 0.954 | 0.94465 |
| 27 | ALBUQUER | 2230 | 3390 | 11130 | 4840 | 15970 | 0.85615 | 0.968 | 0.92362 |
| 28 | LOUISVIL | 6040 | 2860 | 10690 | 5610 | 16300 | 0.82231 | 1.122 | 0.91861 |
| 29 | MEMPHIS | 3950 | 4050 | 10390 | 5030 | 15420 | 0.79923 | 1.006 | 0.90391 |
| 30 | FORTWORT | 11150 | 4200 | 11150 | 4860 | 16010 | 0.85769 | 0.972 | 0.88897 |
| 31 | MINNESOT | 16420 | 5300 | 11440 | 4530 | 15970 | 0.88000 | 0.906 | 0.88634 |
| 32 | CINCINNA | 9750 | 3440 | 11540 | 4320 | 15860 | 0.88769 | 0.864 | 0.88151 |
| 33 | SANANTON | 9050 | 4990 | 11040 | 4660 | 15700 | 0.84923 | 0.932 | 0.87865 |
| 34 | INDIANAP | 7750 | 3940 | 10760 | 4640 | 15400 | 0.82769 | 0.928 | 0.86150 |
| 35 | OKLAHOMA | 6620 | 3450 | 9390 | 5260 | 14650 | 0.72231 | 1.052 | 0.83526 |
| 36 | SALTLAKE | 4080 | 1910 | 8490 | 5460 | 13950 | 0.65308 | 1.092 | 0.79303 |
| 37 | CORPUS_C | 1510 | 1440 | 8160 | 4500 | 12660 | 0.62769 | 0.900 | 0.76062 |
| 38 | EL_PASO | 3320 | 3110 | 9490 | 3860 | 13350 | 0.73000 | 0.772 | 0.75031 |
| 39 | KANSAS_C | 12220 | 4490 | 9090 | 4300 | 13390 | 0.69923 | 0.860 | 0.74243 |

desirable average.

The major factors of influence on the RCIW are established based on the correlation values. It is necessary to know this information about any urban area, especially the earthquake-borne cities because it would help the planners in knowing the critical factors contributing to the congestion in their areas. In order to establish the reliance of the parameters on the RCIW value and thus the roadway congestion, regression analysis was done and General Linear Models (GLM) procedure of Statistical Analysis System (SAS) was used. RCIW was the dependent variable and DVMT per lane-mile values of both the freeway and the principal arterial (independent variables) were forced into the model to determine the worthiness of the variables.

### *5.3.1 Relationship between RCIW & DVMT/Ln-Mile of Freeway*

The relation between the RCIW value and DVMT per lane-mile values of freeway (DVMTLMF) and the arterial were established based on the plots and the regression analysis results. With the DVMT per lane-mile value of freeway as the independent variable and RCIW as the dependent variable, the results are shown in Table 10. The plot of RCIW vs DVMT per lane-mile of freeway is shown in Figure 29. The $R^2$ value worked out to be 0.753 which is good because it means that 76% of the total variation by regression is explained by the model which has DVMTLMF as the independent variable. Also, the F-value is high (112.75) with PR>F equal to 0.0001 which means that the model is significant; however, these are only statistical inferences. Looking at the plot DVMTLMF vs. RCIW, the trend indicates that if a line were to be fitted, it would have a positive slope and most points would lie close to it. But for a few outliers, the general relationship can be taken as linear.

## Table 10. Regression results of RCIW vs DVMTLMF

General Linear Models Procedure

Dependent Variable: RCIW

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 1 | 0.86612869 | 0.86612869 | 112.75 | 0.0001 |
| Error | 37 | 0.28421624 | 0.00768152 | | |
| Corrected Total | 38 | 1.15034493 | | | |

| R-Square | C.V. | Root MSE | RCIW Mean |
|---|---|---|---|
| 0.752930 | 8.509455 | 0.08764428 | 1.02996348 |

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| DVMTLMF | 1 | 0.86612869 | 0.86612869 | 112.75 | 0.0001 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| DVMTLMF | 1 | 0.86612869 | 0.86612869 | 112.75 | 0.0001 |

| Parameter | Estimate | T for H0: Parameter=0 | Pr > \|T\| | Std Error of Estimate |
|---|---|---|---|---|
| INTERCEPT | 0.2996851732 | 4.27 | 0.0001 | 0.07019080 |
| DVMTLMF | 0.0000591454 | 10.62 | 0.0001 | 0.00000557 |

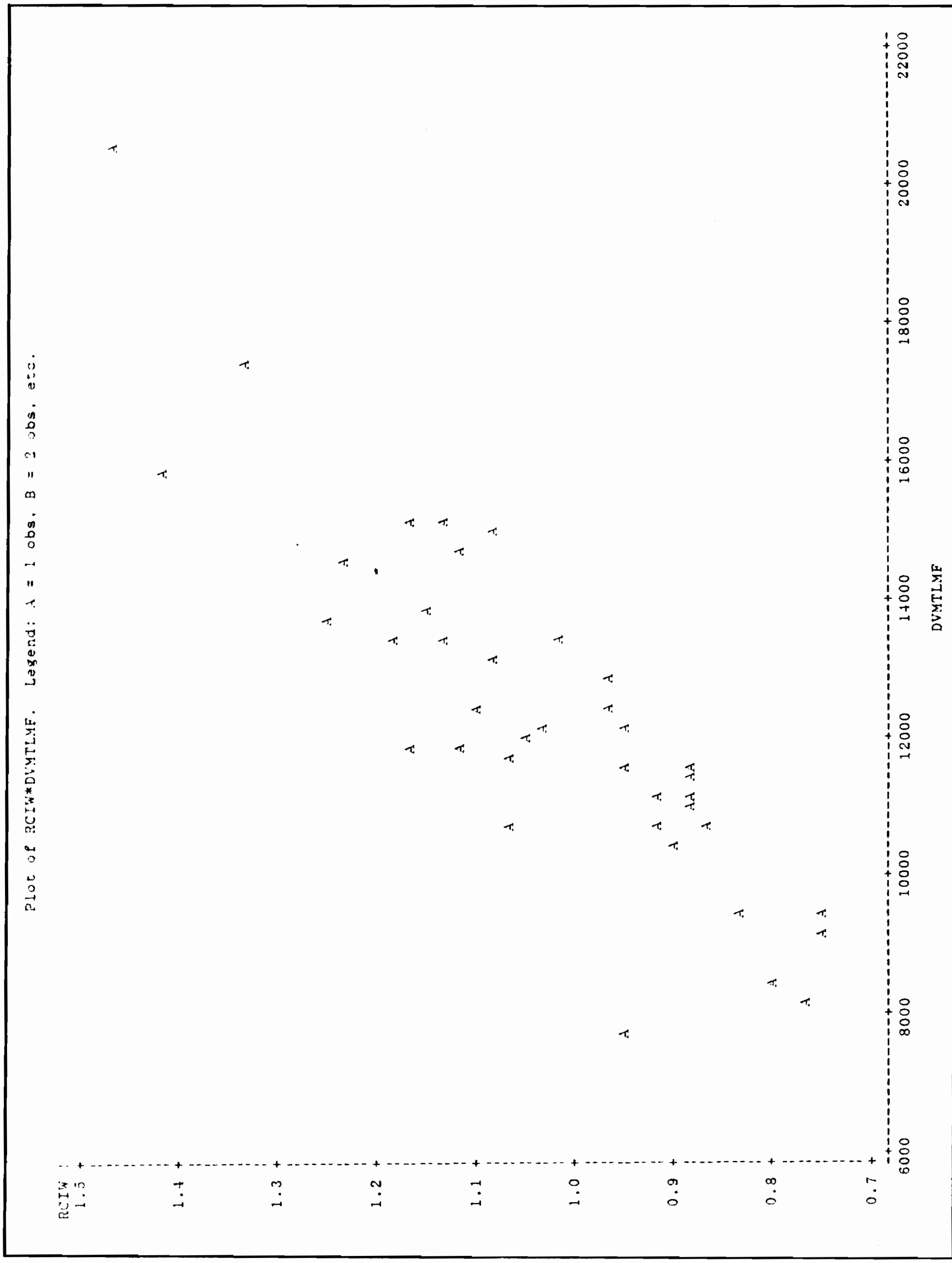



Figure 29. Plot of RCIW vs DVMTLMF

### *5.3.2 Relationship between RCIW & DVMT/Ln-Mile of Arterials*

In order to establish the relationship between RCIW and DVMT per lane-mile of arterial, the results as shown in Table 11 were interpreted while the plot of RCIW vs. DVMT per lane-mile of arterial is shown in Figure 30. The $R^2$ value was 0.685 and the F-value was 80.45. But, looking at the plot, the trend indicates that there would be too many outliers if a line were to be fitted; the relationship cannot be assumed as linear as well.

### *5.3.3 Correlation Analysis*

When stepwise regression was performed with RCIW as the dependent variable and DVMT per lane-mile values of freeway and arterial as independent variables, only the variable DVMTLMF entered the model at 0.15 significance level. The correlation analysis results are as shown in Table 12. DVMT per lane-mile of freeway has a higher Pearson Correlation Coefficient (0.8677) with RCIW when compared with DVMT per lane-mile of arterial's coefficient of 0.82763. Based on the plots and the GLM procedure results, it can be interpreted that DVMT per lane-mile of freeway plays a major role in the congestion of major cities. It can also be concluded that most of the urban areas rely primarily on freeways for moving vehicular traffic.

## 5.4 RCIW Values After Scenario Analysis

Scenario analysis was performed only for the San-Francisco - Oakland cities to study the severe problems that may result from the earthquake that is predicted to hit the San Francisco Bay Area. In the likelihood of this event occurring, a scenario analysis was performed to determine the severity of the impact due to the closure of certain critical

## Table 11. Regression results of RCIW vs DVMTLMA

General Linear Models Procedure

Dependent Variable: RCIW

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 1 | 0.78794493 | 0.78794493 | 80.45 | 0.0001 |
| Error | 37 | 0.36240000 | 0.00979459 | | |
| Corrected Total | 38 | 1.15034493 | | | |

| R-Square | C.V. | Root MSE | RCIW Mean |
|---|---|---|---|
| 0.684964 | 9.608850 | 0.09896764 | 1.02996348 |

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| DVMTLMA | 1 | 0.78794493 | 0.78794493 | 80.45 | 0.0001 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| DVMTLMA | 1 | 0.78794493 | 0.78794493 | 80.45 | 0.0001 |

| Parameter | Estimate | T for H0: Parameter=0 | Pr > \|T\| | Std Error of Estimate |
|---|---|---|---|---|
| INTERCEPT | 0.2035997802 | 2.18 | 0.0359 | 0.09348628 |
| DVMTLMA | 0.0001476596 | 8.97 | 0.0001 | 0.00001646 |

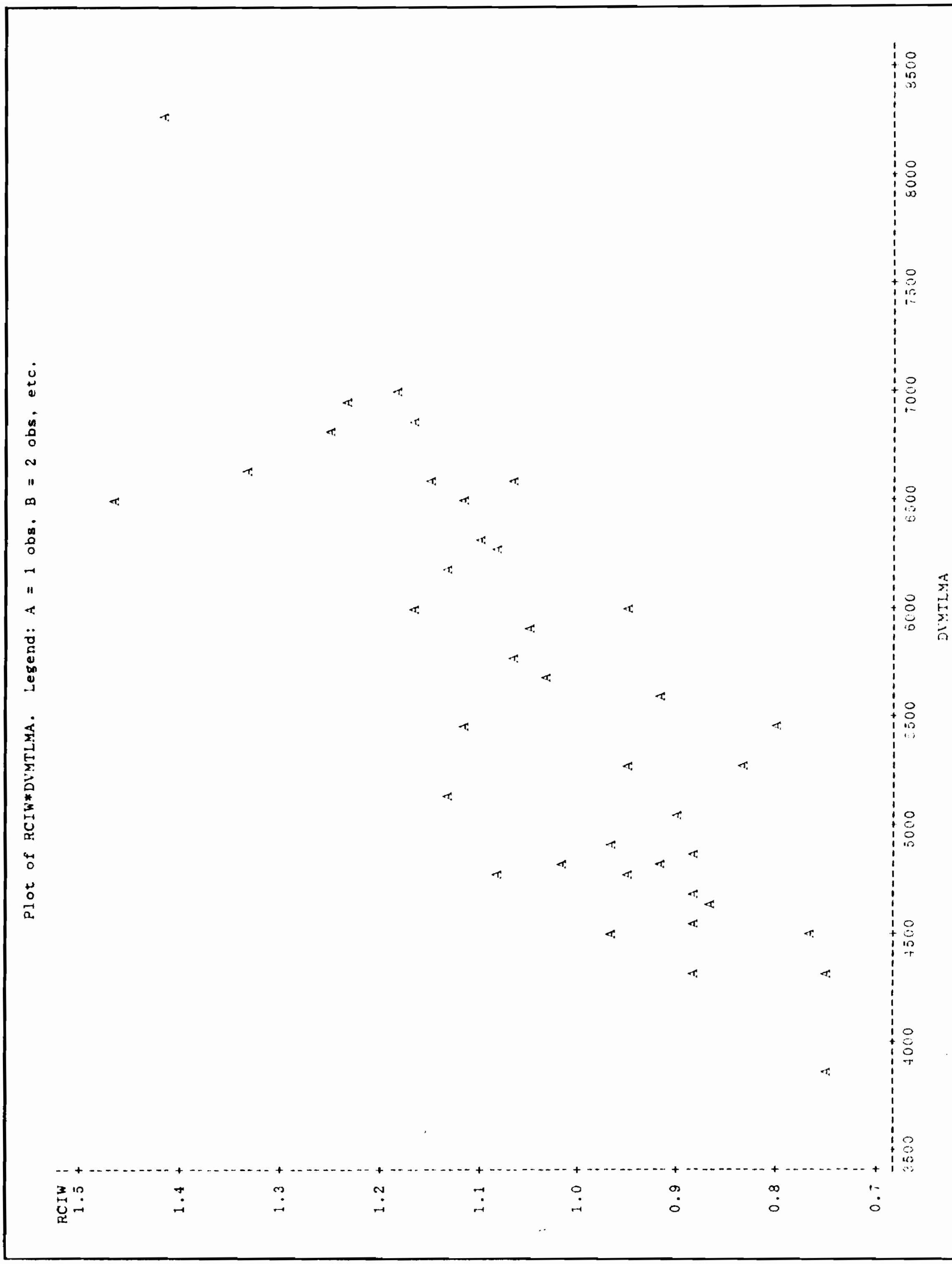



Figure 30. Plot of RCIW vs DVMTLMA

## Table 12. Correlation Analysis of RCIW, DVMTLMF and DVMTLMA

Correlation Analysis

3 'VAR' Variables: RCIW DVMTLMF DVMTLMA

Simple Statistics

| Variable | N | Mean | Std Dev | Sum | Minimum | Maximum |
|---|---|---|---|---|---|---|
| RCIW | 39 | 1.029963 | 0.173989 | 40.168576 | 0.742430 | 1.462463 |
| DVMTLMF | 39 | 12347 | 2552.576561 | 481540 | 7770.000000 | 20590 |
| DVMTLMA | 39 | 5596.410256 | 975.201699 | 218260 | 3860.000000 | 8250.000000 |

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 39

| | RCIW | DVMTLMF | DVMTLMA |
|---|---|---|---|
| RCIW | 1.00000<br>0.0 | 0.86772<br>0.0001 | 0.82763<br>0.0001 |
| DVMTLMF | 0.86772<br>0.0001 | 1.00000<br>0.0 | 0.48723<br>0.0017 |
| DVMTLMA | 0.82763<br>0.0001 | 0.48723<br>0.0017 | 1.00000<br>0.0 |

links. The particular links which are predicted to be closed in this study, are based on the report by U.S. Geological Survey. In the immediate aftermath of the earthquake, due to the closure of certain links, the RCIW value changes, and this changed value is computed using the same equation described earlier in this chapter.

### 5.4.1 Assumptions in the Computation of Changed Values of RCIW

In order to determine the value of the RCIW for San Francisco-Oakland cities, the following assumptions were made:

- The travel patterns of the commuters are assumed beforehand, i.e., if an earthquake hits the Bay Area, what routes will the commuters use for their travel?
- The alternative route due to the closure of a link was assumed to be the nearest freeway link from the closed link in terms of distance. Here it is important to note that BART and Ferries were not assumed as commute alternatives.
- If there is an exit at every 2 miles interval on the freeway, it is assumed that the volume of freeway is 75 percent of all volumes entering the freeway.
- The values of DVMT per lane-mile and lane-miles of freeway and principal arterial are based on 1989 data.

### 5.4.2 Scenario I: Closure of Bay Bridge

In this scenario of closure of the Bay Bridge, the impact was addressed in terms of the changed value of RCIW, which is due to the change in vehicle-miles of travel on the freeway and also the change in lane-miles of freeway. The volumes on the links were based on 1989 traffic volumes for the State of California.

$$
\begin{aligned}
LaneMiles_{DC} &= 2305 - 10*6 \\
&= 2245 \\
DVMTF_{DC} &= 40370K + 240K*(34-6) \\
&= 47090K \\
RCIW_{DC} &= \frac{47090/2245}{13000} * \frac{47090K}{(47090+13540)K} \\
&+ \frac{13540/2005}{5000} * \frac{13540K}{(47090+13540)} \\
&= 1.613*0.7767 + 1.35*0.223 \\
&= 1.553
\end{aligned}
$$

where, DC is Due to Closure

DVMTF is Daily Vehicle Miles of Travel on Freeway

K represents the value in 1,000

The scenario of closure as well as the alternative route is illustrated in Figure 31. Therefore, the changed value of RCIW due to the closure of the Bay Bridge has been calculated to be 1.553.

### *5.4.3 Scenario II: I-880 Closure*

The predicted closure is from Oakland's Market Street to the Intersection with I-238 at San Lorenzo. Here, the volume on the freeway I-880 was 226,000 ADT. The changed value of RCIW was computed due to I-880's closure.

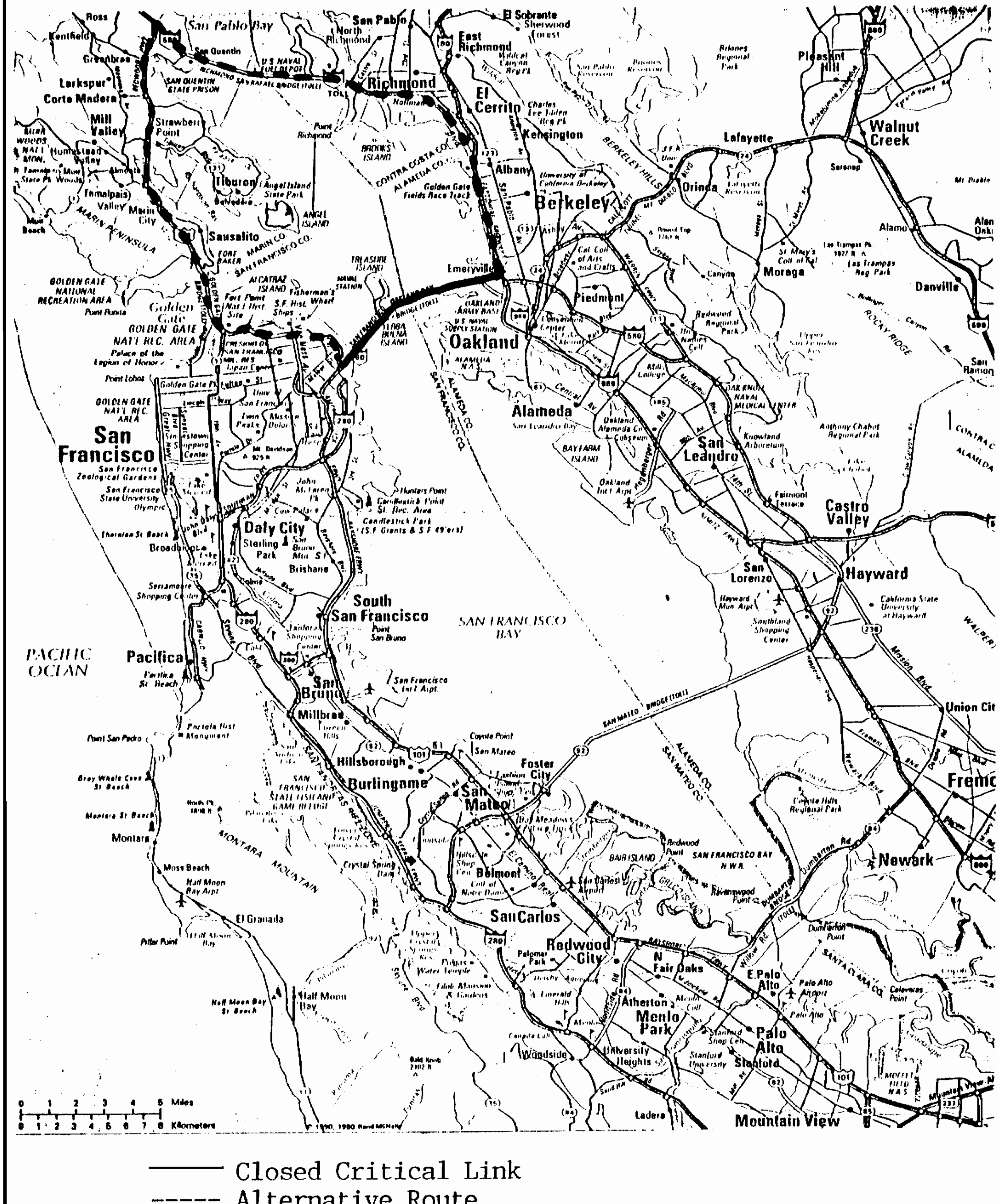



**Figure 31. Scenario of closure of Bay Bridge and the alternative route**

$$
\begin{aligned}
LaneMiles_{DC} &= 2305 - 8*13 \\
&= 2201 \\
DVMTF_{DC} &= 40370K + 226K*(18-13)*(1 - \frac{6}{13*2}) \\
&= 41240K \\
DVMTA_{DC} &= 13540K + 226K*(18-13)(\frac{6}{13*2}) \\
&= 13800K \\
RCIW_{DC} &= \frac{41240/2201}{13000} * \frac{41240K}{(41240 + 13800)K} \\
&+ \frac{13800/2005}{5000} * \frac{13800K}{41240 + 13800} \\
&= 1.441*0.7493 + 1.377*0.251 \\
&= 1.426
\end{aligned}
$$

where, DVMTA represents Daily Vehicle Miles of Travel on the Arterial

The RCIW value due to closure of I-880 is 1.426. I-880's closure and the alternative route are depicted in Figure 32.

### *5.4.4 Scenario III: Closure of Bay Bridge & Golden Gate Bridge*

In the case of the closure of Bay Bridge as well as the Golden Gate Bridge, the alternative route for commuters to Oakland would be through the Hayward-San Mateo Bridge. The scenario, along with the alternative route, are shown in Figure 33. The number of lanes on the Golden Gate is 6 whereas the Bay Bridge has 10 lanes. The volume on the Golden Gate Bridge is 124,000.

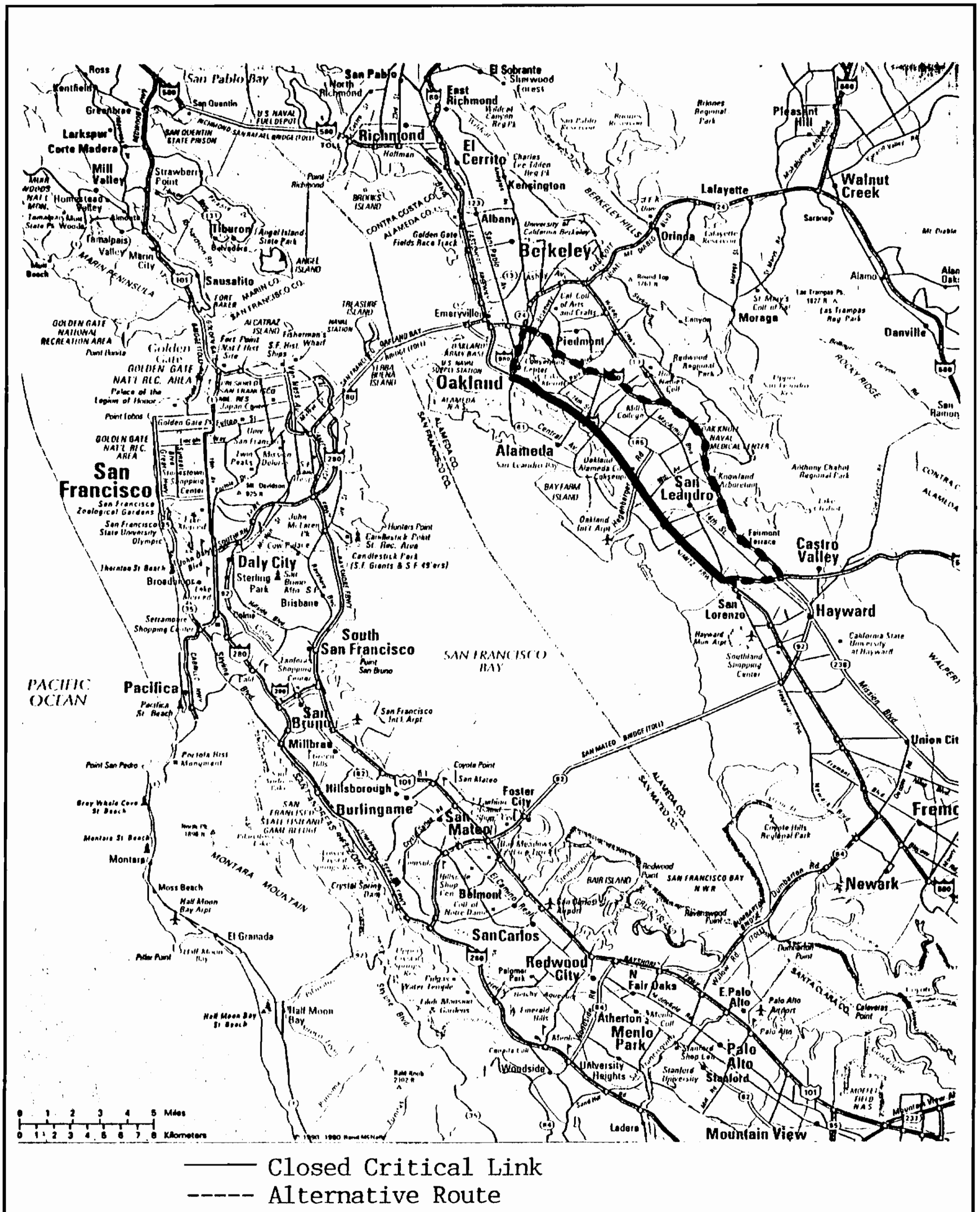
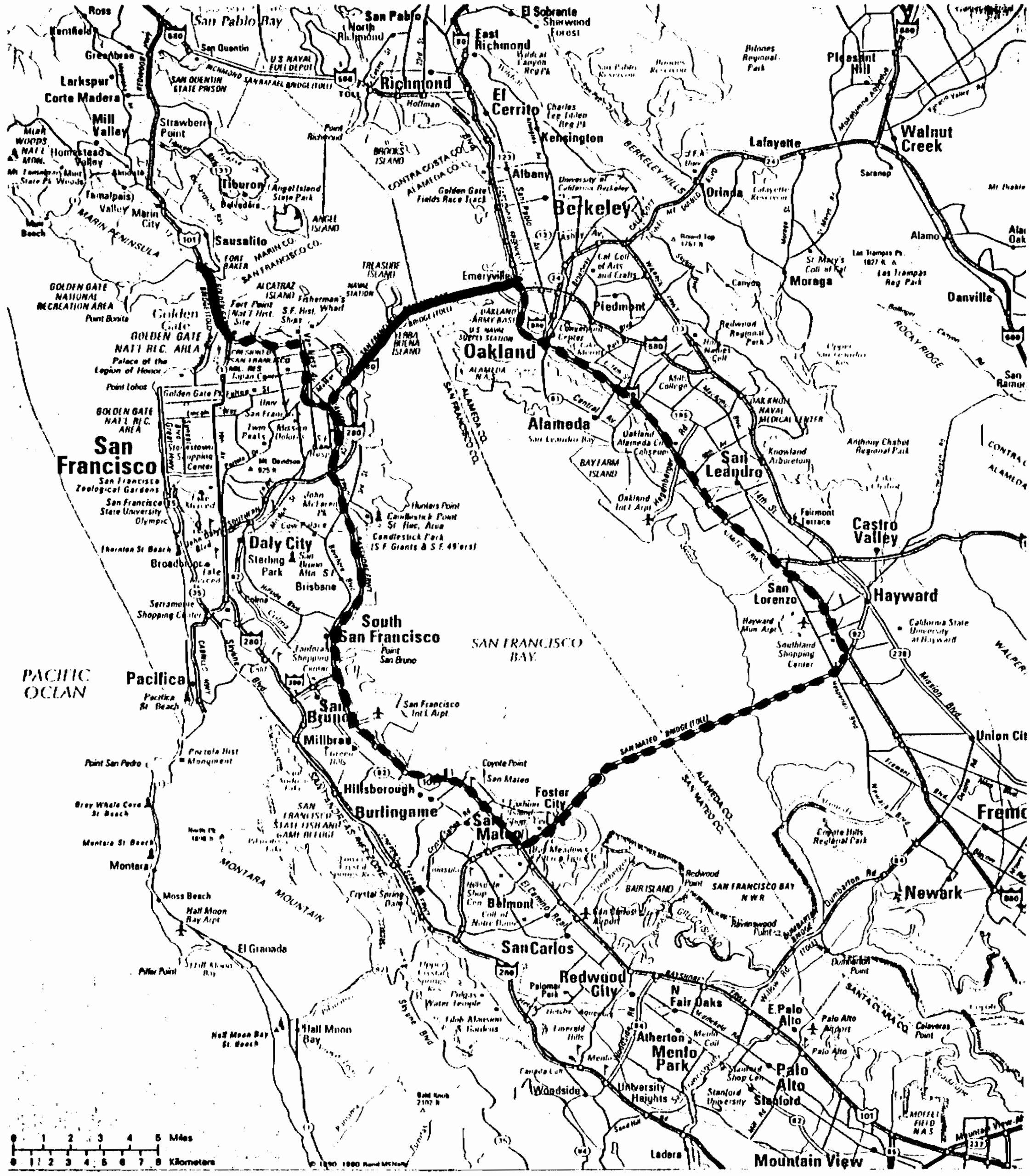



Figure 32. Scenario of closure of I-880 with the alternative route




——— Closed Critical Link

----- Alternative Route

**Figure 33. Scenario of closure of Bay Bridge and Golden Gate Bridge**

$$
\begin{aligned}
LaneMiles_{DC} &= 2305 - 10*6 - 6*20 \\
&= 2125 \\
DVMTF_{DC} &= 40370K + 240K*(54-6) + 124K(70-20) \\
&= 58090K \\
RCIW_{DC} &= \frac{58090/2125}{13000} * \frac{58090K}{(58090 + 13540)K} \\
&+ \frac{13540/2005}{5000} * \frac{13540K}{58090 + 13540} \\
&= 2.1*0.811 + 1.351*0.189 \\
&= 1.958
\end{aligned}
$$

Scenario III seems to be the worst case scenario based on the changed values of the RCIW. **It is very important to note that the RCIW value represents the entire area and not site specific locations, i.e. bridges or other points of congestion.** Hence, the RCIW calculated by performing scenario analysis does not really indicate the exact severity of the closure of critical links. In other words, it does not represent the congestion on a particular link. It is also necessary to observe here that the RCIW is based on an area-wide freeway and principal arterial street travel. Therefore, if a large percentage of the freeways or principal arterial street systems have "good" operational characteristics, the effect of bottlenecks and other sites of congestion may be underestimated.

## 5.5 Relationship between RCIW and Network Parameters

The structure of the network also contributes to the congestion of major cities. In order to establish the relationship between RCIW and a few but critical network parameters, regression analysis was performed using RCIW as the dependent variable.

The number of freeway exits, the number of freeway links, i.e., the segments of the freeway to be travelled before reaching another freeway, lane miles and various other parameters are the inputs. An attempt is made to establish the relationship between the network's structural parameters and the Weighted Roadway Congestion Index of earthquake-borne cities, like Los Angeles, San Francisco-Oakland, Sacramento, Memphis, Dallas, Seattle and Chicago. Correlation analysis is done to establish the relationship between the dependent variable RCIW and the various network structure's parameters.

### *5.5.1 Regression Analysis*

With the RCIW value as the dependent variable, the number of lane-miles per exit and the number of lane-miles per freeway link, were forced into the model using the GLM procedure in SAS to check the relationship with RCIW. The values of the number of exits and links for all 7 cities were determined using the Rand McNally maps. A freeway link was defined as the nearest freeway that can be reached while travelling on another freeway. An attempt was also made to relate other network parameters individually, such as, the number of freeway exits, the number of freeway links, the number of lane-miles etc. Table 13 shows the values of the number of exits and links of the 7 cities which were considered for the study. The results of the GLM procedure with RCIW as the dependent variable and the number of lane-miles/exit (RRATIO in the output) as the independent variable, are shown in Table 14. The $R^2$ value for the model was calculated to be 0.898926 which means that 89.9% of the total variation in the RCIW value is explained by the model, which is very good since $R^2$ value represents the coefficient of determination and its square root, i.e., the value of R represents the coefficient of correlation. In this case, it means that the independent variable is highly collinear with the dependent

**Table 13. Values of Exits, Links and Ln-Miles for 7 earthquake-borne cities**

| OBS | CITY | EXITS | LINKS | LNMIS | RRATIO | RRATIO1 |
|---|---|---|---|---|---|---|
| 1 | LOS_ANGE | 220 | 100 | 4880 | 22.1318 | 43.8000 |
| 2 | SANFRAN_ | 114 | 40 | 2305 | 20.2193 | 57.6250 |
| 3 | SACRAMEN | 46 | 16 | 660 | 14.3478 | 41.2500 |
| 4 | MEMPHIS | 39 | 3 | 275 | 7.0513 | 34.3750 |
| 5 | CHICAGO | 116 | 33 | 2260 | 19.4828 | 68.4848 |
| 6 | SEATTLE | 60 | 30 | 1140 | 19.0000 | 38.0000 |
| 7 | DALLAS | 133 | 33 | 1640 | 12.3308 | 49.6970 |

**Table 14. Results of GLM procedure with RCIW and No. of Ln-Miles/exit**

General Linear Models Procedure

Dependent Variable: RCIW

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 1 | 0.19628900 | 0.19628900 | 44.47 | 0.0011 |
| Error | 5 | 0.02207047 | 0.00441409 | | |
| Corrected Total | 6 | 0.21835947 | | | |

| R-Square | C.V. | Root MSE | RCIW Mean |
|---|---|---|---|
| 0.898926 | 5.661448 | 0.06643865 | 1.17352743 |

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| RRATIO | 1 | 0.19628900 | 0.19628900 | 44.47 | 0.0011 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| RRATIO | 1 | 0.19628900 | 0.19628900 | 44.47 | 0.0011 |

| Parameter | Estimate | T for H0: Parameter=0 | Pr > \|T\| | Std Error of Estimate |
|---|---|---|---|---|
| INTERCEPT | 0.6211141947 | 7.18 | 0.0008 | 0.08656182 |
| RRATIO | 0.0337384528 | 6.67 | 0.0011 | 0.00505939 |

variable and is a very important variable for the model. Also, the F-value is reasonably good at 44.67, with 'PR>F' equal to 0.0001 which means that the model is significant. The above inferences are just the statistical inferences. The plot of RCIW vs. Number of lane-miles/exit (RRATIO) is shown in Figure 34. Looking at the plot RCIW vs RRATIO, the trend indicates that if a line were to be fitted, it would have a positive slope. It can be concluded that as the number of lane-miles to be travelled before reaching an exit increases, the RCIW value increases. The model of RCIW with the Number of lane-miles/exit as the independent variable is shown below:

$$RCIW = 0.03373845 * \frac{Ln\text{-}Miles}{No.\ of\ Exits} + 0.62111419$$

### *5.5.2 Relationship Between RCIW & Number of Lane-Miles/Freeway Link*

The results of the GLM procedure with RCIW as the dependent variable and the number of lane-miles/freeway link (RRATIO1 in the output) are detailed in Table 15. The $R^2$ value was 0.266 which is very low and the F-value was also considerably low at 1.81. The plot of RCIW vs number of lane-miles per link is illustrated in Figure 35. The plot doesn't explain any trend between the RCIW and the number of lane-miles per freeway link. When both the independent variables were forced into the model to add another dimension, there was a very slight improvement in the $R^2$ value which is insignificant.

### *5.5.3 Correlation Analysis*

It was found that the dependent variable, RCIW, has the highest correlation of

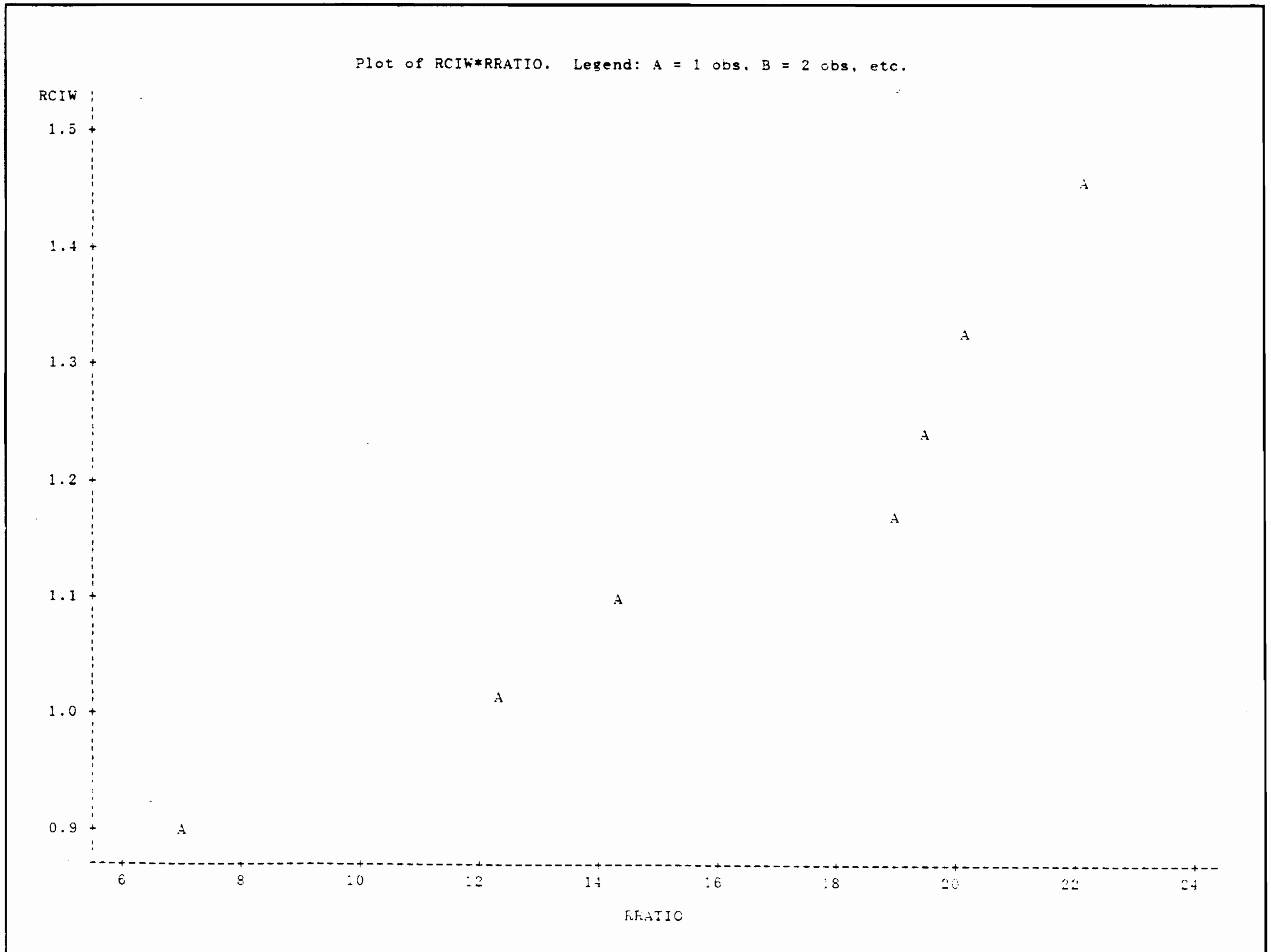


Figure 34. Plot of RCIW vs No. of Ln-Miles/exit

**Table 15. Regression results of RCIW and No. of Ln-Miles/Link**

General Linear Models Procedure

Dependent Variable: RCIW

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 1 | 0.05813912 | 0.05813912 | 1.81 | 0.2358 |
| Error | 5 | 0.16022034 | 0.03204407 | | |
| Corrected Total | 6 | 0.21835947 | | | |

| | R-Square | C.V. | Root MSE | RCIW Mean |
|---|---|---|---|---|
| | 0.266254 | 15.25389 | 0.17900857 | 1.17352743 |

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| RRATIO1 | 1 | 0.05813912 | 0.05813912 | 1.81 | 0.2358 |

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| RRATIO1 | 1 | 0.05813912 | 0.05813912 | 1.81 | 0.2358 |

| Parameter | Estimate | T for H0: Parameter=0 | Pr > \|T\| | Std Error of Estimate |
|---|---|---|---|---|
| INTERCEPT | 0.7730358516 | 2.54 | 0.0522 | 0.30492706 |
| RRATIO1 | 0.0082885195 | 1.35 | 0.2358 | 0.00615342 |

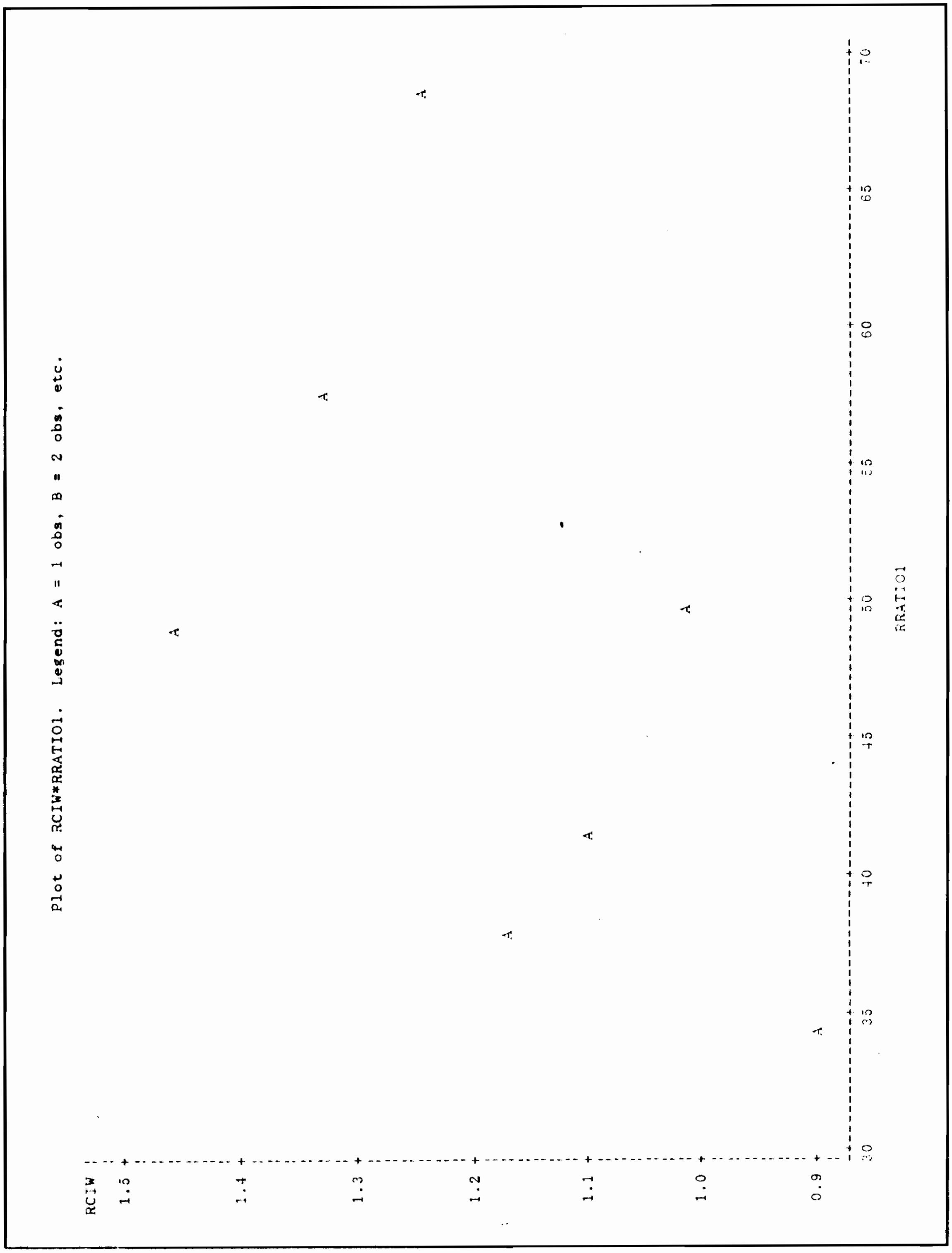



**Figure 35. Plot of RCIW vs RRATIO1**

0.948 with the independent variable, the number of lane-miles/exit. Hence, they are highly collinear and the number of lane-miles/exit is the desirable independent variable. This fact was also endorsed by the plots we saw earlier. The correlation between the number of lane-miles/exit and the number of lane-miles/freeway link is insignificant since the plot of RCIW vs RRATIO1 does not show a linear trend. The correlation analysis results are shown in Table 16. It can be concluded that the dependent variable, RCIW, and the number of lane-miles/exit as the independent variable, formulate the best model for RCIW computations.

## Table 16. Correlation Analysis of RCIW, RRATIO and RRATIO1

Correlation Analysis

3 'VAR' Variables: RCIW RRATIO RRATIO1

Simple Statistics

| Variable | N | Mean | Std Dev | Sum | Minimum | Maximum |
|---|---|---|---|---|---|---|
| RCIW | 7 | 1.173527 | 0.190770 | 8.214692 | 0.903908 | 1.462463 |
| RRATIO | 7 | 16.373401 | 5.361017 | 114.613810 | 7.051282 | 22.181818 |
| RRATIO1 | 7 | 48.318831 | 11.876313 | 338.231818 | 34.375000 | 68.484848 |

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 7

| | RCIW | RRATIO | RRATIO1 |
|---|---|---|---|
| RCIW | 1.00000<br>0.0 | 0.94812<br>0.0011 | 0.51600<br>0.2358 |
| RRATIO | 0.94812<br>0.0011 | 1.00000<br>0.0 | 0.55736<br>0.1936 |
| RRATIO1 | 0.51600<br>0.2358 | 0.55736<br>0.1936 | 1.00000<br>0.0 |

# 6.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this chapter is to present a comprehensive view of the purpose of the study and the analyses, which were conducted to fulfill the objectives of the research. It contains three sections; summary, conclusions and recommendations for further research. Conclusions about the Loma Prieta Earthquake, the "Big One" scenario, RCIW determined using the vehicle-miles of travel and from the network's structural parameters are provided in detail.

## 6.1 Summary

The lack of a comprehensive and simple model to assess the severity of the closure of certain critical links in the aftermath of big earthquakes led to the development of the macro-level measure which was termed, the Weighted Roadway Congestion Index.

The measure was applied to three hypothetical scenarios of closures of critical links in the San Francisco Bay Area. It was also tested by developing a regression model with the number of lane-miles per exit of 7 earthquake-borne cities.

Another objective of this thesis was to appraise the transportation actions taken by the authorities in the immediate aftermath of the Loma Prieta Earthquake of October 17, 1989. Emphasis was placed on the travel demand management strategies adopted to meet the travel needs in the Bay Area and to return traffic to normalcy. The transportation problems that the Bay Area will face if the "Big One" hits were also considered in detail during the course of this research.

## 6.2 Conclusions

Although Loma Prieta earthquake was termed the "Transportation Earthquake," the transportation problems were not significant.

- All disaster sites were accessible.
- The disruptions in traffic circulation were minimal.
- The transportation services were adequate to cope with the adjusted demand.
- The transportation authorities worked hard to return traffic to normalcy and the TDM strategies adopted by them were very effective.

For automobile traffic, the Golden Gate and Bay Bridges are essentially non-redundant systems, with alternative routes, via the other bridges, being very time consuming to a degree that seriously impacts commercial and institutional productivity. In contrast to freeways, which are superimposed over an existing (if inadequate) road pattern that is still available if a section of freeway is knocked out, the bridges have no satisfactory alternative, except planning for another bridge across the bay.

The size and magnitude of the problem in terms of the growth expressed as population, auto ownership, and autos per center-line mile for the year 2010, should give an idea of the problem in the East and as well as the West Bay areas.

Based on the results obtained from the study and analysis pertaining to the roadway congestion index, the following conclusions are drawn:

1. A macro level measure to address the severity of the problem in the case of

closure of certain critical links has been successfully developed.

2. Vehicle-miles of travel on the freeway is very much influential on the Weighted Roadway Congestion Index, whereas the vehicle-miles of travel on the arterial is not highly correlated with RCIW. In other words, almost all the urban areas rely heavily on the freeway system to move vehicular traffic,

3. Scenario analyses were performed to highlight the importance of certain critical links. It is very important to note that the RCIW value is an aggregate measure, i.e., for the whole urban area and does not address the severity of congestion on a particular link.

4. RCIW also depends on the network's structural parameter, i.e., the number of freeway lane-miles per exit. This was established after performing regression analysis with RCIW as the dependent variable and other independent variables.

## 6.4 Recommendations for Further Research

A major contingency planning effort should be undertaken to develop alternative routes and procedures considering a number of alternative post-earthquake closure patterns.

The macro-level measure developed is a rough and quick estimate of the congestion level in any urban area. The methodology adopted does not incorporate the traffic signal system operation and the role of transit. Since these factors affect urban mobility, their complex effects should be included to develop a better representation of the severity of the problem.

There is also a need to determine the real-time traffic diversion strategies after an earthquake. Further studies should also concentrate on simulating on a real-time basis, various traffic diversion strategies and identify the most effective sets of diversions for the management of transportation activities in the aftermath of the disaster.

Another study could be limited to just emergency response operations in the Bay Area, like the dispatch of emergency vehicles, rescue operations and prioritization of street cleanups etc. The study can basically deal with whether the Bay Area's emergency staff can handle the "Big One" or not and also whether any emergency locations will be affected by the earthquake, like the fault crossing hospitals, fire stations etc.

The travel patterns were assumed by the author while performing scenario analysis for the "Big One" in the San-Francisco Bay Area. However, if the actual alternative routes were to be found out by real-time simulation, the RCIW will be very effective in addressing the severity of the problem.

Further study of these recommendations could be of great value to the San-Francisco Bay Area, as a matter of fact for any earthquake-borne city.

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# *APPENDIX A. ESTIMATED AND PROJECTED BIRTHS, DEATHS AND MIGRATION*

To create projections for the year 2010, the demographic assumptions concern fertility, births, deaths, migration. Since 1980 the period fertility rate has been increasing. ABAG used period fertility rates in its models. Table 1. indicates the period fertility rates for the San Francisco Bay Region. Table 2. identifies projected births in the nine-county region between 1986-2005.

Mortality rates are actually increasing as shown in Table 3. Table 4. shows ABAG's migration estimates for the period 1991-2005. Net regional migration is expected to be about 381,000 individuals between 1991-2005. Since total births are projected to be about 1.3 million between 1991-2005, net regional migration will represent about 22 percent of gross population growth (births plus migration) in the nine-county region.

**Table 1. Period Fertility Rates - San Francisco Bay Region**

Period Fertility Rates
San Francisco Bay Region
1970 - 2005

| Period | Region | California |
|---|---|---|
| *Actual* | | |
| 1970 | 2.09 | 2.35 |
| 1977 | 1.54 | 1.77 |
| 1980 | 1.62 | 1.91 |
| 1984 | 1.80 | N.C. |
| 1985 | 1.89 | N.C. |
| *Estimated* | | |
| 1985 - 1990 | 1.93 | N.C. |
| *Projected* | | |
| 1991 - 2005 | 1.90 | N.C. |

Note: N.C. = Not Calculated

Table 2. Estimated and Projected Births - San Francisco Bay Region

**Estimated and Projected Births**
**San Francisco Bay Region**
**1986 - 2005**

| Period | Births | Average Per Year |
|---|---|---|
| *Estimated* | | |
| 1986 - 1990 | 463,500 | 92,700 |
| *Projected* | | |
| 1991 - 1995 | 451,850 | 90,370 |
| 1996 - 2000 | 439,850 | 87,970 |
| 2001 - 2005 | 422,500 | 84,500 |

Table 3. Estimated and Projected Deaths - San Francisco Bay Region

**Estimated and Projected Deaths**
**San Francisco Bay Region**
**1986 - 2005**

| Period | Deaths | Average Per Year |
|---|---|---|
| *Estimated* | | |
| 1986 - 1990 | 219,500 | 43,900 |
| *Projected* | | |
| 1991 - 1995 | 239,650 | 47,930 |
| 1996 - 2000 | 273,500 | 54,700 |
| 2001 - 2005 | 300,150 | 60,030 |

Table 4. Estimated and Projected Net Migration - San Francisco Bay Region

**Estimated and Projected Net Migration**
**San Francisco Bay Region**
**1986 - 2005**

| Period | Migration | Average Per Year |
|---|---|---|
| *Estimated* | | |
| 1986 - 1990 | 169,300 | 33,860 |
| *Projected* | | |
| 1991 - 1995 | 129,500 | 25,900 |
| 1996 - 2000 | 151,500 | 30,300 |
| 2001 - 2005 | 100,000 | 20,000 |

# *VITA*

Mr. Lakshminarayana Manchikalapudi was born on October 5, 1966 in Mothadaka, India. He was brought up in Hyderabad, where he did most of his schooling. Later, he joined Jawaharlal Nehru Technological University in order to pursue a career in engineering. He obtained bachelor's degree in Civil Engineering in July 1988. After graduating, he started working in a private consulting firm in Hyderabad, India. He joined Virginia Polytechnic Institute & State University in Fall 1989 for Master's program in Civil Engineering with Transportation as major. Upon graduation, he will be working in a traffic/transportation engineering firm in order to gain practical experience.

L.N. Manchi Kalapudi.