Measuring Post-Disaster Transportation System Performance:

The 1995 Kobe Earthquake in Comparative Perspective

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ABSTRACT

Recent earthquake disasters have caused major damage to transportation networks, leading to significant economic disruption. While this suggests the need to evaluate total system performance in transportation risk assessment, in addition to examining the vulnerability of individual components such as bridges, no appropriate measures currently exist. This paper develops post-disaster system performance measures and applies them to the urban rail and highway transportation systems in the Kobe, Japan, region devastated by the 1995 Hyogoken-Nanbu earthquake. Performance is evaluated in terms of network coverage and transport accessibility. Performance degradation was much more severe for highways and railways than for other lifeline infrastructure systems. Both transportation systems fared poorly in the disaster, but service restoration proceeded much more rapidly for rail. The restoration of highway system performance correlated closely with the recovery of highway traffic volumes. The paper further develops a measure of subarea transport accessibility and applies this to Kobe's constituent city wards. Results indicate substantial spatial disparity that is maintained throughout the restoration period. Comparisons with the 1989 Loma Prieta and 1994 Northridge earthquakes in the U.S. show that although these disasters caused notable damage to highway bridges, system performance degradation was small in comparison with the Kobe experience. The paper argues that explicitly measuring transportation system performance can greatly facilitate both understanding the effects of historic disasters and preparing for future hazard events.

INTRODUCTION

Recent earthquake disasters have repeatedly demonstrated the seismic vulnerability of urban transportation systems. Spectacular highway bridge failures occurred in the 1989 Loma Prieta event that struck the San Francisco Bay Area, the 1994 Northridge earthquake in the Los Angeles metropolitan area, and the 1995 Hyogoken-Nanbu disaster in the Kobe region of Japan. Highway damage in these earthquakes caused substantial disruption and loss to the regional economies. For instance, Gordon et al. (1998) estimate that of the $6.5 billion in business interruption losses caused by the Northridge earthquake, some $1.5 billion could be ascribed to transportation system damage.

While much attention has been paid to understanding and predicting the performance of individual bridge structures under seismic loading, only recently have researchers begun to evaluate the performance of the transport system as a whole. A recent guidelines document recommended performance criteria for highway bridge structures (Rojahn et al., 1997), but no comparable guidelines exist for overall transportation system performance. Such a systems perspective is necessary for analyzing the impact that highway structures damage will have on regional economies. Studies of systems performance in earthquakes include Wakabayashi and Kameda's work (1992) on network reliability analysis that modeled traffic flow adjustments in Loma Prieta. Basöz and Kiremidjian (1995), in their methodology for bridge retrofit prioritization, utilized a bridge importance measure based on network connectivity analysis. Nojima (1997) proposed road traffic capacity as a basic post-earthquake performance measure for highway systems, where capacity consists of the aggregate flow capacity of links connecting a specific origin-destination pair of nodes. Werner et al. (1997) modeled bridge damage, network traffic flows, and the costs associated with travel time delays. Shinozuka et al. (1998)

further linked traffic flows, transport costs, and regional production losses. None of these studies, however, addressed the problem of how to succinctly measure the seismic performance of the overall transportation system.

System performance measures are important for several reasons. First, they enable comparisons of system conditions across disaster events in different urban areas. They thus facilitate the development of generalized rather than case study understandings of earthquakes and their impacts. Second, they allow comparisons across scenario disaster events for a single study region. With the recent emergence of computerized earthquake loss estimation models, regional disaster scenarios can now be rapidly developed and used for pre-event mitigation planning (see, for example, Eguchi et al., 1997; Werner et al., 1997; Whitman et al., 1997). Summary system performance measures are useful in this context for evaluating the degree of system improvement afforded by various levels of bridge retrofits and other mitigation actions. This aids mitigation prioritization under budget constraints. Performance measures may also facilitate discussions of what levels of risk and potential loss are acceptable or unacceptable. Third, system performance measures can be used in designing efficient post-disaster restoration strategies by prioritizing damage repair such that overall system performance can be optimized. Finally, system performance measures can be implemented for estimating economic impacts in the context of real-time earthquake loss models for emergency response and recovery planning. Summary measures can serve where detailed databases and sophisticated transportation models are not available for rapid post-disaster analysis.

System performance measures have proven useful in evaluating the seismic performance of other lifeline infrastructure systems. For utility lifelines such as water, electric power, natural gas, and telecommunications, performance can be readily measured by the percentage of households in the study area that have lost lifeline service (Takada and Ueno, 1995). This approach cannot be used for transportation systems because transportation service is consumed by an individual user across the network, rather than at a point location. In one study, Chang (1996) developed an area-specific transportation availability measure for economic impact modeling; however, the measure did not consider transportation systems aspects.

Various indicators of transportation quality and accessibility have been developed outside of the context of earthquake disasters. Morris et al. (1979), Pirie (1979), Pooler (1995), and Bruinsma and Rietveld (1998), provide some reviews. These transportation indicators are generally difficult to implement in the post-earthquake case, however, as they require data that are unavailable after a disaster. For instance, Allen et al. (1993) proposed an index for areal transportation quality which requires information on average travel times between all locations comprising an area.

Subsequent sections of this paper develop transportation system performance measures and apply them to evaluate experiences in and gain insights from the three recent earthquake disasters mentioned previously, with emphasis on the Kobe case.

MEASURING SYSTEM PERFORMANCE: THE KOBE CASE

Proposed Performance Measures

In order to effectively compare highway system performance across earthquake disasters, new measures or indices are needed. These measures should be simple to apply and use commonly available data. This facilitates making comparisons across urban areas where data availability may be very different. It is also important for rapid analysis in post-disaster situations. Performance measures traditionally used in transportation engineering are generally inappropriate, as they typically address conditions at individual locations and focus on evaluating traffic congestion. One traditional measure of overall system performance consists of total travel time on the network in vehicle-hours, or the sum of vehicle count over all system links multiplied by travel time on each link. In a post-disaster situation, this measure is not practical because the availability of travel time data (and, often, traffic flow data) is very limited. A post-disaster situation requires performance measures that emphasize physical condition and network functionality.

Three system performance measures are proposed here[1]:

1. Total length of highway open (measure L);
2. Total distance-based accessibility (measure D);
3. Areal distance-based accessibility (measure D_s).

[1] Additional measures based on number of network links open and on the "connected" length of highway open are also presented in an earlier version of this paper (Chang and Nojima, 1997).

Each is estimated as the ratio of post-earthquake to pre-earthquake conditions and ranges from 0 (system non-functional) to 1 (system fully functional). The first two proposed measures pertain to the overall performance of the system. In contrast, the last measure is specific to individual subareas within the study region, such as neighborhoods, and can indicate spatial disparities in transportation performance. The measures are specific to time t after the earthquake.

Measure L reflects the length x of highway in the network that is open to traffic at any point in time t, and is defined as a ratio to the pre-earthquake length open, $\overline{x}$:

$$L(t) = \frac{x(t)}{\overline{x}} \tag{1}$$

Note that performance here is based solely on the extent of damage.

Measure D, on the other hand, is based on minimum network travel distances and thus takes into account both the extent and the location of damage. It attempts to measure changes in accessibility at all nodes on the network:

$$D(t) = \frac{f - A(t)}{f - 1} \tag{2a}$$

where

$$A(t) = \frac{\sum_i \sum_j d_{i,j}(t)}{\sum_i \sum_j \overline{d}_{i,j}} \qquad , 1 \le A \le f \qquad \text{(2b)}$$

f = effective distance multiplier for link closure (scalar)

A = total network accessibility ratio

$d_{i,j}$ = minimum travel distance between nodes i and j on damaged network

$\overline{d}_{i,j}$ = minimum travel distance between nodes i and j on intact network

Here, the basic network is defined as a series of nodes and the links connecting them. For the highway mode, nodes represent on- and off-ramps. In the analysis that follows, other node types such as junctions between highways are modeled but not counted as nodes in the above equations. For the railway mode, nodes are stations.

In a damaged network, the length of any damaged link is multiplied by an "effective distance multiplier" $F(k)$ that depends on the damage state k of the link. The effective distance multipliers are intended to reflect increases in travel times necessary to traverse an area with highway damage. Surface streets may be used to circumvent closed links, for instance, with much higher travel time requirements. For links that are closed due to major damage, $F(k)$ takes on a maximum value of f. However, for damage states where closure is partial or where detours are established, $1<F(s)<f$. Thus, the minimum post-disaster effective distance between nodes i and j can be greater than the pre-disaster distance due to increases in effective distance on the original minimum-distance path. In some cases, the increases in effective distances may be large enough that a different series of links becomes the new minimum-distance path linking the two

nodes. (For methods of calculating minimum distances, see Taaffe et al., 1996). It should be noted that while measure *D* can be defined unambiguously with respect to the network, its values do depend upon arbitrarily defined values of *F(k)*, including *f*. This can be addressed empirically through sensitivity analysis.

In contrast to *L* and *D*, measure D_s pertains to system performance or accessibility from the point of view of subareas such as neighborhoods within the study region. In the Kobe case, subareas are taken to be city wards. Areal serviceability is defined as follows:

$$D_s(t) = \frac{f - A_s(t)}{f - 1} \tag{3a}$$

$$A_s(t) = \frac{1}{n_s} \sum_{i \in N_s} A_i(t) \tag{3b}$$

$$A_i(t) = \frac{\sum_{j \neq i} w_{ij} d_{ij}(t)}{\sum_{j \neq i} w_{ij} \bar{d}_{ij}} \tag{3c}$$

where $D_s(t)$ = accessibility performance measure for area *s* at time *t*

$A_s(t)$ = transport accessibility ratio for area *s* at time *t*

$A_i(t)$ = transport accessibility ratio for node *i* at time *t*

n_s = number of nodes in area *s*

N_s = set of nodes in area *s*

$d_{ij}(t)$ = minimum distance on damaged network from node i to node j at time t

$\overline{d}_{ij}$ = minimum distance on intact network from node i to node j

w_{ij} = destination weight for node j for commuters originating from node i

Note that in contrast to accessibility $A(t)$ for the system, accessibility $A_i(t)$ for nodes is weighted. The destination weights w_{ij} indicate the importance of a particular destination node j to commuters originating from node i. Weights are calculated on the basis of pre-disaster commuter origin-destination data:

$$w_{ij} = \frac{1}{n_r - \boldsymbol{d}_r} \cdot \frac{v_{sr}}{\sum_p v_{sp}} \qquad , i \in N_s, \; j \in N_r \tag{4}$$

where $\boldsymbol{d}_r = \begin{cases} 1 & \text{if } r = s \\ 0 & \text{if } r \neq s \end{cases}$

v_{sr} = commuter traffic volume from subarea s (containing node i) to subarea r (containing node j)

p = index for subareas

n_r = number of nodes in subarea r

N_r = set of nodes in subarea r

$\boldsymbol{d}_r$ = indicator for same origin and destination subarea

and $\sum_j w_{ij} = 1$

Several issues arise in the application of the preceding system performance measures to recent earthquake experiences. The definition of the study network is fundamental yet difficult to maintain in a consistent manner across events and urban areas. Issues include the geographic boundaries of the study area, road classes and routes to be included in the study network, and the definition of nodes and links. Another set of issues arises with regard to the specification of damage (functionality) states, including the definition of damage states, the treatment of detours, and quantification of effective distance parameters $F(k)$. The resolution of these issues is noted below in discussions of the actual earthquake applications.

Aggregate System Performance

The January 17, 1995 Hyogoken-Nanbu earthquake (M=7.2 on the Japan Meteorological Agency (JMA) scale) caused severe damage to highway structures and disruption to the highway network in the Hanshin area including the Hanshin Expressway, Meishin National Expressway and Chugoku National Expressway. The most significant damage occurred to Hanshin Expressway Route 3. Before the earthquake, Route 3 shared approximately 40 percent of east-west corridor traffic at the Ashiya River screen line at the boundary between Kobe and Ashiya cities (average daily traffic (ADT)=252,800), providing an important connection between the Osaka and Kobe metropolitan areas. Approximately half of the 1,175 piers in Hyogo Prefecture suffered major to minor damage. Major damage included turnover of 18 spans at Higashinada-ward in Kobe city and collapse of 10 spans at disparate locations in Nishinomiya and Kobe cities, leaving 13 sections (approximately 28km) closed to traffic. Reopening of small isolated portions began in February 1996, but functional performance in terms of traffic volumes on Route 3 was not much improved because the east-west traffic connection was not yet reestablished. Finally on September 30, 1996, more than 20 months after the earthquake, the entire route was reopened, completing restoration of damage to the entire regional highway system. National Route 43, a surface artery parallel to Route 3, was unfortunately degraded due to reconstruction work on Route 3.

On Hanshin Expressway Route 5 (pre-quake ADT=28,300 at Ashiya River screen line), collapse of the Nishinomiya-ko Bridge and major damage to three bridges occurred. After partial reopening, Route 5 began to serve as a main alternative to Route 3, together with Routes 7 and 16, which did not experience physical damage. During the daytime, access was limited to emergency transportation for reconstruction work and disaster relief activities based on the Road Traffic Act.

On the Meishin National Expressway, viaducts suffered severe damage between Toyonaka Interchange(IC) and Nishinomiya IC. Pre-quake traffic volumes in the affected sections were approximately 50,000 to 70,000 in ADT. While even the worst-damaged sections were opened to traffic with reduced lanes after February 25, 1995, traffic volume was reduced to 30 to 55 percent of pre-quake levels because the direct connection with Hanshin Expressway Route 3 was lost and access was allowed for emergency transportation only during the daytime.

On the Chugoku National Expressway, damage to the viaduct between Toyonaka IC and Nishinomiya-kita IC (pre-quake ADT=98,700) caused closure of the main connector between the Chugoku/Kyusyu and Kansai/Kanto regions. Despite relatively short-term closure, the national economy was significantly affected because of additional origin-destination (OD) distance, OD travel time, and suspension of various activities. In mid-February 1995, 4 lanes were opened to traffic (out of 6). Since then, Chugoku National Expressway served as an alternate route to Hanshin Expressway Route 3, etc., carrying approximately 10 to 20 percent additional traffic volume.

Analysis of highway system performance in the Hyogoken-Nanbu earthquake focused on Hanshin Expressway Routes 3, 5, 7 and 16, Daini Shinmei Expressway (from Tsukimiyama to Akashi-Nishi IC), Chugoku National Expressway (from Yokawa Jct. to Suita Jct.), and Meishin National Expressway (from Suita Jct. to Nishinomiya IC). The study network is depicted in Figure 1. Immediately after the earthquake, traffic was controlled in a wider area for damage inspection and emergency transport prioritization. However, because major interest herein is on more long-term impacts on the economy, the network under consideration was defined to include routes that suffered physical damage and/or served as major alternate highway routes, as listed above.

Configuration of the relevant network can be represented as a linear system because of geographic properties in the Hanshin area. The study network consisted of 63 nodes and 62 links. Data on highway length, pre- and post-earthquake monthly ADT, and status of re-openings of damaged sections during the reconstruction period were obtained from the authorities concerned through private communications. Each measure was evaluated on a monthly basis.

The performance measures developed previously were applied with a few minor modifications. Note that the study region includes several other cities besides Kobe. In assessing measures *D*, only origin nodes within Kobe City were included (i.e., the summation in equations (2b) included only origin nodes *i* within the Kobe City limits). Also, only one damage state (link closure) was considered, with associated distance multiplier f=5, and no detour adjustments were made. This is because local arterial streets had insufficient capability to accommodate detouring highway vehicles due to damage, reconstruction work, and/or traffic control.

Traffic restoration data for the Hyogoken-Nanbu earthquake were obtained from several sources. Japan Highway Public Corporation (JH) monitors traffic count data on National Expressways at every interchange toll gate nation-wide. Hanshin Expressway Public Corporation monitors traffic count data at every on- and off-ramp on its own routes using traffic counters. Those data, stored as monthly ADT, were made available for this study. Based on the data, time series of ADT between interchanges or ramps were compiled on a monthly basis for the study network during the pre-earthquake ordinary period and post-earthquake reconstruction period from October 1994 through October 1996.

These data were used to construct a measure of traffic volume restoration, *T*. The sum of section ADT multiplied by section length adds up to total daily traffic volume in vehicle-kilometers over the entire study network. This total was normalized by pre-quake average traffic volume, using data from October through December 1994, to derive the ratio *T*. A level of T=1.0 indicates that the system has regained pre-disaster traffic levels.

Figure 2 shows the restoration of traffic on a monthly basis following the Hyogoken-Nanbu earthquake with plots of performance measures *L* and *D*, together with the traffic ratio *T*. (Monthly values for *L* and *D* are shown in Appendix Table 1.) Immediately after the earthquake, it is estimated that performance dropped from 1.00 to 0.14 according to measure *L* and 0.11 according to measure *D*. Overall, performance measure *D* tracks actual traffic volumes *T* very closely throughout most of the restoration period. Measure *L* is consistently high. Although system performance recovered rapidly in the initial few months, for example to *D*=0.70 by May 1995, progress stalled for over a year until July 1996. At that time, the reopening of Hanshin Expressway Route 3 began to accelerate until full restoration was completed at the end of September 1996. Traffic was lower than the performance measures in the initial period. Once conditions became less confused, however, traffic conditions recovered rapidly. Seasonal fluctuation could be clearly observed on the Chugoku National Expressway in August, the period when many Japanese take annual vacations.

Railway serves as the primary mode of commuting in the Kobe region. The urban rail system, too, suffered extensive damage in the earthquake. It was repaired more quickly, however, than the highway system, requiring some 8 months for full restoration. Analysis of railway system performance included the following lines: JR-West (Tokaido/Sanyo and Fukuchiyama lines), Hankyu (Kobe, Itami, Koyo, Imazu and Takarazuka lines), Hanshin (main, Mukogawa and Nishiosaka lines), Sanyo main line, Kobe Railway (Arima and Sanda lines), Kobe Rapid Transit Railway line, Kobe City subway line and Hokushin Expressway, Port Liner, and Rokko Liner. Note that the JR Sanyo Shinkansen (bullet train) was not included, as it is an interregional rail line. Virtually all of the lines noted suffered major damage in the earthquake. In total, the system contains 185 nodes or stations and 202 links, as shown in Figure 3. The rail system is much more redundant than the highway system. The system performance measures were applied to railways in a similar manner to highways.

System performance in terms of measures L and D are summarized in Appendix Table 1 on a monthly basis. In terms of performance immediately after the earthquake, the L value for the rail system is 0.29, indicating less than 30% of total network length is operational. By the end of one month, this has improved greatly to 0.80. Measure D for the rail system is initially 0.22, but after one month also increases to 0.80.

The severity of the disruption to transportation systems can also be seen by comparing highway and railway performance to that of other urban lifeline systems in the Kobe area. Figure 4 provides information on the relative severity of lifeline outage in the Hyogoken-Nanbu earthquake, specifically showing restoration times for different levels of system serviceability. Restoration of, for example, 30 percent service in the highway or railway transportation cases corresponds to a performance measure of D=0.30. In the case of the other utility lifelines, 30 percent service corresponds to 30 percent of customers having utility service. Note that for all lifelines shown, service was disrupted to the vast majority of households in the Kobe region. Figure 4 shows that the duration of highway transportation disruption was much more severe than that of electric power, water, or natural gas utilities.

Because the measure D is dependent upon the factor f as noted in equation (2), which was arbitrarily assigned a value of f=5, sensitivity analysis was conducted. Results showed that D is in fact highly robust to assumed values of f. In all cases tested, values of D under the assumption of f=3 differed by less than 1% from values under the assumption of f=100. For example, for the highways case, D=0.135 at t=1 (January 1995) when f=3, and D=0.134 when f=100.[2]

Areal Performance

To investigate the extent to which post-disaster transportation accessibility varied within the study area, areal serviceability index D_s, as defined in equation (3) above, was evaluated for each of Kobe City's 9 constituent wards. For weights w, data were obtained from commuting information from the 1990 Japanese Census (Management and Coordination Agency, 1990). Census data showed that in Kobe City, some 49% of commuters (employed persons and those attending school over the age of 15) travel by rail. A much smaller percentage -- roughly up to 14%[3] -- commute by highway. The remainder use other modes such as walking, bus, or motorcycle. The geographic scope is limited here to the study region, including the cities of Kobe, Akashi, Ashiya, Nishinomiya, Amagasaki, Itami, Sanda, Takarazuka, and Kawanishi in Hyogo Prefecture and Osaka, Toyonaka, Ikeda, and Suita in Osaka Prefecture. The study area accounts for some 96 percent of work and school destinations for Kobe City commuters.

Figure 5 shows the geographic distribution of commuter origins (within Kobe City only) and destinations within the study area. The top graph shows that highway commuters originate primarily from the peripheral wards of the city to the north, west, and east. To a large extent, they journey to work or school in the central wards, particularly the central business district

[2] Measure D_s is also dependent upon f. Similar results were obtained in sensitivity analysis.

(CBD) in Chuo ward. Relatively few commuters use the highway to go to Osaka and other neighboring cities to the east. More detailed data indicate that Chuo ward is either the primary or secondary destination of highway commuters originating from each of the other wards. Osaka is the second most popular destination for those driving from the easternmost ward, Higashi-nada, but is lower on the list for all other wards.

The lower graph in Figure 5 shows the corresponding data for railway commutes. While the pattern of origins is similar to that for highway, the destinations are much more concentrated. The vast majority of rail commuters are headed toward the Kobe CBD or Osaka city. Indeed, Osaka and Chuo ward are the two most popular destinations for commuters from each of Kobe city's wards.

To evaluate measure D_s, weights w_{ij} are needed. Detailed data on commute destinations by mode at the city and ward level were used. For the highway mode, weights were determined on the basis of commutes between city wards only. It was assumed that data on intra-ward commutes referred to car trips on local roads or surface arterials, rather than the regional expressway system. In the railway case, both intra- and inter-ward commute data were used. Finally, since the commuting data were only available at the ward level, commuters within a particular ward were distributed uniformly among all nodes within that ward.

Accessibility D_s was evaluated for each of Kobe's city wards for highway and rail transportation, respectively, over the post-disaster restoration period. Figure 6 shows D_s for highway

[3] Inferred as those traveling by private car or taxi to areas outside the city ward of residence. In some cases, this may include travel on local roads, so the 14% figure can be taken as a rough upper bound estimate for highways.

transportation by ward in July 1995 (t=month 7), after the initial rapid restoration phase had been completed. The central coastal wards, which contained about 44 percent of Kobe's population, have the lowest serviceability, while the mountainous outer wards (Nishi and Kita, accounting for 27 percent of City residents) have the highest. Values range from D_s=0.50 for Hyogo, Nagata and Suma wards to D_s=0.76 for Kita ward. Figure 7 shows the restoration of highway accessibility over time for selected wards. It demonstrates the vast disparity in highway service loss between the wards, indicating that a city-wide average does not adequately represent the situation across the study area. Furthermore, it shows that relative highway serviceability remained fairly consistent throughout most of the restoration period, so that spatial disparities were for the most part preserved for a long period of time.

Figure 8 shows the same information for railway accessibility. Note that because of the more rapid repair time, the horizontal time axis differs from that of the previous figure. Rail service also shows tremendous disparity over space. As with highways, the mountainous outer wards suffer relatively little railway accessibility loss while the coastal wards had the greatest loss. For instance, in Nagata ward -- among the most heavily impacted and slowest to recover from the disaster -- railway accessibility remained below 75 percent of pre-disaster levels for 2 months and highway accessibility for 19 months. In Nishi ward, an area with new town development that actually gained population after the disaster, 75 percent accessibility for rail was gained within one month for rail and 13 months for highways. However, there were some notable contrasts between disruption to highways and railways. For instance, highway accessibility was relatively high in Higashi-Nada ward in eastern Kobe City after the disaster, as compared for example to Tarumi ward in the west. On the other hand, rail service was generally much better in Tarumi.

COMPARATIVE ANALYSIS

In the previous section, post-disaster transportation performance measures were developed and applied to the case of Kobe City after the 1995 earthquake. Results showed that these measures provide a very useful means for summarizing the earthquake's effects -- specifically, for quantitatively assessing the loss of transportation service in the region, evaluating the spatial and temporal dimensions of this service loss, and making comparisons with the performance of other urban lifeline systems. This section applies some of these performance measures to the 1989 Loma Prieta and 1994 Northridge earthquakes in the United States and demonstrates how insights can be gained by making comparisons across disasters.

Loma Prieta

The October 17, 1989 Loma Prieta earthquake (magnitude M_w=7.0) caused damage to 91 state highway bridges, of which 13 were closed due to heavy damage (Caltrans, 1994). The most serious transportation disruption, however, occurred in the San Francisco Bay Area as a result of bridge deck collapses on the San Francisco-Oakland Bay Bridge and the Cypress Street Viaduct in Oakland. Due to the lack of nearby alternate routes, the impact of the Bay Bridge closure was especially significant. Many motorists chose alternate modes of transport including Bay Area Rapid Transit (BART) and ferry (Deakin, 1991; Ardekani, 1992). BART daily ridership, for example, increased from 224,400 to 314,100 after the earthquake. The Bay Bridge was closed for one month following the earthquake.

The study network was defined to incorporate major highway connections between Oakland (the East Bay) and San Francisco, similarly to the network studied by Wakabayashi and Kameda (1992). Specific routes included US-101 between San Rafael and Palo Alto, major viaducts in San Francisco, I-580 between San Rafael and Jct. I-80, I-80 from Jct. I-580 to San Francisco (including the Oakland Bay Bridge), I-880 from I-80 in Oakland to Fremont, SR-92 between Hayward and San Mateo, and SR-84 between Fremont and Palo Alto. The study network included 123 nodes and 125 links. Highway length data were obtained from the Caltrans website.[4] In the post-earthquake damaged state, major highway closures were modeled that were associated with damage to the Bay Bridge, the Cypress Viaduct in Oakland, the SR-92/US-101 interchange in San Mateo, and the Embarcadero, Terminal Separation, Central, China Basin, and Southern Freeway Viaducts in San Francisco. While the Bay Bridge required about one month to reopen, in some cases such as the Embarcadero and Cypress Viaducts, the damaged structures took several years to rebuild or have not been reconstructed.

Results indicate that the overall system performance was much better than in the Kobe case. Initial post-earthquake performance was estimated at L=0.87 and D=0.90. This level of highway transportation disruption was not regained by the Kobe region until some 19 to 22 months after the earthquake (depending on the performance measure used). Further, the undamaged rapid transit BART system and cross-bay ferry systems provided effective and highly used alternatives to the Bay Bridge as it was being repaired.

Northridge

The January 17, 1994 Northridge earthquake (M_w=6.7) caused damage to 286 state highway bridges, of which seven major ones collapsed (Caltrans, 1994). This caused disruption to critical highway routes at four locations in the northwestern Los Angeles metropolitan area (Wesemann et al., 1996; Yee et al., 1996). These main damage areas occurred on State Route 118 (pre-earthquake ADT =123,000), on Interstate 10 (ADT=310,000), and at two locations on Interstate 5 (I-5) (ADT=133,000). On I-5 at the Gavin Canyon crossing, a detour was opened on January 29 and the mainline was reopened on May 18, four months after the earthquake. At the I-5 interchange with State Route 14, limited detours were implemented using undamaged connectors and truck bypasses. Contractors completed reconstruction of two of the four ramps in July and the remaining two in November. On SR-118, damage caused closure of over 9 miles of the highway west of the junction with I-210, and detours were implemented on local streets. In mid-February, partial restoration reopened about 5 miles of highway and allowed reduced-lane highway usage to replace detours on local streets. Reconstruction was completed in September. On I-10, bridge collapses occurred at La Cienaga/Venice Boulevards and at Washington Boulevard/Fairfax Avenue. Detours on local arterial streets were implemented during reconstruction. The mainline was reopened on April 12, less than 3 months after the earthquake. In Northridge, travel patterns were able to adjust flexibly to highway system disruption because of network redundancy and the availability of a dense surface arterial system (Giuliano et al., 1996).

[4] http://www.dot.ca.gov/hq/traffops/traffsys/trafdata/trafdata.htm.

Analysis of damage following the Northridge earthquake focused on the four areas of major highway bridge damage on I-5 (Gavin Canyon and SR-14 interchange), I-10, and SR-118. The relevant network was defined to include routes significantly impacted by the earthquake damage, either directly or indirectly by serving as major highway detour routes (see Figure 9). This area was delimited in part by the ten highway locations where Caltrans regularly collected post-earthquake traffic data. Routes included I-5 from Santa Clarita to downtown Los Angeles, SR-170/US-101 from the junction (Jct.) with I-5 to Jct. I-110, I-405 from Jct. I-5 (in L.A.) to Jct. I-105, I-110 from Jct. I-5 to Jct. I-105, SR-118 from Simi Valley to Jct. I-210, US-101/SR-134 from Thousand Oaks to Jct. I-5, and I-10 from Santa Monica to Jct. I-110. The study network included 166 nodes and 171 links. Highway length data were obtained from the Caltrans website noted above.

In each of the damage locations, detours onto arterial or local streets had been implemented during the reconstruction period. These were accounted for in measure L through the use of a detour factor r that served to increase the performance measure:

$$Z' = Z + r_l \cdot (\overline{Z} - Z) \qquad (4)$$

where *Z*¢ = measure L, adjusted for detour l

Z = same measure, without adjustment for detour l

r_l = detour factor for l

$\overline{Z}$ = same measure, with full restoration at detour location l

The factor *r*, which specifies the extent to which the detour was able to make up for the damaged link, depends upon traffic capacity of the detour route relative to the damaged highway section. This factor was approximated as 0.5 for all of the Northridge detours except for the Gavin Canyon area, where it was estimated to be 0.375. For measure *D*, the effective distance multipliers *F(k)* were assumed to be 5 for link closure and 2 for links with established detours.

Results indicate that immediately after the earthquake, highway system performance was comparable to the Loma Prieta case. Measure *L* was 0.89 and measure *D*, 0.95. System performance was also evaluated at regular time intervals as restoration of highway damage progressed. In contrast to the Kobe case, where analysis was conducted at montly intervals, for Northridge, estimates were made on a weekly basis. Data were available to compare the restoration of physical system performance to changes in the actual traffic volumes observed after the events.

Caltrans collected areal traffic count data at 10 locations for somewhat over 5 months following the Northridge earthquake using loop counters embedded in the highway pavement (see Figure 9 above). These included various locations on I-5, SR-134, SR-170, I-405, I-10, I-105, US-101, and SR-118. The unpublished data were made available for this study by the Caltrans District 7 office. Except for one case where monthly data were reported, these counts were provided on a weekly basis beginning about a week after the earthquake. Pre-earthquake daily traffic data at these locations were also provided for the corresponding months in 1993.

As in the Kobe case, these data were used to estimate values of the traffic volume index *T*. Data at the count locations were allocated to links on the network by first estimating ratios of post- to pre-earthquake ADT for each count location and assigning results to sections of the network. In some cases, averages of two nearby count locations were assigned. These ratios were multiplied with base-year ADT data to approximate post-disaster ADT for each section of the network. Weighting these vehicle count data with section lengths yielded estimates of post-disaster network traffic volume in vehicle-miles. Base-year ADT data, available from the Caltrans website, pertained to 1996 conditions and indicate "normal" traffic patterns. The ratio of post- to pre-disaster traffic volume represented the traffic restoration measure *T*.

Figure 10 shows the restoration of traffic volume (*T*) in the L.A. area on a weekly basis starting from one week after the Northridge earthquake (i.e., week number 2). The figure also plots the restoration of performance measures *L* and *D* over this period. Measure *L* correlates very closely with *T*. Measures *D* is consistently somewhat higher than *L*. However, traffic conditions are generally lower than the performance measures in the initial period and improve more rapidly than the measures would suggest. From week 19 (early June) onward, traffic actually exceeds pre-earthquake volumes.

These data point to a number of interesting similarities and contrasts between the Northridge and Kobe experiences. Figures 2 and 10 show that the shape of the restoration curves (in terms of both traffic volume and system performance) is similar in both disasters, including a period of rapid restoration followed by a prolonged plateau. In both events, for a brief period immediately following the disaster, traffic is lower than what system performance or functionality would indicate. The relationship between system performance and traffic may be interpreted in terms of three temporal phases following the disaster -- an emergency phase, followed by a period of rapid restoration and a final restoration phase.

Contrasts between the disasters are nonetheless striking. To begin with, the scales of Figures 2 and 10 are very different. This relates to both the scale of disruption and the scale of the time axis, or the duration of disruption. Thus, while system performance exceeded 0.9 after one month in Northridge, long-term degradation can be seen in the Kobe case. This clearly indicates significantly greater impact on the local and national economy. In addition, the ordering of the performance measures differs, with $D>L$ for Northridge and $L>D$ for Kobe. Furthermore, observed traffic volumes correlate closely with L in Northridge, but with D in Kobe. At least two hypotheses can be advanced to explain these observations: that they arise from contrasts in the extent of damage (i.e., between a moderate and a catastrophic disaster); or, that they arise from differences in network redundancy characteristics. Both factors may be at work simultaneously.

Comparative Analysis of System Performance

Damage to transportation systems in general and highway bridges in particular figured prominently in the impacts of the Loma Prieta, Northridge, and Hyogoken-Nanbu earthquakes. However, these disasters differed significantly in the extent of transportation damage, level of system disruption, and restoration timeframes. Important contrasts can also be found in the urban settings of the disaster-impacted regions, particularly in terms of transportation network redundancy or lack thereof.

Table 1 summarizes some of the principal contrasts between these three disasters:

[Table 1 about here]

As indicated, overall post-disaster highway system performance was somewhat better in Northridge than in Loma Prieta due to the availability of detours and the greater redundancy of the network. Despite much local inconvenience caused by the damage, however, in both of these cases the highway system retained some 90 to 95 percent of pre-earthquake functionality (as measured by *D*). In Kobe, by contrast, less than 15 percent of pre-disaster service was maintained.

CONCLUSIONS

This paper has developed summary measures of transportation system performance and demonstrated their usefulness in the context of earthquake loss assessment. The methodological approach emphasized simple measures that require only readily available data on network configuration, damage, and pre-disaster origin/destination traffic. These measures can be used to evaluate not only immediate post-earthquake system deterioration, but also performance restoration over the course of the reconstruction period. They are also useful in making comparisons between the levels of disruption in transportation and other urban lifeline systems, as well as for determining the spatial disparity in transportation service loss within an impacted region. For any particular urban area, of course, these purposes can be served by more sophisticated transportation-economic models (for an application to Los Angeles, see Shinozuka et al., 1998). Such models are generally data-intensive and often empirically unvalidated. Further, they are typically unique to the city at hand. Simple summary measures, in contrast, are uniquely suited to making rapid post-disaster assessments and comparing across disasters in different urban areas.

Further research can certainly improve the accuracy and applicability of the system performance measures developed here. Methodologically, considerations could be made of pre-earthquake network capacity. It would be interesting to validate the performance measures wth results from detailed traffic simulation models (for example, for Los Angeles following the Northridge earthquake).

Even to the extent that they have been developed here, however, performance measures can provide a very useful tool for earthquake hazard mitigation. By quantifying overall transportation system performance, they allow decision-makers to discuss performance objectives -- what levels of risk are "acceptable" -- with reference to maintaining regional transportation service, not merely containing physical damage. By the same token, they can facilitate mitigation plans such as prioritizing the seismic retrofit of individual highway bridges before a disaster strikes. Transportation system performance can be meaningfully compared across various "what-if" scenarios of potential earthquake disasters and the ensuing transportation disruption, with and without mitigation efforts. Moreover, once the disaster has occurred, they provide information that can help in prioritizing repairs and minimizing losses through efficient system restoration.

The Kobe earthquake provides a precious opportunity for observers from the U.S. to learn about urban earthquake vulnerability, if lessons can be appropriately transferred to this country. It is obvious that transportation system damage in the Kobe earthquake was much worse than in the Northridge earthquake, but how much worse was it? Could a “Kobe-like” disaster could happen in the U.S.? System performance measures can be useful in providing quantitative answers to such questions at the urban systems level.

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TABLE 1. Highway Disruption in Recent Earthquakes

	1989 Loma Prieta	*1994 Northridge*	*1995 Hyogoken-Nanbu (Kobe)*
Pre-earthquake network redundancy	Moderate-Low	High	Low
Damage to network	Concentrated	Concentrated	Extensive
Most disruptive damage	Bay Bridge	I-10, I-5/SR-14	Hanshin Exp. #3
Detours during reconstruction?	No	Yes, Yes	No
Restoration completed at:	1 month	3 mos., 10 mos.	20 mos.
System Performance[a]: Measure *L*	0.87	0.89	0.14
Measure *D*	0.90	0.95	0.14

Note: (a) immediately after earthquake.

Appendix Table A. System Performance, Hyogoken-Nanbu Earthquake, by Month

Month/Year (Month no.)	**Highway**		**Railway**	
	L	***D***	***L***	***D***
Jan. 1995 (1)	0.14	0.14	0.29	0.22
Feb. 1995 (2)	0.72	0.56	0.80	0.80
Mar. 1995 (3)	0.74	0.59	0.86	0.87
Apr. 1995 (4)	0.79	0.62	0.90	0.91
May 1995 (5)	0.83	0.65	0.91	0.91
June 1995 (6)	0.83	0.65	0.95	0.95
July 1995 (7)	0.84	0.66	0.97	0.97
Aug. 1995 (8)	0.84	0.66	1.00	1.00
Sept. 1995 (9)	0.84	0.66	1.00	1.00
Oct. 1995 (10)	0.84	0.66	1.00	1.00
Nov. 1995 (11)	0.84	0.66	1.00	1.00
Dec. 1995 (12)	0.84	0.66	1.00	1.00
Jan. 1996 (13)	0.84	0.66	1.00	1.00
Feb. 1996 (14)	0.86	0.70	1.00	1.00
Mar. 1996 (15)	0.86	0.70	1.00	1.00
Apr. 1996 (16)	0.86	0.70	1.00	1.00
May 1996 (17)	0.86	0.70	1.00	1.00
June 1996 (18)	0.86	0.70	1.00	1.00

July 1996 (19)	0.88	0.75	1.00	1.00
Aug. 1996 (20)	0.92	0.83	1.00	1.00
Sept. 1996 (21)	0.95	0.89	1.00	1.00
Oct. 1996 (22)	1.00	1.00	1.00	1.00

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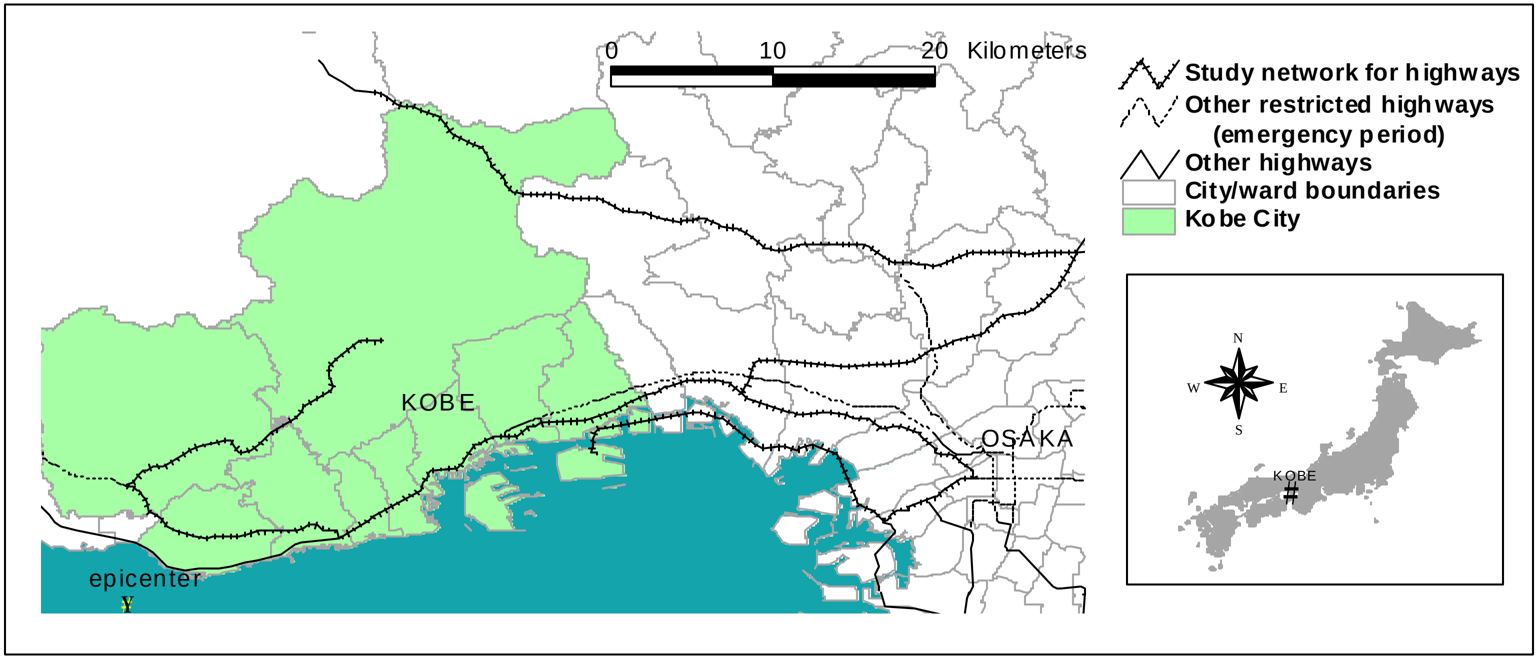


Figure 1. Study Network for Highways, Hyogoken-Nanbu Earthquake

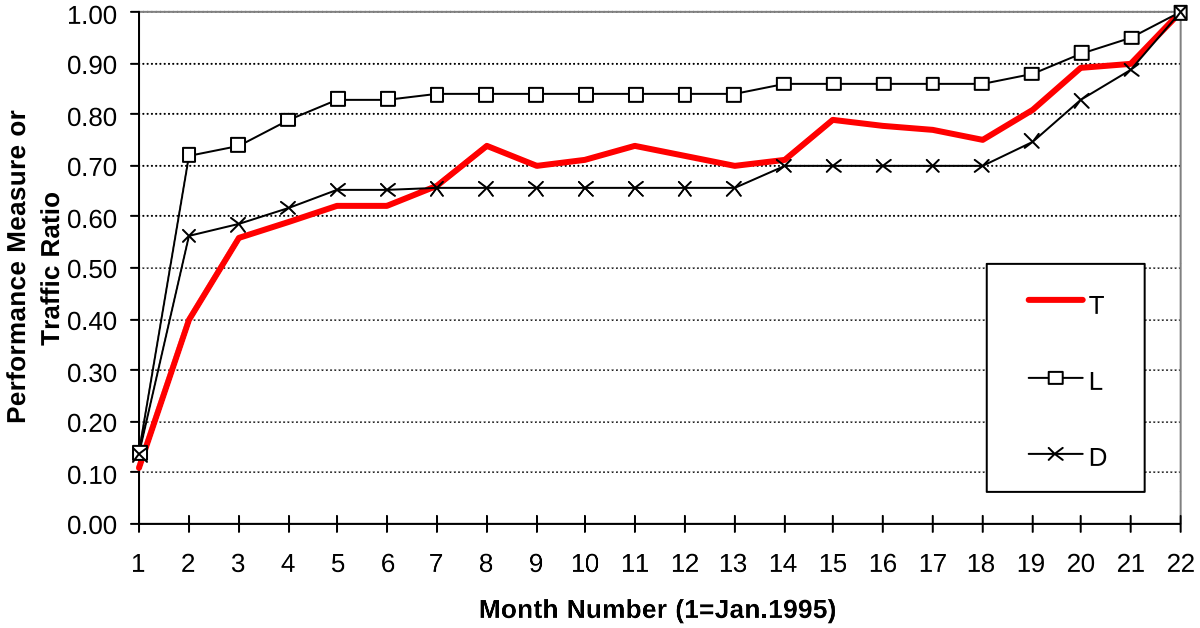


Figure 2. Highway System Performance and Traffic Restoration, Hyogoken-Nanbu Earthquake

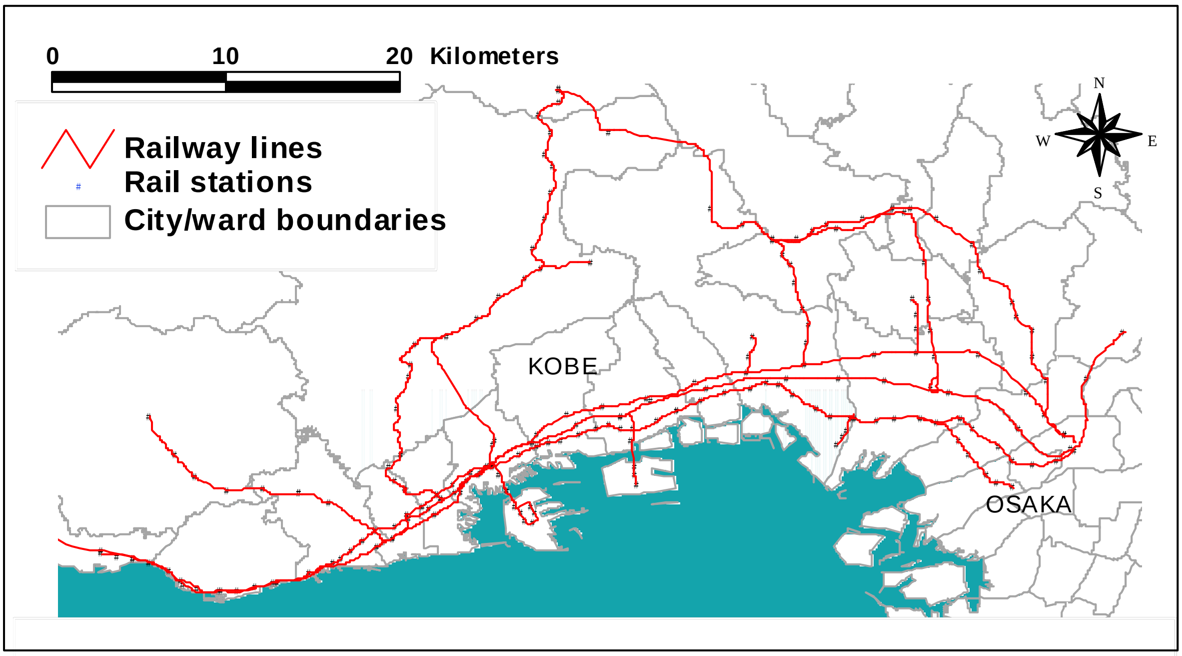
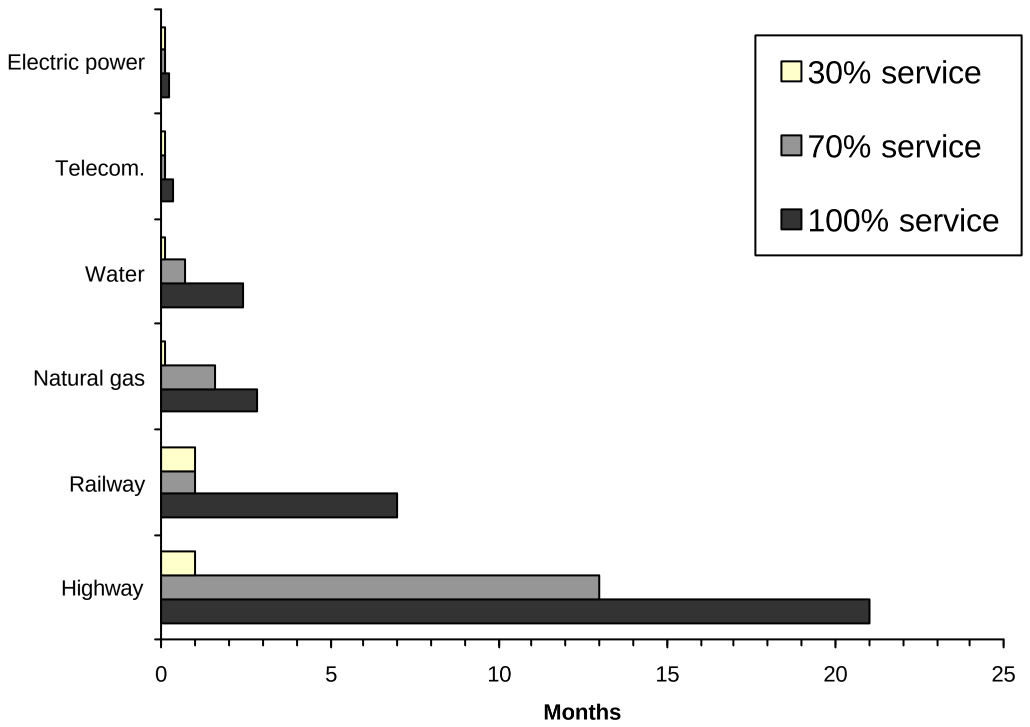
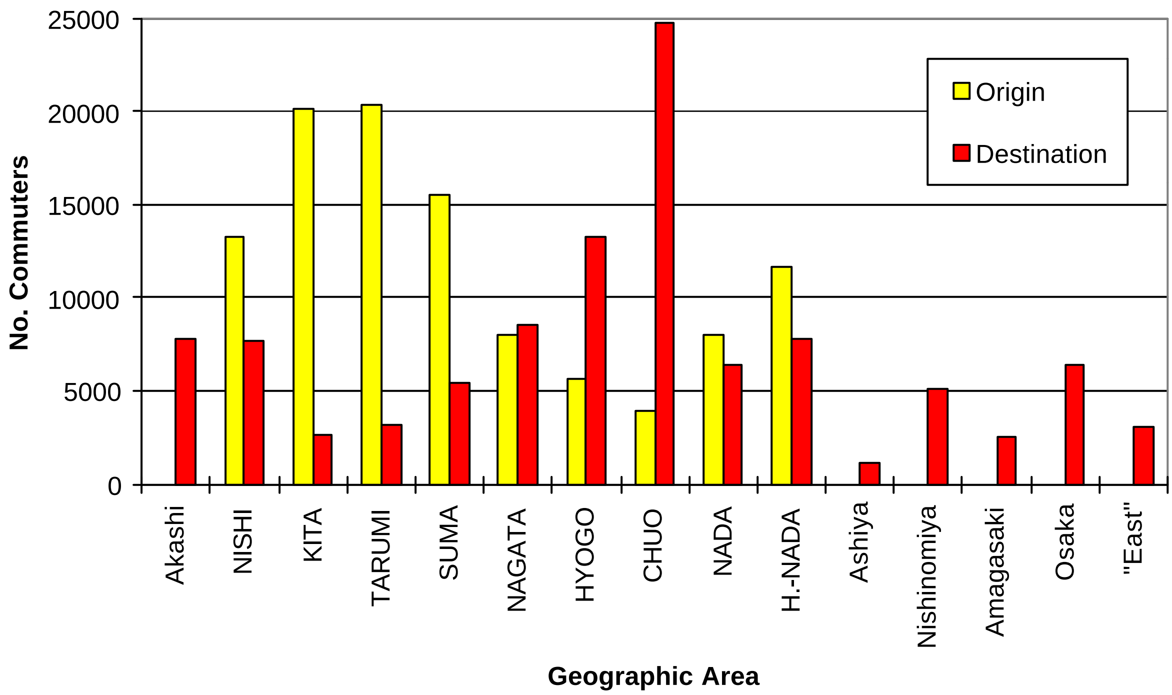


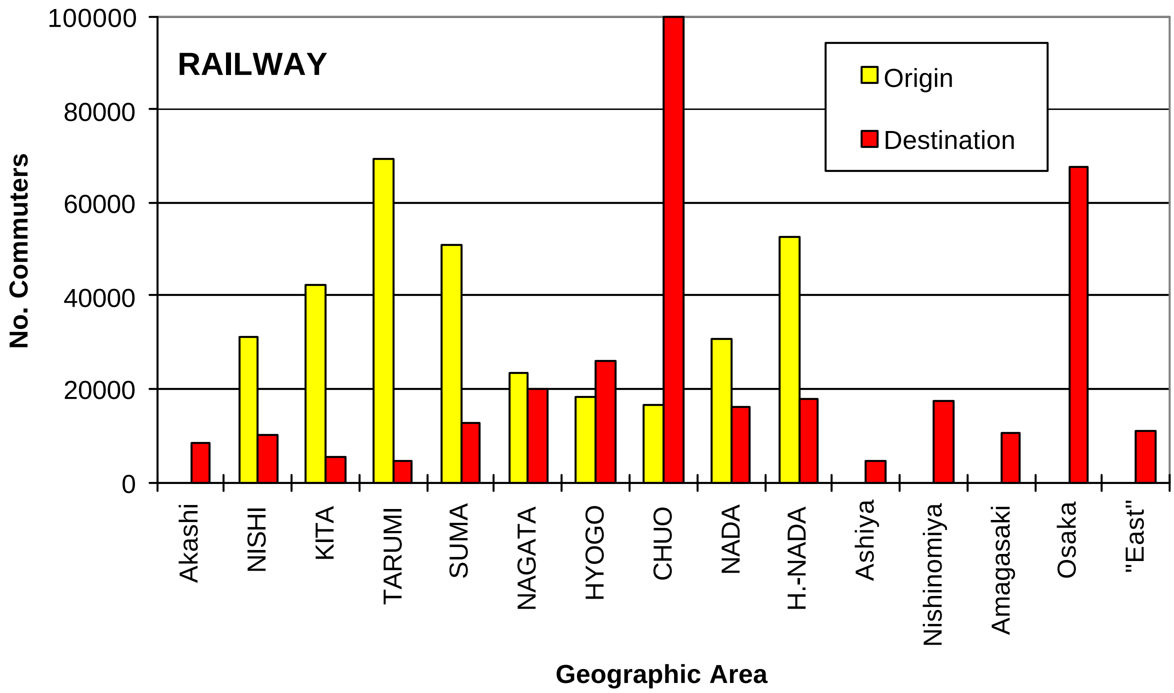
Figure 3. Study Network for Railway, Hyogoken-Nanbu Earthquake



Note: except for railway and highway, data are based on Takada and Ueno (1995) and represent percent of customers with service restored.

Figure 4. Lifeline Restoration Timeframes, Hyogoken-Nanbu Earthquake





Notes: (1) CAPS = ward of Kobe City; Lowercase = other city/area;
(2) "East" = Takarazuka, Itami, Kawanishi, Ikeda, Toyonaka and Suita;
(3) Areas are ordered in approximate geographic sequence, from west (left) to east (right).

Figure 5. Commuting Origins and Destinations within Kobe Study Area by Mode

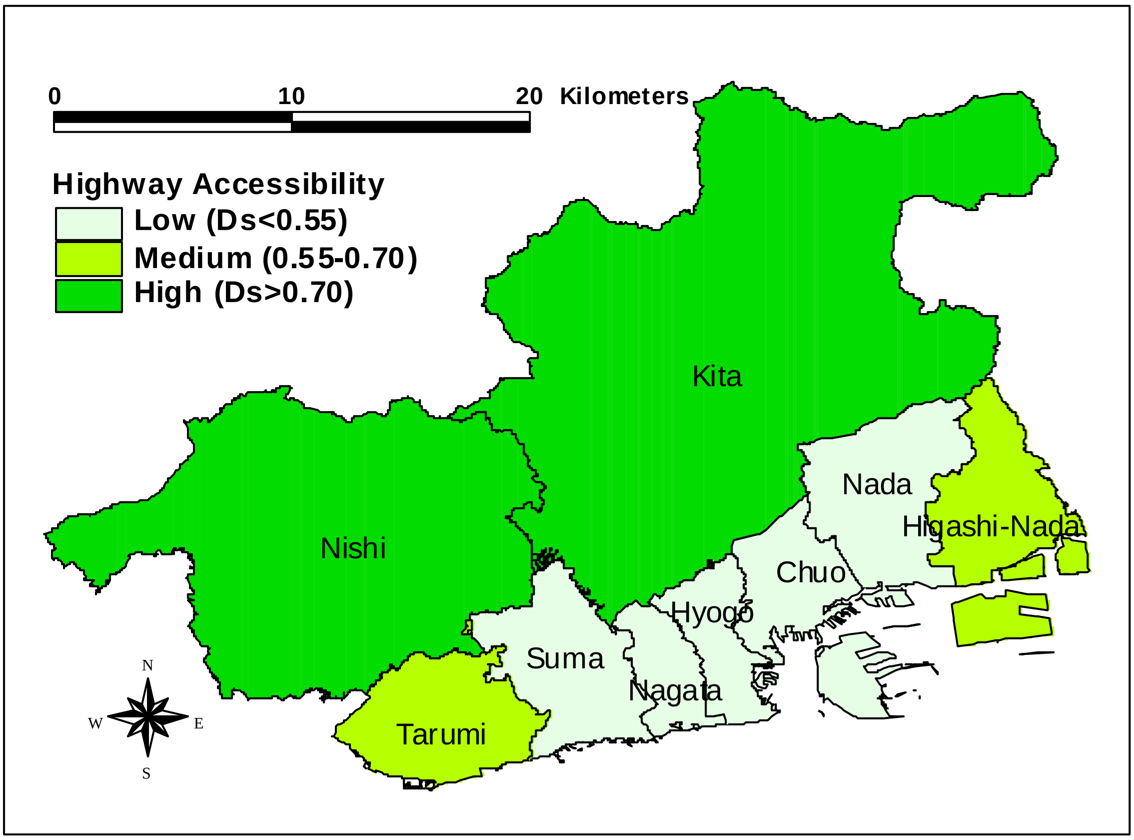


Figure 6. Highway Accessibility by Kobe City Ward, July 1995

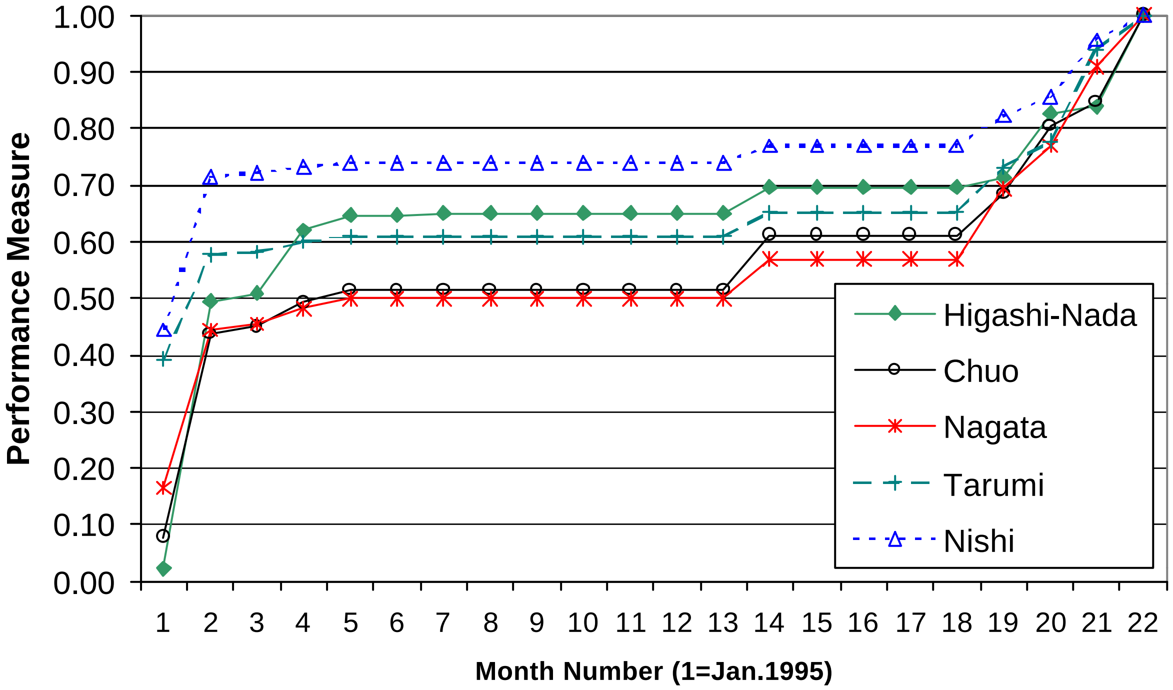


Figure 7. Highway Performance Restoration, Selected Kobe City Wards

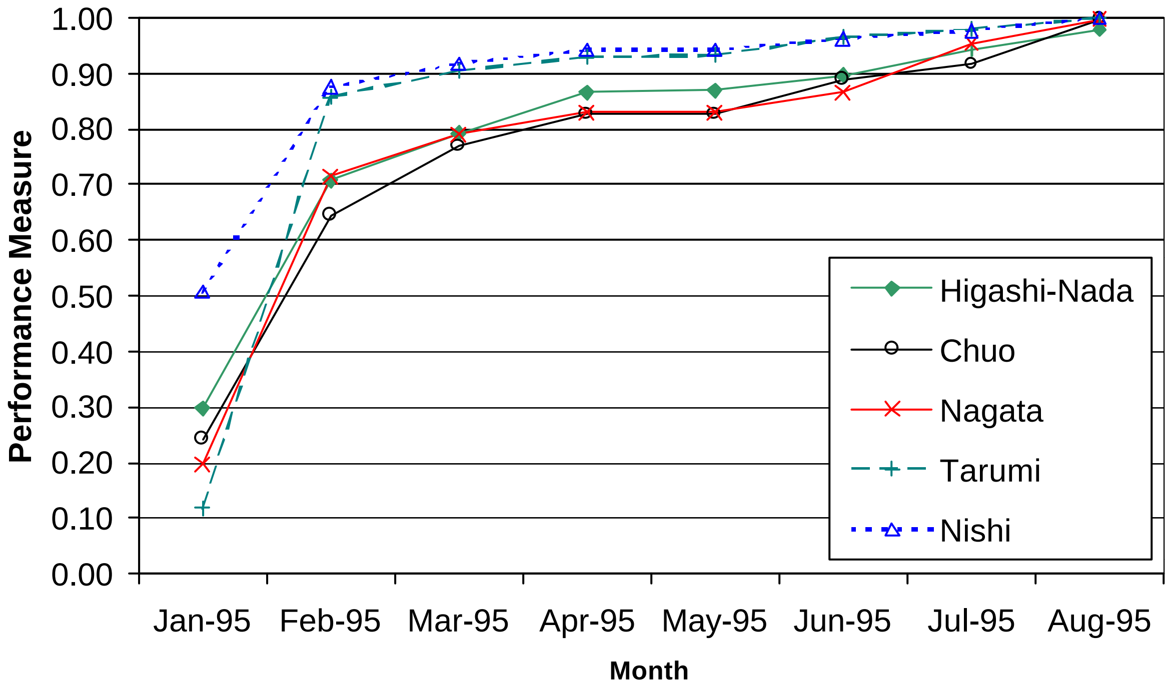


Figure 8. Rail Performance Restoration, Selected Kobe City Wards

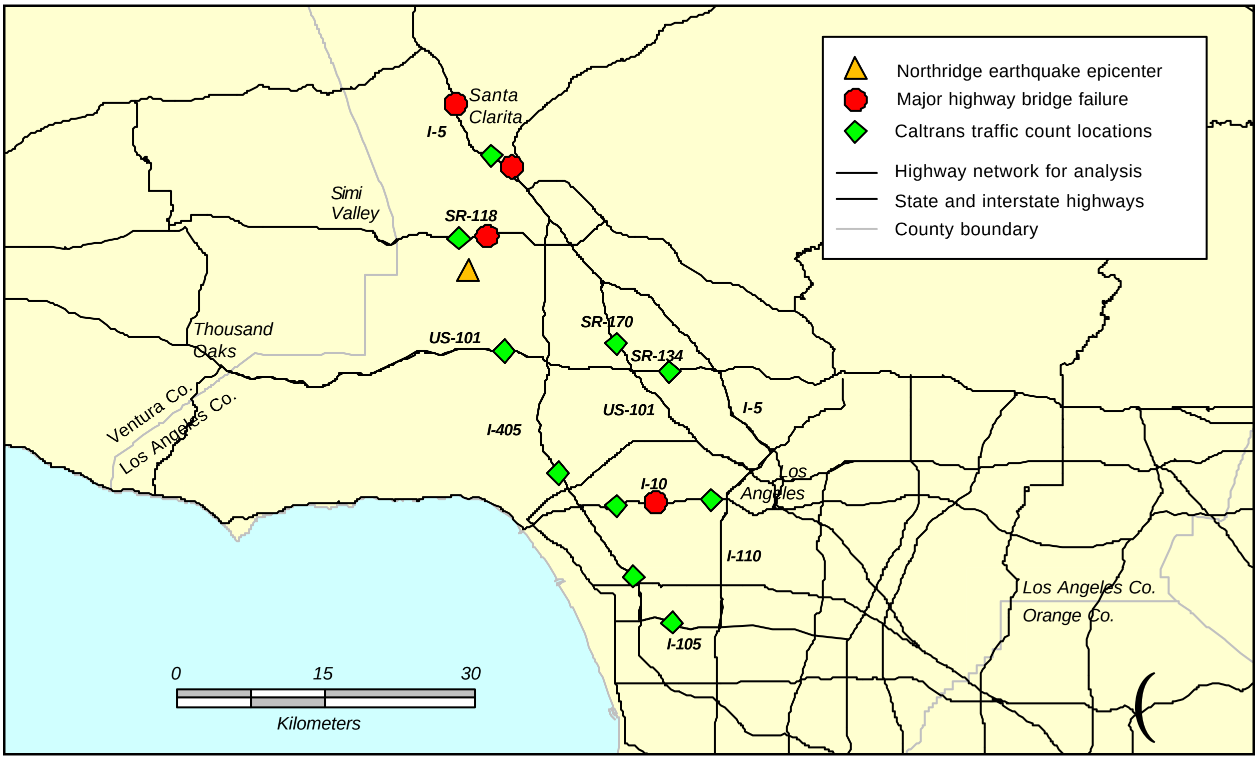


Figure 9. Study Network for Highways, Northridge Earthquake

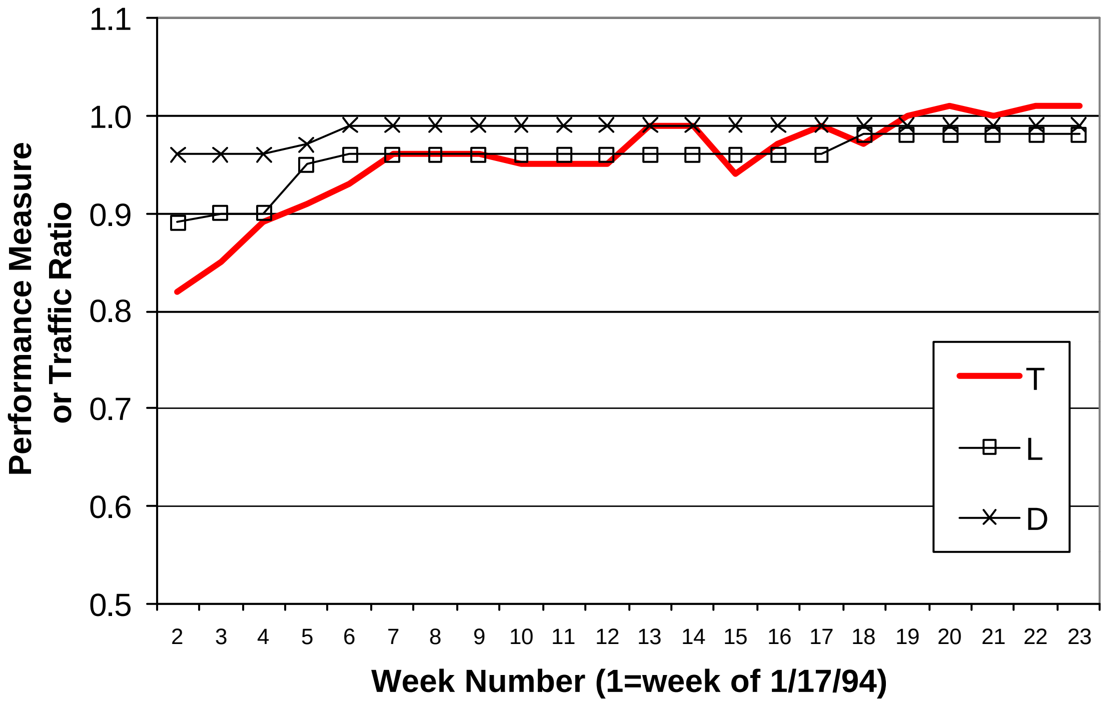


Figure 10. System Performance and Traffic Restoration, Northridge Earthquake