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MEASURING LIFELINE SYSTEM PERFORMANCE: HIGHWAY TRANSPORTATION SYSTEMS IN RECENT EARTHQUAKES

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Abstract

Discussion of seismic performance standards for engineered structures and systems involves the issue of how to best measure performance. Moreover, summary measures of post-disaster system disruption and recovery are useful for evaluating the ensuing economic impact and for making comparisons across events. Measurement of lifeline system performance is particularly complex because of network and spatial characteristics, the multiplicity of users, and the critical nature of lifeline services for post-disaster response and recovery. This paper addresses the measurement of lifeline system performance by focusing on highway system disruption in three recent urban earthquake disasters in the U.S. and Japan -- the 1989 Loma Prieta, 1994 Northridge, and 1995 Hyogoken-Nanbu (Kobe) earthquakes. Several alternative measures of the physical performance of highway systems are proposed, implemented, and compared. The paper further analyzes the correlation between these measures and observed traffic conditions in Northridge and Kobe. Results suggest that some measures may be used advantageously in further study of the economic impact of highway damage in earthquakes.

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Introduction

Recent earthquake disasters such as the Loma Prieta, Northridge, and Hyogoken-Nanbu events have demonstrated the seismic vulnerability of highway systems and the significance of the ensuing economic impact. In addition to engineering studies of highway bridge damage, several studies have investigated the consequences of the damage in terms of travel behavior and regional economic impacts. However, few studies have utilized a systems perspective to analyze the link between structural damage and economic impact. While existing earthquake loss estimation models can indicate the likely pattern of damage to highway bridges, an evaluation of the entire system's performance is needed to estimate the economic consequences. Wakabayashi and Kameda (1992) perform network reliability analysis to explain traffic conditions in Loma Prieta but do not consider overall performance measures. Chang (1996) models the economic impact of transportation and other lifeline disruption in the Hyogoken-Nanbu earthquake but employs a simplified transportation measure that does not consider systems aspects.

Measures of system performance are useful for economic impact modeling, as well as for identifying effective mitigation and reconstruction prioritization strategies. Such measures can further facilitate comparisons across disaster events and lead toward generalized rather than case study evaluations of highway damage impact. For utility lifelines, the percentage of households with service restored has been used to measure system restoration. This measure cannot, however, be directly applied to transportation systems.

This paper focuses on developing appropriate measures of the physical performance of highway networks following a disaster. It first provides an overview of highway damage and restoration in the three earthquakes. Several alternative measures of system performance are then proposed and implemented, indicating the relative severity of damage in these disasters. The paper next analyzes the correlation between the four measures and observed traffic patterns. It concludes with a discussion of potential applications and areas for further research.

Highway Damage and Restoration in Recent Earthquakes

The October 17, 1989 Loma Prieta earthquake (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 failures 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. The Bay Bridge was closed for one month following the earthquake.

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 severe disruption to four critical highway routes in the northwestern Los Angeles metropolitan area -- Interstate 5 (I-5), State Route 14 at the interchange with I-5, State Route 118, and Interstate 10. On I-5 at the Gavin Canyon crossing, a detour was opened on January 29 and I-5 was reopened on May 18, four months after the earthquake. At the I-5/SR-14 interchange, 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. (Caltrans, private communication, March 1997)

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 nationwide economy had been 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.

Measures of Post-Disaster Network Performance

In order to effectively compare highway system performance across earthquake disasters, new measures or indices are needed. Performance measures traditionally used in transportation engineering are generally inappropriate for assessing post-disaster situations. These traditional measures typically address conditions at individual locations and focus on measuring traffic congestion. One measure of overall system performance that is sometimes used consists of total travel time on the network in vehicle-hours, that is the sum over all system links of the number of vehicles multiplied by travel time on each link. However, in a post-disaster situation, this measure is not practical because the availability of travel time data is very limited. In this section, new measures are developed for summarizing highway system damage and restoration following an earthquake. These indices emphasize physical condition and network functionality and are estimated for the Loma Prieta, Northridge, and Hyogoken-Nanbu earthquakes.

Selected Measures

Four alternative measures of structural and/or network performance are investigated in the analysis, all of which are estimated as ratios of post-earthquake to pre-earthquake conditions and range from 0 (system non-functional) to 1 (system fully functional):

1. Total number of highway sections open (measure *N*);
2. Total length of highway open (measure *L*);
3. Total “connected” length of highway open (measure *C*);
4. Total weighted connected length of highway open (measure *W*).

Perhaps the simplest measure, *N*, refers to the number of sections of highway that are open to traffic. Each section of road between two consecutive highway entrance ramps constitutes one section. Thus *N* indicates damage, rather than network degradation. Measure *L* is similar, but is based on length of highway open. Measure *C* attempts to capture the functionality of the highway system by recognizing the remaining degree of connectedness within the network. For a linear or non-redundant system, it is estimated as:

$$C = \frac{\sum_m l_m^2}{\sum_n \bar{l}_n^2} \qquad (1)$$

where l = connected length in damaged network (i.e., length between terminal nodes)
$\bar{l}$ = connected length in intact network
m = index for connected segments of damaged network
n = index for connected segments of intact network

Both the extent and location of damage contribute to this index. For example, a linear system with four nodes connected by three unit-length sections might have the middle section closed by earthquake damage. In that case, l_1=l_2=1 and $\bar{l}_1$=3. Thus C= (2x1^2)/3^2 = 0.22. However, if an end segment had been closed, l_1=2 and $\bar{l}_1$=3, so C= 2^2/3^2 = 0.44. Network degradation is lower if an end section rather than a middle section is closed. Note that for either damage scenario, N=L=0.67 and is higher than C.

While the highway network in Kobe can be adequately represented as a linear system, the networks affected by the Northridge and Loma Prieta earthquakes cannot. For these types of redundant systems, Equation 1 is modified as follows:

$$C = \frac{1}{K}\sum_k \left(\sum_m l_{m,k}^2 \Big/ \sum_n \bar{l}_{n,k}^2 \right) \qquad k = 1, 2,..., K \qquad (2)$$

where k = index for route directional group
K = total number of route directional groups being considered

Equation 2 modifies the criticality of a route according to the degree of redundancy of the network in K directions. For example, routes may be classified as either north-south or east-west if K=2. Thus, the significance of damage to an east-west route may be reduced if other parallel routes are intact. For a linear system, K=1 and Equation 2 reduces to Equation 1. (Similarly, measures N and L can be specified in terms of K directions.)

Measure W is similar to C, but further modifes the significance of damage to a particular route according to its importance. Importance (w) is indicated by the share of traffic in the relevant direction carried by that route prior to the earthquake.

$$W = \frac{1}{K}\sum_k \left(\sum_m (w_{m,k} \cdot l_{m,k})^2 \Big/ \sum_n (w_{n,k} \cdot l_{n,k})^2 \right) \qquad (3)$$

where $$w_{i,k} = \frac{V_{i,k}}{\max_j \left(V_{j,k} \right)}$$

where $w_{i,k}$ = weight for highway section i in directional group k, $0 \le w \le 1$
j = index for highway sections in a given directional group
V = pre-earthquake traffic volume

These four measures require only information on pre-earthquake network configuration, pre-earthquake traffic volumes, and post-earthquake physical damage and restoration patterns. As will be discussed below, adjustments can also be made to take into account the ameliorative effects of surface road detours around highway damage sites during reconstruction. Detours restore a portion of the connectedness of a damaged route.

A fundamental question concerns the relevant network to be analyzed. Too spare or limited a network would not adequately capture the extent of damage or availability of alternate routes, thus overestimating the deterioration in system condition. Too extensive a network would dilute the significance of the damage and provide little useful information. One approach is to consider the area of physical damage to the highway system together with major alternate routes that are undamaged.

Application to the Loma Prieta Earthquake

Analysis of highway system performance in the Loma Prieta earthquake focused on damage and restoration of the Bay Bridge on Interstate 80. The relevant network was defined to include significant alternate highway connections between Oakland (the East Bay) and San Francisco, as indicated in Wakabayashi and Kameda (1992). Two directional groupings (north-south and east-west) were used. Specifically, east-west routes included I-580 between Richmond and San Rafael, I-80 between Oakland and San Francisco, SR-92 between Hayward and San Mateo, and SR-84 between Fremont and Palo Alto. North-south routes included US-101 between San Rafael and Palo Alto, and I-580/880 between Richmond and Fremont.

Highway length and normal average daily traffic (ADT) data were obtained from the Caltrans website (http://www.dot.ca.gov/hq/traffops/traffsys/trafdata/trafdata.htm). While the ADT data pertained to conditions in 1996, rather than pre-earthquake conditions, these can reasonably be used for estimating the section weights w in Equation 3. The importance weight for the Bay Bridge was 1.0.

Results indicate that for the month in which the Bay Bridge was closed after the earthquake, N=0.88, L=0.89, C=0.92, and W=0.66. In this case, C is greater than L because three east-west routes were available following the earthquake as alternatives to the Bay Bridge. However, W indicates significantly greater system loss than C owing to the relatively high east-west traffic volume carried on the Bay Bridge under normal circumstances.

Application to the Northridge Earthquake

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. This area was delimited in part by the ten highway locations where Caltrans regularly collected post-earthquake traffic data. Again, routes were grouped into north-south and east-west categories. The former 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, and I-110 from Jct. I-5 to Jct. I-105. East-west routes included: 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. Normal highway ADT data were obtained from Caltrans as noted above.

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

$$Z' = Z + d_i \cdot (\overline{Z} - Z) \tag{4}$$

where *Z¢* = measure N, L, C, or W, adjusted for detour i
Z = same measure, without adjustment for detour i
d_i = detour factor for i
$\overline{Z}$ = same measure, with full restoration at detour location i

The factor d depends upon on traffic capacity of the detour route relative to the damage 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.

Results immediately after the earthquake show that N=0.90, L=0.89, C=0.84, and W=0.89. Results over the restoration period will be discussed below. Here, in contrast to the Loma Prieta case, C is somewhat less than L because two of the four east-west routes suffered significant mid-route severance. However, if weighted by normal traffic loadings, the system functionality measure improves. For Northridge, the four measures provide very similar estimates of system degradation due to the highly redundant nature of the highway network and the distribution of damage. These measures also indicate that initial highway system degradation in Northridge was somewhat less than that in Loma Prieta, which is consistent with expectation.

Application to Hyogoken-Nanbu Earthquake

Analysis of highway system performance in the Hyogoken-Nanbu earthquake focused on Hanshin Expressway Routes 3, 5, 7 and 16, Chugoku National Expressway (from Yokawa Jct. to Suita Jct.), and Meishin National Expressway (from Suita Jct. to Nishinomiya IC). 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 Hanshin area. Therefore, directional grouping was not applied in this case. 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 rather than weekly basis.

One of the reasons is data availability, and the other is longer period of traffic closure than the former two cases in the U.S., i.e., more than 20 months on Hanshin Expressway Route 3. Detour adjustments were not made to the measures since local arterial streets had insufficient capability to accommodate detouring vehicles due to damage, reconstruction work, and/or traffic control.

Results immediately after the earthquake show all the measures dropped to 0 due to full closure of highway networks. In February 1995, after non-damaged segments were made open to traffic, these measures rose to N=0.63, L=0.67, C=0.57, and W=0.47. The measure W was much smaller than the remaining three, because sections of high importance with heavy traffic in Hanshin Expressway Route 3 were severed. Table 1 provides a comparative summary of the various measures in the three earthquakes. Even after the emergency period, the Hanshin network is much more degraded than its counterparts in the other two disasters.

Table 1. Post-Earthquake Measures of System Performance

	Measure N	Measure L	Measure C	Measure W
1989 Loma Prieta EQ (immed. after EQ)	0.88	0.89	0.92	0.66
1994 Northridge EQ (immed. after EQ)	0.90	0.89	0.84	0.89
1995 Hyogoken-Nanbu EQ (after 1 mo.)	0.63	0.67	0.57	0.47

Correlation Between Network Performance and Traffic Restoration

The various measures developed above may each be useful for different purposes. The objective of this study was to determine measure(s) that would be informative for economic impact analysis. The four measures of physical restoration were therefore compared with actual traffic conditions in the post-disaster restoration period for the Northridge and Hyogoken-Nanbu earthquakes. Insufficient traffic data precluded similar analysis for the Loma Prieta earthquake. This analysis aimed to evaluate (1) which measure of physical system degradation could best explain observed traffic conditions, (2) the extent to which highway system degradation and restoration alone could explain post-earthquake traffic patterns, and (3) whether such a correlation differs between moderate and catastrophic disasters.

Northridge Earthquake

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. 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 the monthly data were reported, these counts were provided on a weekly basis. Pre-earthquake daily traffic data at these locations were also provided for the corresponding months in 1993. Ratios of post- to pre-earthquake ADT were estimated for each count location, and assigned to segments of the study network. In some cases, averages of two nearby count locations were assigned. These ratios were applied to base-year ADT data to approximate post-disaster ADT for each section of the network, and weighted with section length data. As noted previously, base-year ADT data pertained to 1996 conditions. The resulting weighted sum (*T*) indicates system vehicle-miles of travel on a weekly basis.

Figure 1 shows the restoration of traffic on a weekly basis following the Northridge earthquake. The figure also plots the restoration of each of the four system performance measures over this period. All four measures show fairly good correlation with actual traffic restoration. However, traffic conditions are generally lower than the performance measures in the initial period and improve more rapidly than the four measures would suggest. From week 19 (early June) onward, traffic actually exceeds pre-earthquake volumes.

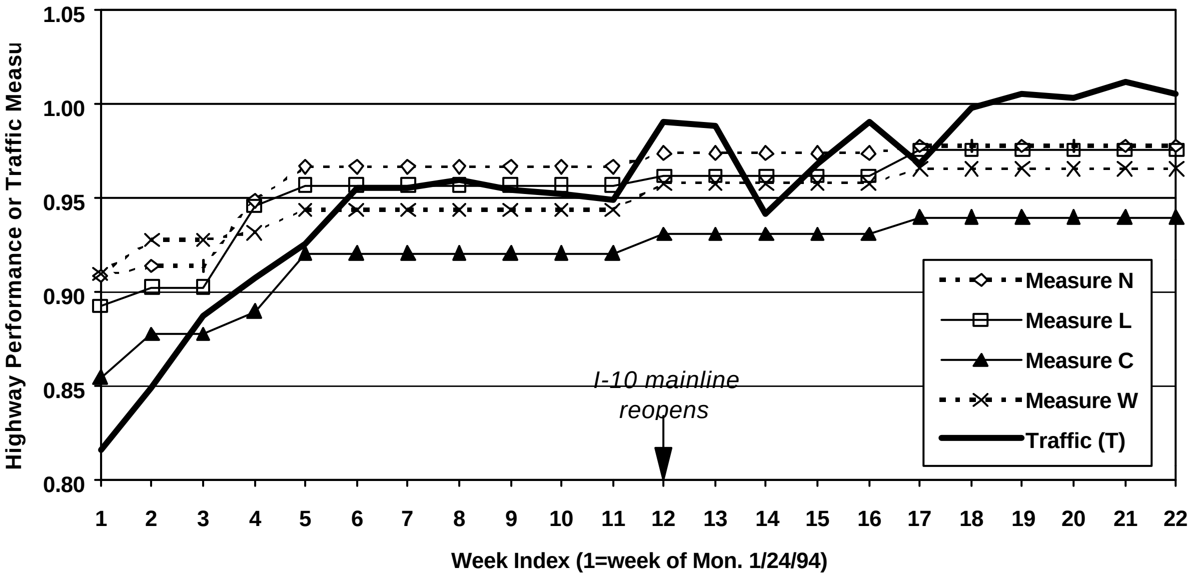

Figure 1. System Measures and Traffic Restoration, Northridge Earthquake

Hyogoken-Nanbu Earthquake

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 average daily traffic volumes (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. The sum of section ADT multiplied by section length adds up to total vehicle-kilometers of transportation volumes over the entire study network. Normalized by pre-quake (from October through December 1994) average levels, the sum was compared with the four performance measures.

Figure 2 shows the restoration of traffic on a monthly basis following the Hyogoken-Nanbu earthquake with plots of the four performance measures. Although the measures recovered to N=0.75, L=0.81, C=0.69, and W=0.52 by May 1995, progress stalled for over a year until July 1996, when reopening of Hanshin Expressway Route 3 began to accelerate until full restoration was completed at the end of September 1996. While these measures exceed 0.9 after one month in the Loma Prieta and Northridge cases, long-term degradation can be seen in the Hanshin case, which clearly indicates significantly greater impact on the local and national economy.

The four measures are consistently ordered as L, N, C, and W from the highest to the lowest. Measure W tends to exaggerate the impact of physical damage because of damage to heavy traffic sections on Route 3 and is much lower the others throughout the reconstruction period. As seen in Northridge, traffic is lower than the performance measures in the initial period. Once conditions become less confused, however, traffic conditions recover rapidly. While seasonal fluctuation is clearly observed on the Chugoku National Expressway in August, it can be seen that measures L and C serve as an upper bound and an approximately lower bound, respectively.

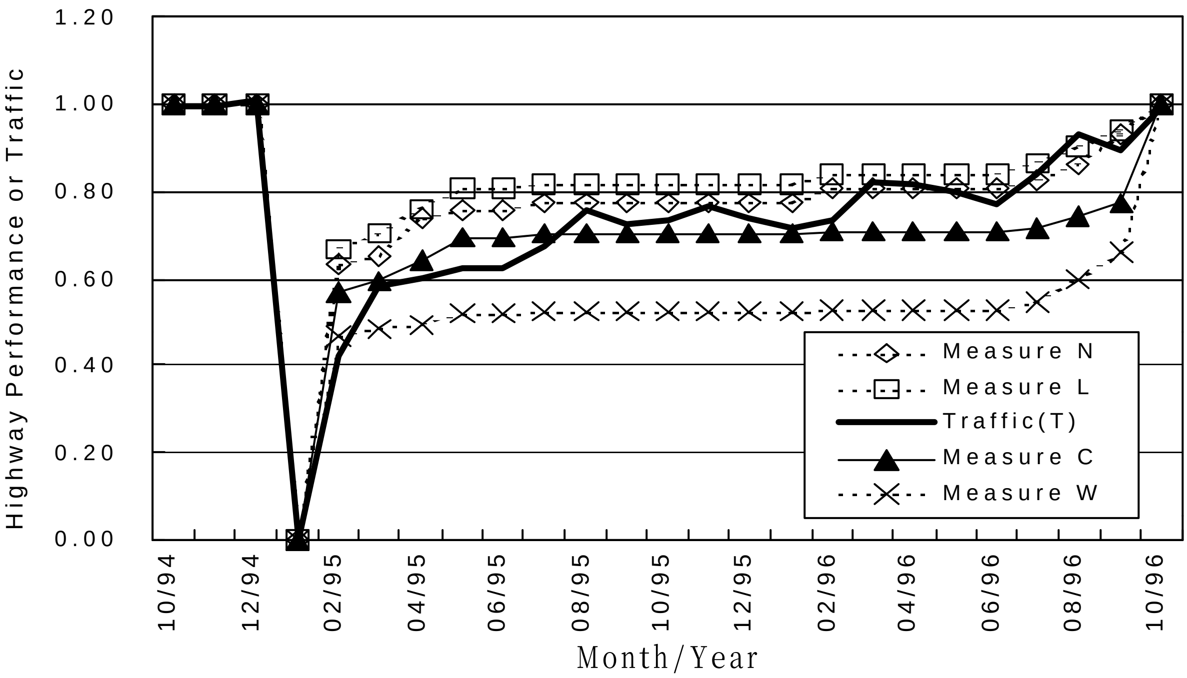

Figure 2. System Measures and Traffic Restoration, Hyogoken-Nanbu Earthquake

Regression Analysis

It is not obvious from Figures 1 and 2 which of the four measures most accurately predicts observed traffic conditions. Indeed, it is expected that system condition represents but one factor that would influence post-earthquake traffic. A simple regression model is estimated to compare the correlation between the four measures and an index of traffic conditions (T):

$$T = \alpha + \beta X + \varepsilon \qquad (5)$$

where X = system performance measure (N, L, C or W)
α, β = parameters to be estimated
ε = error term

Results are shown in Table 1. For Northridge, the explanatory power of the models is similar and very high, with adjusted-R^2 values from 0.85 to 0.90. In the Hyogoken-Nanbu earthquake, measures N and L have explanatory power as high as in Northridge, but C and W do not.

Table 2. Regression Results, Northridge and Hyogoken-Nanbu Earthquakes[(a)]

	$X = N$	$X = L$	$X = C$	$X = W$
Northridge Earthquake				
Constant (α)	-1.14	-0.93	-0.94	-1.97
Coefficient (β)	2.17	1.98	2.05	3.08
Adjusted R^2	0.85	0.87	0.90	0.86
Hyogoken-Nanbu Earthquake				
Constant (α)	-0.44	-0.68	-0.17	0.31
Coefficient (β)	1.49	1.71	1.28	0.78
Adjusted R^2	0.84	0.86	0.63	0.42

Note: (a) all estimated coefficients α and β are significant at the 1 percent level.

If any of the measures had a direct correspondence to actual traffic, α would be 0 and β would be 1. The difference between highway network performance (as indicated by any of the four measures) and observed post-earthquake traffic conditions may be due to many factors. Some of the more likely ones are:

1. **Economic impact -** In the initial period following a disaster, economic activity is typically dampened by the occurence of damage, the need to implement emergency measures, debris cleanup, etc. Some time afterward, however, normal activity resumes and reconstruction commences, which may lead to above-normal activity for several weeks or months. In L.A., economic indicators suggest that this reconstruction boom may have occurred primarily in the period from 3 to 7 months after the earthquake. Greater economic activity leads to higher traffic volumes on regional highways.
2. **Traffic control –** In the initial period following a disaster, particularly for a catastrophic disaster, ordinary traffic may be controlled to give priority to emergency vehicles responding to the disaster. During the first month following the Hyogoken-Nanbu earthquake, in particular, traffic control was very strict and widely carried out.
3. **Trip length -** When certain highway links are damaged, some motorists may take alternate highway routes rather than use arterial street detours. Thus if origin-destination flows

remained constant, these longer trips would increase total traffic volume on the network as measured in vehicle-miles.

Conclusions

This paper developed several alternative measures of post-disaster highway system performance and applied them to recent earthquakes. The analysis explored the extent to which these system performance measures correlate with traffic data over the restoration period. Regression analysis found that the measures have generally high correlation with traffic recovery, with measure *L* providing the best fit in both the Northridge and Kobe cases (with R^2 values of 0.86-0.87).

Inspection of each time period, however, suggests that the restoration timepath can be differentiated into three phases. In the first "emergency" phase, detours around highway damage are instituted and traffic may be controlled for emergency response. Economic activity is generally depressed due to the need to clean up earthquake damage and reestablish normal modes of operation. In this phase, traffic volume restoration is lower than the performance measures would imply. Several weeks later, a "rapid restoration" phase begins, in which lesser and/or critical repairs are made quickly to restore the network to a temporarily stable system. At the same time, similar recovery patterns are seen in economic activity. In this phase, measure *C* appears to most closely correlate with traffic restoration, indicating that the degree of connection within the network is important and highway capacity may to some extent constrain recovery. Following this, restoration reaches a lengthy plateau during which the most difficult repairs are made. Economic activity and traffic volumes may recover somewhat more rapidly than network restoration during this period, spurred in part by reconstruction activity. In contrast to Kobe, a catastrophic disaster, traffic in the moderate-sized Northridge disaster actually exceeded pre-earthquake volumes for part of this period. Measure *L* appears to correlate most closely with observed traffic during this "final restoration" phase.

These observations suggest several areas for further research. For example, account should be made of the impact of detour routes on travel time, the availability of alternative modes of transportation such as railway or perhaps even telecommuting, the changes in highway demand in the post-earthquake emergency period, and network connectivity between OD pairs in the system. Links between system restoration and economic impact and recovery are also important topics further research. By establishing the relationship between highway damage and economic activity, system performance measures such as those explored here can potentially be used in earthquake loss estimation (e.g., in real-time applications), recovery planning, bridge retrofit prioritization, as well as economic impact modeling.

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