SEISMIC RISK ASSESSMENT OF UTAH TRANSPORTATION SYSTEMS AND RECOMMENDATIONS FOR RISK REDUCTION

SEISMIC SAFETY
ADVISORY
COUNCIL

STATE OF UTAH

807 EAST SOUTH TEMPLE STREET
SUITE 103
SALT LAKE CITY, UTAH 84102

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Prepared By

Dr. Craig E. Taylor
Research Analyst

Under State Contract Number 80-5006

and

Delbert B. Ward
Executive Director
Seismic Safety Advisory Council

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FOREWORD

The Utah Seismic Safety Advisory Council, established in 1977, is charged to prepare assessments of earthquake hazards and associated risks to life and property in the State of Utah, and to make recommendations for mitigating hazards that may be found.

This report presents an assessment of earthquake risk for tranportation systems in Utah. The report includes recommendations for reducing risks that are believed to be reasonably manageable within available resources. The recommendations are set forth as judgements of the Seismic Safety Advisory Council in terms of effectiveness of the suggested action for reducing risk to life, health, and property.

This report is divided into a summary of findings, a discussion of earthquake effects upon highway and railroad transportation systems in general, and an assessment of earthquake risks to highways and railroads in Utah, with emphasis given to highway bridge structures. Recommendations for earthquake risk reduction also are made that deal primarily with policies, though some technical matters also are treated.

The report presents an overview of earthquake risk to selected transportation systems and treats the vulnerability of bridge structures in greater detail. The vulnerabilities of particular types of bridge structures to earthquake effects are discussed, and guidance is provided by which highway designers may undertake detailed evaluations to establish priorities for mitigation efforts in accordance with aspects or components of greatest vulnerability or of greatest importance to public purposes. The vulnerability assessment of railroads to earthquake effects considers bridge structures as well as geologic conditions susceptible to earthquake-induced failure.

Most, although not all, major bridge structures in Utah are State-owned facilities designed, constructed, managed, and maintained by or for the State Department of Transportation. These structures are the focus of this report. Damage to them, as might be caused by earthquakes, would cause the greatest inconvenience and economic loss among the various types of transportation facilities. Not only have highway systems been created through huge investments of public funds, but public dependence upon them, for commerce and leisure activities, also is great. Hence, unnecessary earthquake risk to these facilities is a matter in which the State and the public have direct interest.

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SECTION 1

INTRODUCTION

The earthquake vulnerability of transportation systems in Utah has been the subject of separate study by the Seismic Safety Advisory Council for two principal reasons: (1) Transportation systems are essential in the day-to-day functions of business carried on in the State and may be critical in certain situations to post-earthquake disaster response activities, and (2) Highway systems are costly investments, paid for by public funds, that merit a reasonable degree of security against failures or loss. Any unnecessary loss to the transportation systems likely will result in inconvenience and assuredly will result in high repair costs that the public would be called upon to pay. Another factor, not considered in depth in this report, is the importance of the interstate highway system and the railroads passing through the State to national security and defense.

Earthquake risk to highway systems is associated primarily with particular structures or facilities along the linear transportation routes. Foremost among the points of risk are bridge structures which, if failure were to occur, could render the transportation route unusable. Highway systems typically are less vulnerable in this regard than are railroad systems, because alternative or bypass routes often are available in the event of a highway bridge structure failure, whereas for railroads bypasses normally are not available. On the other hand, highway systems occur more widely, are used by a greater number of people, and are used for a greater of variety of purposes. The inconvenience caused by any dysfunction, therefore, would be more immediate and have wider impact.

In this report, the vulnerabilities and possible hazards posed to facilities of transportation systems are examined, particularly with a focus upon bridge structures for highway sytems. Consideration has been given mostly to bridge structures along major arterial routes in regions of highest seismicity and regions of greatest highway use. Damage to roadbeds, although a definite possibility resulting from ground displacments as might be caused by earthquakes, has not been treated in this report, since such damage likely would not render the systems completely inoperative and the damage is easier and less costly to repair.

Vulnerability analysis in this report is based (1) upon damage to highway bridge structures caused by earthquakes in other regions of the nation and (2) upon a general engineering evaluation of bridge construction practices in the State of Utah. Detailed engineering analysis of specific bridge structures has not been attempted in this report, although such analysis will be required before recommended actions are implemented.

Special emphasis is given in this report to practices in the design of highway system bridge structures as have been followed by the Utah Department of Transportation. These past practices are deemed to constitute current State policy concerning the earthquake safety of highway systems. We have found these past practices deficient in the attention given to earthquake-resistant design and, as a consequence, have found that some portions of principal arterial highway systems in the State are unnecessarily vulnerable to earthquake damage. This vulnerability occurs randomly and without pattern among the bridge structures owing to the fact that different types of structural arrangements have been used and also to the fact that earthquake effects upon these different types of structural systems vary.

Recommendations made herein for earthquake risk reduction to transportation systems, more particularly highway transportation systems, generally are of a policy type rather than technically specific. Such technical details are left to the agencies having jurisdiction over the design and construction of the facilities.

No evidence has been discovered that the earthquake safety of transportation systems has been a subject of public discussion or dialogue in Utah in past years. Thus, the present policies being followed as regards earthquake safety for highway systems have been decided by staffs of government agencies and may or may not reflect public concern for the current situation. The current situation is that no special attention has been or is being given to earthquake-resistant design of highway bridge structures. The Seismic Safety Advisory Council believes that present policies should be modified to take advantage of state-of-the-art knowledge and, when conditions are appropriate, to include provision for improved earthquake resistance of the facilities. The Council urges adoption and implementation of the recommendations contained herein.

SECTION 2

SUMMARY OF FINDINGS

Principal findings resulting from the seismic risk assessment of transportations systems in Utah reported herein are summarized in this section without elaboration or extensive discussion. More detailed information is provided in Sections 4 and 5, using information drawn primarily from damage assessments to transportation systems in other parts of the nation and world that have been subjected to earthquakes and from a more detailed evaluation of engineering practices in the State of Utah. In Section 4, a general overview of the seismic response of transportation systems is furnished, with special attention given to highway bridge structures. In Section 5, earthquake risks to transportation systems in Utah are described, based upon information about Utah's seismic environment, and a provisional listing of possibly high-risk bridge structures is provided. Recommendations for earthquake risk reduction to transportation systems are presented in Section 3.

The perspective taken in this report is that highway systems are essential to the activities of day-to-day commerce and industry and critical to disaster response activities. Other parts of the perspective are that highway systems are extremely costly to construct, cannot be easily replaced in short periods of time, and, under certain conditions, they may pose direct threat to life safety. It is noted that a recent earthquake in Northern California caused loss of life to drivers of vehicles using the highway system at the time, and the San Fernando earthquake in 1971 also resulted in loss of life. Thus, public safety and economic investment both are at risk for tranportation systems in earthquake conditions.

Earthquake Damage To Highway Bridge Structures

Data on earthquake damage to bridge structures caused by earthquakes in other regions of the country are not extensive, although enough information was obtained as a result of earthquakes during the 1970's to suggest that earthquake damage to bridges is possible and also to indicate those situations or conditions of bridge design and construction which are more vulnerable than others. Failures have been observed in support foundations, abutments, and rocker-type support points for girders, and displacment has occurred as a result of discontinuity at expansion joints in spans. As well, failures of spans supported on the high pedestal-type columns have been observed. Complete collapse of spans has occurred, although the more prevalent damage is less obvious, such as displacment at supports, differential movement at abutments, and cracking of reinforced concrete at abutments. Data is too sparse to allow statistical conclusions to be drawn regarding earthquake intensity levels at which threshold damage to bridge structures appears. The available data indicates that displacements have occurred in earthquakes of Richter magnitude in the 5+ and 6+ range, although the more prevalent damage appears to occur in the high 6 and 7+ Richter magnitude range.

Seismicity In Utah

Seismicity is common in most of the State of Utah with the possible exception of the easternmost portion. The most severe and frequent earthquakes historically have occurred along a central region extending form the north-central border to the southwest border. This seismic region is part of an area that has become known as the Intermountain Seismic Belt. Geologic evidence suggests that severe seismicity in the future most likely will occur within this same region, with the Wasatch Fault zone being the zone of greatest risk. Although the probable frequency of strong earthquakes is expected to be very low, the Wasatch Fault is said to be capable of producing earthquakes in the 7.3 Richter magnitude range. Earthquakes in the 6+ Richter magnitude range not only have occurred in historic time in the State, but Utah can expect to experience more such events in the future. These earthquake strengths are above the threshold levels of damage for highway bridge structures that have been observed from earthquakes in other regions.

Seismic Vulnerability Of Highway Bridges In Utah

Preliminary engineering evaluations of a very small number of bridge structures along the interstate highway system in Utah's Wasatch Front region suggest, for certain conditions, that the structures are capable of resisting earthquake forces in the range of about 0.13 g acceleration. In seismic Zone U-4 (see Figure 2) seismic forces in the range of 0.2 g or larger appear possible. In Zone U-3, similar accelerations are possible, although much less frequently. Expected ground accelerations in the other seismic zones of the State appear to be of 0.1 g or less. It therefore is concluded that highway bridge structures in seismic Zones U-3 and U-4 are vulnerable to damage by stronger earthquakes. Note is made, however, that the point of first vulnerability appears to be the bearing connection for bridge girders and that this condition in most, if not all, instances can be remedied by the installation of restrainers to withstand the displacement tendency.

Similar engineering analyses were not undertaken for railroad bridge structures, and so parallel conclusions could not be derived for this report.

Based upon a report which summarizes indicators of earthquake vulnerability for highway structures, prepared by consultants retained by the Seismic Safety Advisory Council, bridge structures along principal arterial highway and interstate roadways in the Wasatch Front region were evaluated, using construction information furnished by the Utah Department of Transportation, to provide a provisional assessment of probable earthquake risk. The factors considered were (1) Type of construction, (2) Number of spans, (3) Skew of the bridge, (4) Vertical clearance of the bridge, and (5) Length of the structure. From this assessment, a listing of priorities for seismic inspection, review, and possible retrofit of highway bridge structures was compiled. Priorities were based upon the number of risk indicators found in the data for each structure included in the sample survey. As is shown in Table 5, the number of structures in the priority listing is not extremely large, and hence, a program for technical review and evaluation of the list of bridge structures appears to be both manageable and feasible.

SECTION 3

RECOMMENDATIONS FOR REDUCING EARTHQUAKE RISK TO UTAH TRANSPORTATION SYSTEMS

The following recommendations result from a study of the expected impact of earthquakes upon existing highway and railroad transportation systems and facilities in Utah. The study, titled "Seismic Risk Assessment Of Utah Transportation Systems," provides information upon the extent and nature of earthquake hazards to highway and railroad systems in Utah's seismic environment. The recommendations that follow are based upon the findings of this study.

The safeguarding of transportation systems from earthquake damage is a matter of special concern in State earthquake safety policy for at least two reasons. The first reason is that particular transportation systems, especially arterial highways and freeways, may be essential for effective emergency response activities immediately following a severe earthquake. Movement of emergency fire and medical vehicles and of disaster assistance teams are likely to be important life safety activities. The second reason, which gives added importance to highway systems, is that the associated facilities represent tremendous investments of public funds, a consequence being that any loss or damage could be severely crippling to the economy of an area, not only as a result of direct losses but also as a result of longer term losses to commerce and industry. The public therefore has a significant interest in the continuing operation of highways and the security of these systems from damage. The following recommendations regarding earthquake safety of transportation systems, then, are designed to safeguard the public's dependence upon transportation systems and, as well, as to protect public investments in these facilities.

The recommendations presented here are especially intended to correct past practices which have disregarded the earthquake safety of highway systems, especially facilities such as bridges and overpasses, which are components of the systems. Utah's earthquake environment is sufficiently severe and the expended life or use period of highway systems is sufficiently long to warrant at least minimum consideration of earthquake resistance in their design. The findings of this study are that earthquake safety typically has not been considered in the design of highway systems by the Utah Department of Transportation and its predecessor agencies even though accepted standards of highway construction would suggest that this should have been done in recent years. The general problem is believed to be of enough importance to the public, and the earthquake risk in Utah's regions of higher seismic activity great enough, so that the Seismic Safety Advisory Council cannot accept arguments that have been heard that the design of earthquake-resistant bridge structures is economically infeasible. It is the Advisory Council's view that state-of-the-art engineering techniques and knowledge of earthquake vulnerability of bridge structures allows for improvement in design practices. Thus, continuation of past practices in which earthquake safety considerations have been set aside should no longer be acceptable public policy.

1. <u>It is recommended that all designs for new highway bridges and other structures in Utah be in accordance with state-of-the-art engineering techniques and earthquake standards appropriate to the locale.</u>

The purpose of this recommendation is intended primarily to alter prevailing past attitudes and consequent practices concerning the feasibility of creating highway structures that have greater resistance to earthquake effects. The impact of this recommendation would largely be upon design philosphy which, in turn, would extend into structural concepts and details. State-of-the-art concepts for earthquake-resistant design of highway structures has progressed significantly since the 1971 San Fernando earthquake in which a number of costly highway structures in California suffered severe damage. Such factors as structural ductility, structural continuity, girder bearings, and column-abutment interaction are found to significantly affect the earthquake performance of bridge structures. There are engineering techniques to deal with these problems, and they should be applied in accordance with the ground accelerations expected in the various seismic regions of the State of Utah.

2. <u>It is recommended that engineering evaluations be undertaken by the Utah Department of Transportation to determine the seismic resistance of existing bridge structures along the major arterial and expressway routes in the State in accordance with the priority listing or some similar listing as included in this report.</u>

The purpose of this recommendation is to identify more precisely the extent and degree of earthquake risk for major highway facilities in the State. There is information available which allows preliminary evaluation to be made of the earthquake vulnerability of various assemblies and details of bridge structures. Such information can be compared with the actual configurations and details of existing bridge structures to accomplish this recommendation.

3. <u>It is recommended that a program be established by the State of Utah for retrofit of existing important highway structures to provide restrainers for the purpose of resisting failures at support bearing points of selected types of bridge structures, and that this program for retrofit be implemented in accordance with the priority listing of bridge structures provisionally listed in this report, or as this listing may</u>

be modified by implementation of Recommendation 2.

Various analyses by knowledgable experts concerning the earthquake vulnerability of particular types of bridge structure assemblies indicate special vulnerability to damage resulting from displacment of bridge structure girders. Information also is available which indicates that retrofitting to restrain such displacement can be incorporated into existing bridge structures relatively inexpensively. Such retrofit should be undertaken for those bridge structures in the State which may be identified as having this type of vulnerability to damage by lateral forces.

4. It is recommended that consideration be given to the potential for soil liquefaction in the design of new bridge structures for Utah highways, to include appropriate borings and laboratory tests as well as use of state-of-the-art methodologies to resist liquefaction-type failures at sites where such failure potential has been determined to exist.

It has been recognized for some time that earthquake-induced ground vibrations can alter the bearing capabilities of soils under special conditions. Wet, sandy-type soils are especially prone to such effects, and bridge structures supported on these types of soils thereby become vulnerable to settlement and, possibly, damage or even failure. It happens that valleys along the Wasatch Front have an abundance of potentially liquefiable soils, the result being that bridge structures located in such areas face a special type of possible earthquake failure. Increased awareness of this type of failure is warranted under the circumstances, and this recommendation is intended to cause increased consideration for such soil conditions as a means to reduce this type of possibly costly highway system failure.

SECTION 4

A GENERAL OVERVIEW OF THE SEISMIC RESPONSE OF TRANSPORTATION SYSTEMS

In this section, the expected earthquake response of Utah transportation systems is described. Special emphasis is upon highway systems. Some attention is given to railway systems. A discussion of air transportation systems is ommitted. Airports are at some distance from each other, so that simultaneous failure of airports as a result of an earthquake is unlikely, although localized dysfunction could result.

Emphasis is placed upon highway and, especially, freeway systems for a variety of reasons. First, roadways are essential for moving people and goods to their points of destination. Highways are the equivalent of distribution systems for natural gas, water, or electric power supply systems in the sense that they are essential elements of today's social and economic fabric. Second, highways also are the most important general means of transportation, at least in Utah, for serving a broad range of transport purposes. Due to this historical dependence, even evacuation of a community, if needed, would be by highway or freeway. Other important long-distance transportation also occurs on freeways and highways.

Special investigation and study are needed to draw any definite results concerning the risk of any of the transportation systems to earthquakes. In this report, the investigation focuses upon highway bridge structures because these appear to be the most critical to the continuing functional operation of a highway system.

Investigations of liquefaction potential, expected to be made at some later date, should throw further light upon claims already made that the Salt Lake International Airport is located in an area of potentially liquefiable soil ([19], pp. 250, 251) and therefore is vulnerable to earthquake effects.

In order to examine the expected response of Utah transportation systems in earthquakes, it is first necessary to examine the response of such systems in past earthquakes around the world. Such an examination, made in this section, provides ample evidence for the need to employ expert engineering consultants to investigate highway bridge structures. In Section 5, Utah's transportation systems are described generally in regard to expected response to seismicity in various portions of the State. Some broad conclusions, resulting from the work of Agbabian Associates, engineering consultants, also are described.

PAST EARTHQUAKE DAMAGE TO HIGHWAY BRIDGE STRUCTURES

Although the number of cases of earthquake damage to highway structures is limited, data upon past damage are rich in engineering analysis of those damaged structures. Considerable analysis has been made of damaged structures in the 1971 San Fernando Valley earthquake, as well as of damaged structures in the 1964 Alaska earthquake. Further data come from bridges damaged in the 1923 Kanto (Japan), the 1948 Fukui (Japan), the 1964 Niigata (Japan), and the 1960 Chile earthquakes ([12], p. 1,951; [15], p. 104).

Prior to 1971, earthquake damage to California bridges has been estimated to result in losses less than $100,000 ([4], p. 97). However, according to one source, prior to 1971 no bridges had been close to the region of intense ground shaking ([8], p. 2,301). In the 1971 San Fernando earthquake, 62 bridges suffered some damage, of which 42 suffered significant damage. Two structures collapsed, and a total of five required complete replacment. One collapse caused two deaths, and another death occurred as a result of a fall from a freeway structure. Total damage has been estimated at $15 million ([1], p. 64; [9], p. 171; [13]). In response to such damage, the State of California retrofitted 158 highway bridges to provide improved lateral-force resistance at a cost of $5.7 million ([7], p. 127).

Numerous bridges also failed in the 1964 Alaska earthquake. One report about such failures emphasizes how those bridges built on poor soil conditions, such as on granular soils or in transition areas from bedrock to silts and fine sands, tended to suffer more severe damage. One typical example of such failure was the three-span Resurrection River Bridge, built with steel stringers on a reinforced-concrete deck, with reinforced-concrete piers on timber piles, and with reinforced-concrete abutments on 3-rail steel piles. Failure of retaining walls that were adjacent to piers caused piers to rotate severely, and led to buckling of decks ([14]).

Table 1 lists earthquake damage to highway bridge structures in Japan. The table indicates that a number of bridges have suffered significant damage in past earthquakes.

Analyses of the San Fernando earthquake have tended to stress several engineering design weaknesses, some owing to weaknesses in existing codes and standards, in those bridge structures that were damaged. One report emphasizes problems at the ties between superstructures and reinforcement of concrete columns ([4]). Another emphasizes vulnerable rocker-type support bearings ([8], p. 23). Another report concentrates upon the vulnerability of certain types of long curved reinforced-concrete bridges ([10]). Still another report stresses the variety of structural weaknesses that allowed severe damage ([13]).

One Japanese report states that the most common type of earthquake damage to bridge systems is failure or subsidence of backfill soil near abutments ([6], p. 129). According to another Japanese report, earthquake damage to superstructures owing to purely vibrational effects is rare, although during the San Fernando earthquake vibrational effects caused large relative displacements in expansion joints and some severe failures ([9], p. 173). One report subsequent to the Alaska earthquake indicates that soil problems are actually design problems:

> The possiblity of movements of earth-retaining structures due to increased lateral pressures must be considered a significant design problem in seismic regions ([15], p. 106).

In a report prepared for the Federal Highway Administration, R.R. Robinson and others assess vulnerability of bridge structures to earthquake damage in terms of the structural types ([16], p. 31). The degree of vulnerability is matched with particular types of configurations and structural arrangements.

Certain Survivability:	(i)	Single span, rigid frame.
	(ii)	Continuous, multiple span rigid frame without expansion joints.
Probably Sound:	(iii)	Simply supported spans with continuous, composite slabs.
	(iv)	Long, continuous, composite reinforced-concrete slab bridges without expansion joints in an adjacent span having a hinge.
	(v)	One, two, or three-span bridges with high backfilled or bin type abutments.
Probably Unsound:	(vi)	Continuous span bridges with at least one hinge or with expansion joints on one or both sides of a pier.
Certain Failure:	(vii)	Simply supported single and multiple span bridges with two hinges or hangers in any one span or in adjacent spans.

In another report from Japanese data on existing bridges, ground condition, and liquefaction portential are two of eleven criteria for evaluating the seismic safety of existing bridges ([12], p. 1,956). The other nine criteria are type of substructure, type of bearing, maximum height of abutment or pier, number of spans, width of substructure's crest, length of suspended joint, severity of shaking, foundation, and material of abutment or pier. Specially vulnerable structures are simple or cantilever superstructures. Other vulnerable features include those without aseismic bearing devices, those with high abutments or piers, those with multiple spans, those with pile bents, and those with unreinforced-concrete or masonry abutments or piers ([12], p. 1,956).

Factors considered in the California retrofit program were type of bearings, width of bearing seat, restraint at supports, height of structure, type of supports, flexibility of supports, curvature in alignment, and other general factors relating to public hazards ([4], p. 99).

One Japanese report and other studies of earthquake risk tend to indicate that the threshold of severe damage to bridge structures is Intensity IX on the Modified Mercalli Intensity Scale. For a more complete account of the Modified Mercalli Intensity Scale, see Appendix A and also [20], pp. 202-205. For attempts to correlate intensity and maximum effective peak acceleration values, see [21]. A conservative estimate of 10-percent collapse at Intensity IX or above is indicated in the Japanese report, and an estimate of 5 percent, where no ground rupture or liquefaction occurs, is given in the other report ([17], pp. 234, 235; [12], pp. 1,954-1,956).

IMPORTANCE OF HIGHWAY BRIDGE STRUCTURES TO THE HIGHWAY SYSTEM

Highway structures (overpasses, grade separations, elevated roadways, and bridges) are commonplace in any 20th-century urban highway network and interstate system. Given their prevalence, one must seek some means to decide the importance of one such structure over another. This sort of priority ranking, of course, depends heavily upon the subjective criteria of rating, because, for instance, interstate transport on a daily basis has different economic and social implications than does, say, commuter travel of a work force. For this study, the criteria for rating of importance were developed primarily around the function of post-earthquake response and recovery activities.

Given the variety of uses of vehicles, from going on errands to going to work, and from shopping to picking up emergency victims, one can organize such functions into possible post-disaster relief functions and into long-term functions.

Possibly post-disaster relief functions, as well as some implicit long-term funtions, are captured in the ratings of bridges that R.R. Robinson and others provide ([16], pp. 22-30). On their analysis, a bridge is critical if one of the following conditions is met.

(1) The bridge is on an interstate highway or expressway.

(2) The bridge is required for survival.

(3) The bridge is essential in security or defense matters and is nonbypassable.

(4) The annual average daily traffic exceeds 80,000 vehicles.

Condition (3) is rare, since most bridges are bypassable either by use of other routes or by use of off- and on-ramps. Condition (4) brings in some possible long-range consequences of bridge damage, to the extent that alternative routes entail greater transportation costs or lost business. Condition (2) pertains to use of routes in medical support, food, water, law enforcement, fire, and disaster functions. Transporting disabled victims to health-care centers, along with transporting routine pregnancy and other cases to such centers, imply the need for many available routes. Similar remarks apply to search and rescue operations, maintenance of law and order, delivery of food and water, moving people to shelters, control of traffic, and restoration of utilities and other damaged facilities, including movement of people to communications centers, utilities companies, and other operations that might be placed on emergency status.

On the same analysis, all primary or major arterial bridges are classified as at least "desired." Other bridges may be classified "convenient" or "expendable."

Consideration of long-range consequences of bridge failure also suggests that a host of other factors may be involved in evaluating bridges. Long-term loss of a bridge may entail not only increased transportation costs owing to use of detours but also changes in commercial activities as a result of changed driving patterns. Deliveries, shopping habits, and business all can be affected owing to such changes. Airports, bus terminals, ski resorts, or shopping centers also can be affected by such long-term changes.

PAST EARTHQUAKE DAMAGE TO RAILROADS

Data on past earthquake damage to railroads are severely limited except for building damage data that may, by analogy, be applied to railroad facilities. Data here come principally from studies of the 1964 Alaskan earthquake and the 1964 Niigata (Japan) earthquake.

Earthquake damage to railroads can be severe. In the 1923 Kanto (Japan) earthquake, 111 people died when a landslide swept a train into the sea ([9], p. 171). Railroad reconstruction costs after the 1964 Alaska earthquake amounted to $22.1 million ([25], pp. 958, 959).

In the Alaskan earthquake, damage to bridges cost $1,567,000. One hundred nine bridges were damaged, of which 71 were totally unserviceable for train operation ([25], p. 978). Some damage occurred to 73 bridges in the Niigata earthquake, especially where soft soils were prevalent, but only a few bridges were damaged enough to stop railway traffic ([26], p. 451).

Railway bridges may be damaged for a variety of reasons, including structural weaknesses magnified by ground-shaking, failures at embankments, cracking of sidewalls, girder displacement, and failures of soils such as with liquefaction. In the Niigata earthquake, little damage apparently occurred to bridges as contrasted to other civil engineering structures and buildings ([26], p. 454). Statically determinate continuous girders are preferred over statically determinate girders consisting of simple beams for earthquake resistance ([26], p. 457).

Railway building facilities can range from depot and terminal facilities to road sheds, offices, equipment warehouses, communication centers, and car shops. Such facilities generally can be analyzed in terms of how they are constructed to resist lateral loads. In the Niigata earthquake, the main station and also communications capability were damaged ([27], pp. 463, 480). In the Alaska earthquake, damage occurred to facilties in Seward, Anchorage, and Whittier. In Seward, a key terminal, numerous buildings were severely damaged. In Anchorage, a wheel shop, a general office annex, a car shop, and a storage building were severely damaged. In Whittier, a depot building and a transit shed were destroyed. In Portage, some damage occurred to a communications building ([25], pp. 959 ff.).

Damage to tracks and roadbeds has occurred in several earthquakes. In the San Fernando Valley earthquake, in spite of all the other damage that occurred generally, only $40,000 of damage occurred to railway systems. That damage was confined to tracks near Sylmar that shifted laterally about 2 meters and suffered kinked rails and one broken rail and also to 25 kilometers of track that heaved and whose underlying material subsided ([28]). In Niigata, where liquefaction was a major problem, most roadbeds on loose sand were destroyed or settled and made impassable. Roadbeds also heaved, sand banks moved and covered track, some track was displaced laterally, and landslides caused further damage. Track displacment was caused when the ground surface elongated and compressed with earthquake waves ([27], pp. 467, 478, 480). In the Alaska earthquake, four miles of track suffered bending and kinking. Eleven miles of track were damaged by a landslide, fifty-two miles of track were damaged as a result of local subsidence, and forty-four miles were damaged by tidal erosion ([25], p. 981).

Earthquake damage to tunnels as a result of earthquakes has been negligible. In the Alaska earthquake, eight unlined tunnels in affected areas suffered little damage except for some "overhead raveling of material," which fell on the track ([25], pp. 985, 986). A summary of Japanese earthquakes indicates that damage to portals can occur as a result of landslides or failure of sloping ground, and that damage to interior linings, in the form of minor cracking and spalling, occurs only with poor construction or direct fault rupture ([9], p. 173).

A complete survey of earthquake damage to rock tunnels has been made by Charles H. Dowding and Arnon Rozen ([29], pp. 185-189). They conclude that neither lined nor unlined tunnels have been damaged at ground surface accelerations up to 0.19 g. Only very few cases of minor damage (falling stones and formation of new cracks) have been observed at surface accelerations up to 0.25 g. Few cases of minor damage have been observed at surface accelerations up to 0.4 g. And no major damage (major rock falls, severe cracking, and closure, typically at portals) has been due to ground shaking alone where such accelerations did not exceed 0.5 g. Only minor damage to tunnels has been observed in Intensity VIII to IX levels ([29], p. 187). Fault displacements and other ground failures thus appear to be the chief failure modes for tunnels.

Data thus indicate that railway bridges, facilities, and tracks and roadbeds can suffer damage by earthquakes. Data on buildings, as described in other reports prepared by the Seismic Safety Advisory Council and others, can be used to analyze expected response of transportation system buildings. Analysis of other facilities depends upon the availability of special soil-structure investigations. In the San Francisco earthquake of 1906, for instance, most damage to non-building railway structures occurred on soft or structurally poor ground ([17], pp. 155-157).

SECTION 5

EARTHQUAKE RISKS TO TRANSPORTATION SYSTEMS IN UTAH

In this section, general characteristics of transportation systems in Utah are described along with the general seismicity in the State so that, on the basis of findings in Section 4, some preliminary results can be derived concerning possible future effects of earthquakes upon transportation systems.

SEISMICITY IN UTAH

Locations in Utah vary considerably in terms of expected seismicity. The zonation map of Utah contained in the recent Uniform Building Code indicates, for instance, that a large portion of the State lies in an area of high seismic activity, a Zone 3 region, whereas other portions of Utah lie in zones of lesser activity (See Figure 1). More recent research has indicated that a slightly different group of macrozones is warranted, and that, in locations close to the Wasatch fault, even more seismic activity is expected in the future than has been recorded in the limited historical past. The new zones are outlined in Figure 2.

In Figure 2, the zone of highest expected seismicity is Zone U-4, followed by Zone U-3, Zone U-2, and then Zone U-1. Large portions of eastern Utah lie in no macrozone owing to the negligible seismicity expected in such locations.

The most appropriate measurement of seismicity for a given site might seem to be the return interval at a given acceleration (g) value. However, not only is such a measurement difficult to develop from other data, but some evidence has been reported that peak g-values may not accurately indicate dynamic structural response. Here, in place of g-values, we shall employ intensity values as an indicator of expected seismicity.

Intensity values, given in Roman numerals, are indicators of earthquake effects upon human works. At Intensity VI, some buildings have failed. As intensities increase, damage to various structures also increases. Intensity VIII corresponds roughly to an acceleration of 0.15 g, and 0.5 g is exceeded at Intensity IX or X.[1]

In Zone U-1, the maximum expected earthquake, based upon the historical record, is a near-field Intensity VI ([22], p. 17). Such an earthquake could damage some bridge structure components, but bridge structures themselves should be undamaged. Hence, not much direct seismic damage to transportation systems is expected in Zone U-1.

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[1] For a more complete account of the Modified Mercalli Scale, see Appendix A and also [20], pp. 202-205. For attempts to correlate intensity and maximum effective peak acceleration values, see [21].

So, the only zones where much expected direct damage should occur are Zones U-2, U-3, and U-4.

In Zone U-4, the maximum expected earthquake, based upon geological evidence, is an epicentral Intensity X. Such an earthquake could cause considerable damage to transportation systems.

In Zone U-3, the maximum expected earthquake is an Intensity IX, as based upon historical records. Here, again, such an earthquake could damage bridge structures and other transportation system structures.

In Zone U-2, the historical record indicates the maximum earthquake is an epicentral Intensity VII ([22], p. 17). Such an earthquake could damage some older more vulnerable structures.

Another way to compare the main zones is to examine recurrence intervals for expected earthquakes. Estimated recurrence intervals for the different zones may be misleading unless one takes into account the diverse sizes of the zones. Zone U-1 is about 261,000 sq. km., Zone U-4 is only about 14,000 sq. km, Zone U-3 is about 29,200 sq. km., and Zone U-2 is about 76,400 sq. km.

Table 2 indicates the expected recurrence intervals of epicentral intensities equalling or exceeding the given intensity somewhere within the zone. If one recognizes that recurrence intervals for given intensities being located in the zone are a result of either having epicentral intensities in the zone or attenuation from earthquakes lying outside the zone, then one can bear in mind that the intervals in Table 2 do not take into account attenuation from outside the zone.

Not all earthquake epicenters are expected to lie close to transportation system facilities or structures. But, Table 2 indicates that large earthquakes are expected that could damage vulnerable facilities.

Given the wide differences in area among the various zones, a more direct measure of the vulnerability of a given structure or facility comes from estimates of recurrence intervals for earthquake intensities equalled or exceeded at sites randomly chosen within a given zone.

Table 3 indicates clearly that sites in Zone U-4 are considerably more susceptible to levels of ground shaking that cause earthquake damage than are such structures in other macrozones. At the same time, structures and equipment that are designed to resist the effects of lower intensities are much less likely to suffer damage.

In summary, not only does Utah have considerable seismicity, but certain portions of the State have much more expected seismicity than others. When recent geological evidence is added to historical records, only California clearly has a higher expected seismicity among the contiguous United States than the seismicity in Zone U-4, a macrozone that compares in seismicity to portions of Nevada and other high risk portions of the United States (Cf. [15], pp. 17, 18, plus adjustments in the methodology).

EXPECTED EARTHQUAKE RESPONSE OF UTAH RAILROADS

Figure 3 provides a map of primary Utah railroads. No known significant seismic damage has occurred to Utah railroads in the historic past. A response from R.M. Brown, chief engineer of Union Pacific in Omaha, indicates that no record exists of seismic damage to Union Pacific railways or facilities. Vulnerabilities of railroad systems, then, must be surmised from a survey of structures and routes in conjunction with an assessment of expected seismicity in Utah.

According to Ferron Wimmer, engineer at Southern Pacific, the Southern Pacific line across the Great Salt Lake causeway is a main transcontinental line, carrying as much as half of all material that is shipped from the West Coast. Cargo includes military goods, grain, lumber, automobiles, and steel. Oil is shipped from Richmond, California, to the Davis County and North Salt Lake refineries.

The main offices for Southern Pacific are located in Ogden and were constructed in 1920. Although such offices were built with masonry and steel, they may not have much lateral resistance. A newer building, in contrast, probably does have such resistance.

Settlement on the causeway is a routine and recurring problem that has occurred since when the track was built. Routine inspection of the causeway and daily work forces deal with the problem.

Bridges in the line are either steel or prestressed concrete. Four exist between Ogden and Nevada. There are two steel bridges at West Weber and two concrete bridges at Warren.

Communications along the line is maintained both by telephone and by high frequency microwave systems.

Jerry Pearson, engineer for the Denver and Rio Grande Railroad (D&RG), provided information on the D&RG line. Cargo on the D&RG line includes general merchandise, foodstuffs, oil, and propane. The yard office in Ogden is wood frame. Major facilities in Salt Lake City include a corrugated metal diesel house, a yard office of brick construction built in 1943, and a main office built with a cinder block frame and brick exterior wall. The main office includes communications equipment. A standby generator exists, and both microwave and telephone systems are used.

Bridges on the D&RG have been converted to steel during past years. Near Salt Lake City, steel bridges cross Millcreek, Little Cottonwood Creek, and the Jordan River. Figure 4 shows the proximity of the D&RG track near the Jordan River as it passes through the southern part of Salt Lake County.

Mr. Pearson noted that the company has experienced soil problems in Davis County, Springville, and Mapleton, flood problems in Spanish Fork Canyon, and high winds in Davis County.

Western Pacific Railroad Company (WP) houses its main equipment in Elko, Nevada. Soil problems were noted to exist near the Salt Flats as the WP line proceeds very close to the Great Salt Lake. A short two-span bridge exists near Burmester in Tooele County.

Main Union Pacific facilities, located in Salt Lake City, are chiefly made of steel-frame construction. One exception is the passenger depot building, used as a passenger depot with some office space. The passenger depot building was constructed in the early 1900's.

Union Pacific bridges in the high risk seismic zones are described in Appendix B. In addition, tunnels exist at Wasatch, Curvo, Castle Rock, Devil's Slide, and Gateway.

Union Pacific transports lumber, food, building supplies, heavy duty construction and farm equipment, and automobiles. Crude oil is shipped both from Richmond and from Wyoming. Figure 5 shows the location of railways in the refinery area in southern Davis County and northern Salt Lake County. Also shown is the relationship of faults to the railroads.

In the U.S. Geological Survey report on a postulated 7.5 Richter magnitude earthquake in the Salt Lake area, it is estimated that older railroad terminals at Salt Lake City and Ogden will suffer damage, and that one bridge will be seriously damaged. Landslides and extensive ground settlement to railways going east up the canyons from Ogden and going south from Provo also were expected. Vertical and horizontal misalignment of tracks on poor wet soils near and over the Great Salt Lake were expected from a postulated earthquake near the Magna fault ([19], 244, 245).

In general, special vulnerabilities to railway structures exist for some of the older structures and for tracks in the Wasatch fault zone of deformation, in swampy or marshy areas, and in rockslide or landslide areas. Indirect evidence from other earthquakes indicates that tunnels are not specially vulnerable to earthquake damage. Bridge damage can only be estimated from the indirect evidence provided from a study of highway bridges, some of which cross railways. In general, then, further assessments of soil conditions in Utah are needed in order to assess much of the possible earthquake damage to railroads, although poor soil conditions can already be identified. Possible damage to some of the older buildings also could be very expensive if they contain expensive equipment. Communications, however, should be able to be maintained on high frequency radio systems.

EXPECTED EARTHQUAKE RESPONSE OF HIGHWAY BRIDGE STRUCTURES

Highway Bridge Survey Sample

As an initial step in assessing the potential earthquake risks to highway bridge structures in Utah, a sample of bridges had to be chosen from among the very large number of bridge structures.

The first criterion for the selection of bridges was their location in Zone U-4. If bridge structures in Zone U-4 do not appear to be seismically vulnerable, then one can assume that bridge structures in other seismic macrozones also will prove not to be vulnerable. If, in contrast, seismic vulnerabilities exist in Zone U-4, then lesser vulnerabilities may exist in other portions of the State.

The second criterion for the selection of sample bridges was their use in possible evacuation routes. A discussion of evacuation plans with members of the State Divison of Comprehensive Emergency Management narrowed the selection to bridges on interstate highways and on some major arterial roads. All bridge structures were determined to be bypassable along alternate routes. However, bypassing some structures at the north and south portions of Salt Lake City, especially where State Highway 89 converges with I-15, could cause serious problems in earthquakes. Since, moreover, I-15 lies to the west of Provo and Ogden, not all structures along I-15 were surveyed. Figures 6, 7, and 8 locate by maps the vast majority of surveyed structures, all of which rate fairly highly in terms of comparative criticality but perhaps no one of which is indispensibile for operations after an earthquake. Figure 9 provides average daily traffic flow for I-15 in the Salt Lake City area, where the highest traffic averages exist in the State. Figure 10 fills in traffic averages for all major highways and streets in the Salt Lake City area, so that one may compare traffic flow in different portions of the county. Similar traffic flow information also is available for other parts of the State ([Cf. [23]).

Information made available by Ray Behling and Arlan Winterton at the State Department of Transportation enables one to determine general bridge characteristics of those sampled. Such information is found in Table 4.

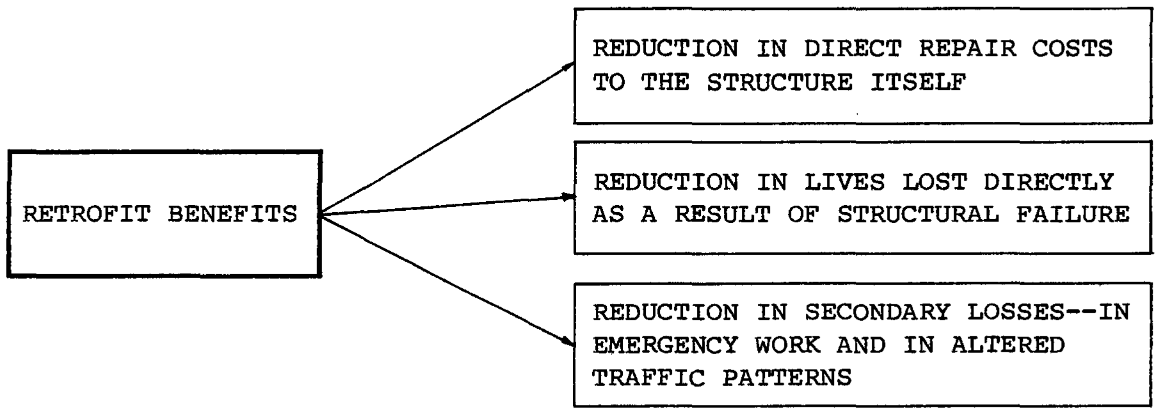
A summary of Table 4 is described in chapter 3 of a report prepared by Agbabian Associates [30] which is supplementary to this report.

Preliminary Findings Concerning Earthquake Risk To Utah Highway Bridge Structures

The report prepared by Agbabian Associates ([30]) outlines the potential seismic vulnerability of Utah highway bridge structures and also provides suggestions for retrofit priority. This subsection summarizes very briefly the Agbabian Associates report, discusses socioeconomic factors pertaining to seismic retrofit programs, and uses the Agbabian Associates report to sketch very generally a provisional program for inspection and possible retrofit of selected highway bridge structures. The program sketched is flexible enough to allow for reasonable modifications when a more definitive program is undertaken.

In the Agbabian Associates report, calculations indicate that the bearing connection for prestressed concrete girder structures is capable of resisting a lateral load of approximately 0.13 g. Similar results were found for steel structures ([30], 5-2). Such results, among others, indicate that the seismic vulnerability of pre-1971 bridge structures may be significant, even though such structures were designed in accordance with federal engineering standards used prior to the 1971 San Fernando Valley earthquake. Hence, the potential seismic vulnerability of pre-1971 highway bridge structures in Utah cannot be dismissed as being inconsequential.

In assessing the feasibility of a retrofit program to correct potential deficiencies for earthquake resistance, three potential categories of benefits need to be considered. The three categories are sketched below.



Attempts to estimate reductions in secondary losses would be, at best, partial without a complete transportation system analysis. When a bridge structure fails, and traffic needs to be rerouted, any of a number of results may come about. The bridge structure may be part of a major route that becomes used less. Alteration of transportation routes can affect energy consumption, air quality, traffic safety, industrial siting, the distribution of commerce, and the tourist industry.

Considerable redundancy exists in Utah's major highway network, although failure of one or more bridge structures could impede emergency work or even possible evacuation. A discussion of evacuation routes with Jim Brown, Utah Division of Comprehensive Emergency Management, indicates that there also is considerable redundancy in evacuation routes. That is, if one or more bridge structures should fail on one route, then other routes appear to be available.

In addition, an examination was made of the possibility that some locale might be severed from emergency services, apart from helicopter services, in the event that such a locale was surrounded by a loop containing bridges, two or more of which failed. An examination of Figures 6, 7, and 8 indicates that the only such highway loop system exists in Salt Lake County, proceeding south from 21st South, with I-215 and I-15 forming the major part of the loop (see Figure 7). Figure 11 indicates the locale surrounded by a loop. Closer examination indicates that Fire Station #23 exists within the specified locale. No hospitals appear to exist within the specified locale, although several appear to be close to the locale (see Figure 12). Yet, it is extremely improbable that all bridge structures in the specified loop would fail. Some were constructed in the 1970's and others constructed earlier do not appear from limited data to have vulnerable characteristics.

Emergency response activities also can be maintained if damaged bridge structures are bypassed. Emergency vehicles in many cases can exit the ramp prior to the damaged bridge and return to the route by means of the on-ramp. Figure 13 illustrates two bridge layouts that make such a detour possible (the upper two plans) and one bridge layout that hinders such a detour (the lower plan).

Given the limitations on data noted above, assessment of secondary benefits from seismic retrofitting of highway bridge structures is very difficult. Information about average daily traffic flows, as in Figures 9 and 10, can serve as rough indices of socioeconomic importance, and critical travel routes can be examined and loops can be looked for. But, developing a model to estimate the economic gains and losses resulting from the failure of a highway bridge structure would be most difficult, except for direct loss to the structure. In the long run, some enterprises might indeed thrive from route changes, some routes might be used that turn out to be more safe, and other benefits could accrue from route changes. Such outcomes are speculative at best. To account for both gains and losses due to all secondary effects of route changes, brought about by any temporary interruption of traffic flow, is presently beyond the state-of-the-art of analytical methods, although detailed study of various possible alterations can enhance one's understanding of the effects of various alterations in the transportation system.

Estimating the number of lives lost directly as a result of collapse of highway bridge structures likewise involves consideration of a number of contingencies--including number of vehicles on the structure at the time of collapse (a number that varies with time of day, etc.), number of vehicles on the route that do not stop when the earthquake occurs, number of bystanders affected by the collapse, etc. These also are much to speculative for any conclusive analysis beyond rough estimates, and even any such estimates would not be very useful.

Economic consideration of the direct benefits from reducing losses to the bridge structure itself also are difficult to develop. Given development of appropriate seismic estimates, as described briefly in Section 4 of this report and in greater detail in other reports that are referenced, and also given estimates of expected reduced losses resulting from seismic retrofitting, derived benefits from retrofitting can be obtained. Use of an appropriate social discount rate then would enable one to compare retrofitting costs against such reductions in direct repair costs.

Although such a method can be used, data appear to be too scarce to justify any such effort or to obtain results for which one would have a sufficient degree of confidence. The Agbabian Associates report does indicate that, for some Utah highway bridge structures, retrofitting may decrease seismic vulnerability by increasing structural resistance to ground acceleration forces from 0.13 g to perhaps 0.50 g. Details of construction of such structures would need to be known in order to confirm such estimates. Another constraint on any benefit-cost analysis is that only limited data on seismic repair costs exist, primarily in [13], pp. 207-212. Finally, use of such a method does not incorporate benefits either from lives directly saved or from reduction in secondary losses. Trial calculations indicate that the benefit-cost ratios on an aggregate level do not exceed 0.5 where benefits include only reduction of direct repair costs in Utah's seismic environment. However, these trial calculations do not consider either enormous variations in the possible seismic vulnerability of Utah's bridge structures or other possible benefits from retrofitting programs.

In summary, existing procedures for use of the above diagram are not yet adequate for developing a decision-making guideline concerning the retrofit of highway bridge structures to reduce their earthquake vulnerability.

Another set of procedures for determining retrofit decisions is found in a study authorized by the U.S. Department of Transportation [16]. Data gathered for this report are insufficient in detail to use the decision procedures found in [16], although such procedures possibly could be used by the State Department of Transportation. Based on a conversation with Ray Behling, and after prior study of the criticality factors referred to in [16], it appears that retrofit decision procedures in [16] may be tailored more to California's seismic environment and may be inappropriate for transfer to areas less seismically active. Thus, further study appears to be needed to justify the use of retrofit decision procedures in [16] outside California's seismic environment. Without additional study, such procedures as authorized in [16] might unjustifiably lead to a belief that blanket retrofit of all Utah highway bridge structures is necessary.

Given the paucity of arguments regarding data constraints affecting policy decisions for bridge structure safety in Utah's earthquake environment, one can only point at this time to general suspected problems and possible actions to alleviate such problems. Some such problems and remedial actions are identified in the concluding paragraphs of this section. However, these are presented more as guidelines for further study than as indisputable facts, and the overall thrust of such suggestions aims at causing greater attention to be given to consideration of earthquake effects upon bridge structures so that uncertainties are removed in due time.

In the Agbabian Associates report ([30]), guidelines are suggested for a program of inspection, analysis, and possible retrofit of Utah highway bridge structures.

In the abovementioned report, proposed mitigation measures include use of restrainers, which tend to cost between $20,000 and $40,000 for each bridge span. In the State, there are approximately 2,350 total structures, of which almost 1,460 are structures on State highways. Approximately 503 lie on major routes in seismic Zone U-4, of which 322 are on I-15, 69 are on I-80, 52 are on I-215, and 60 are on State Highway 89. Hence, a blanket retrofitting program, even for major structures in Zone U-4, would entail large public expenditures that may not be warranted.

Computerized data available about highway bridge structures include five categories pertinent to a preliminary survey of seismic vulnerability of bridge structures:

(1) type of construction (concrete tee-beam, etc.),

(2) number of spans,

(3) skew,

(4) vertical clearance, and

(5) length of structure.

Computerized data are not available relating to construction detailing, and the available data cannot be used to determine directly the seismic vulnerability of highway bridge structures. At best, computerized data available can suggest criteria for inspection priority.

According to the Agbabian Associates report, steel or prestressed-concrete girder designs have a higher inherent resistance to lateral earthquake forces than do heavier reinforced-concrete girder designs, such as box girder construction ([30], 3-11). In addition, the following response characteristics of bridge structures are noted in the report ([30], pp. 3-11, 3-15).

--Structures having three or less spans are less vulnerable to the displacements resulting from superstructure response during the earthquake ground motion.

--Structures skewed more than 20 degrees are highly susceptible to rotational displacment toward acute corners.

--Structures having a vertical height over 20 feet may be vulnerable to large displacements of the superstructure that could result from relatively flexible tall columns or bents.

--Structures having multiple spans and exceeding 200 feet may be sensitive to the phasing of the ground motion input to individual foundations as the seismic wave travels along the structure.

Based upon such structural factors, rough priorities can be developed for inspection and possible retrofit. In seismic Zone U-4, heavier reinforced-concrete girder designs have a higher priority for inspection than do steel and prestressed-concrete girder designs. Subcategories for inspection priority include number of spans, skews, vertical height, and span length, in accordance with abovementioned considerations. As well, traffic density can be used to establish inspection priority for bridge structures.

Table 5 uses such inspection and review criteria to outline a provisional list for retrofit priority of highway bridge structures sampled. Table 5 should not be regarded as providing a definitive list of comparative structural vulnerabilities; the criteria used needs to be supplemented with very important information on detailing. Also, "continuous" structures are listed (here, tending to imply absence of expansion joints between two spans) that may have expansion joints. Information available to personnel at the Structures Division, Utah Department of Transportation, may allow some structures to be placed either in higher or lower priority. Some structures, moreover, may require only a quick site inspection in order to ensure that detailing practices are seismically sound. Post-1970 structures were omitted in Table 5 even though some sampled were non-continuous (e.g., F 169, F 178, F 205, F 235, F 283, F 133, F 163, F 156). Figures 14, 15, and 16 locate most of the bridge structures by symbols that are listed in Table 5.

Other bridge structures not contained in the list have no seismic rating characteristics, although there is some lesser chance that some such structures are specially vulnerable to earthquakes.

Figures 14, 15, and 16 also graphically depict the priorities among surveyed structures that are suggested in Table 5.

More complete lists such as are in Table 5 can be developed easily from computerized data available to the Structures Divison, Department of Transportation, and inappropriate structures (truly continuous systems) can be deleted from the lists.

In conclusion, the Agbabian Associates report [30] indicates that some Utah highway bridge structures likely are vulnerable to earthquake damage. A program for inspection and review of such bridge structures, especially in seismic Zone U-4 (and also possibly near Richfield) is indicated in [30].

The economic feasibility of retrofitting cannot be precisely determined, although seismic failure of operationally important bridge structures may justify comparatively low-cost retrofit measures. The economics of seismic retrofit programs also can be improved upon if such programs can be combined with others, such as deck repair programs where salt has produced corrosion problems. The economics of compliance with existing criteria in the design of new bridge structures tends to be superior to retrofit of existing bridges, since intial costs of seismic design and effectiveness of seismic design in new structures appears to be more cost-effective.

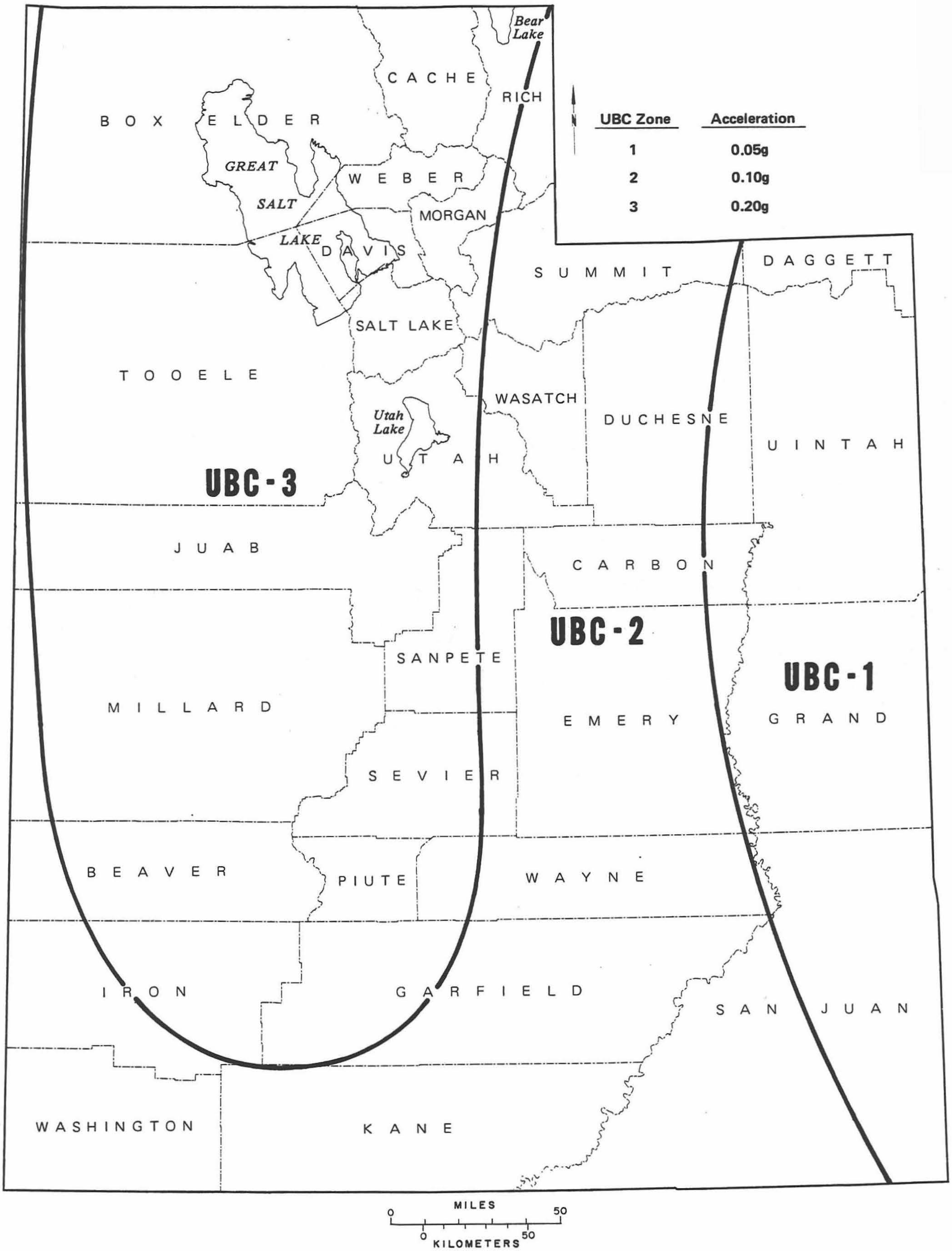


Figure 1
SEISMIC ZONES—1976 UNIFORM BUILDING CODE
STATE OF UTAH

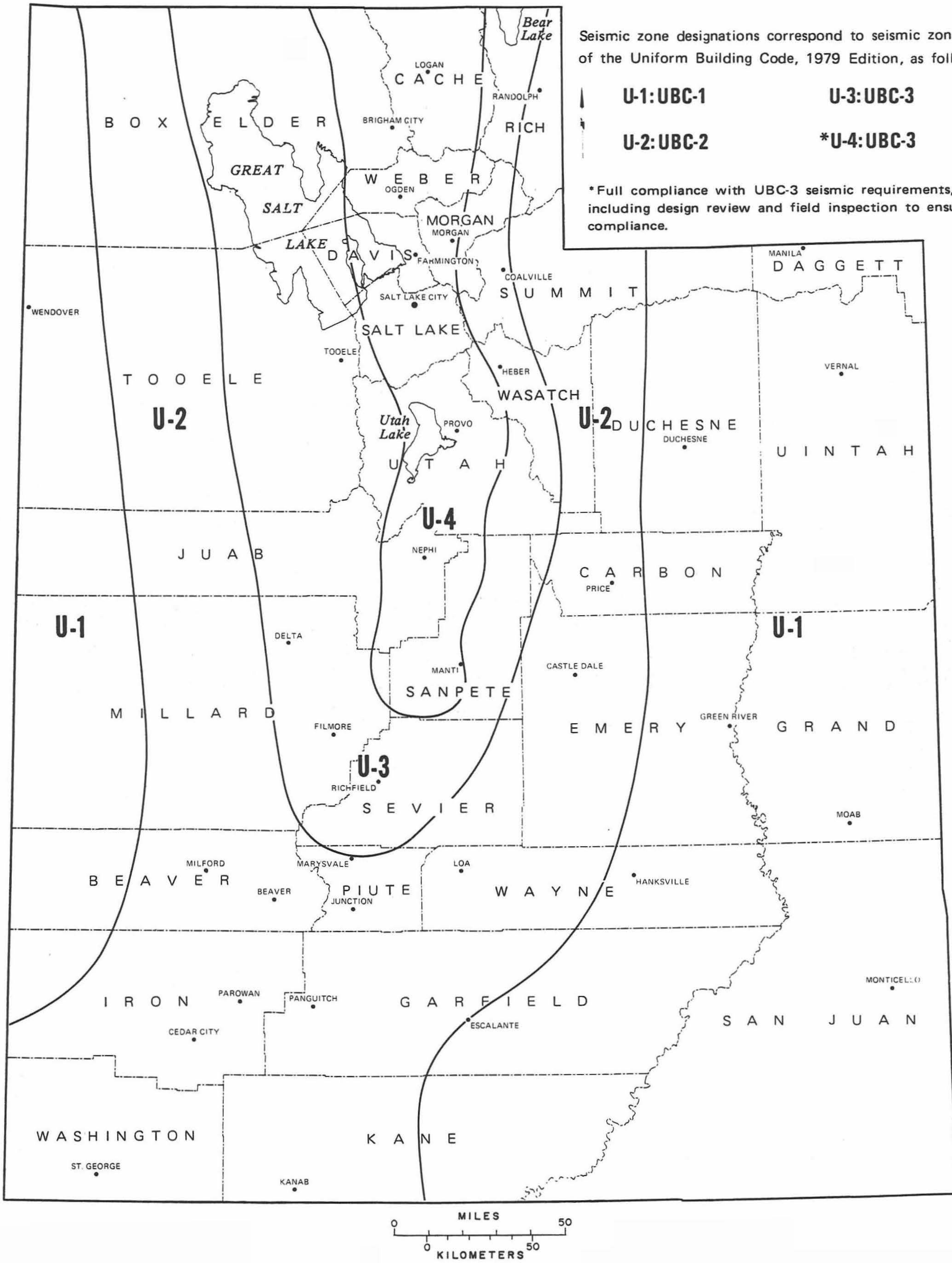


Figure 2
SEISMIC ZONES
January 1980
(Recommended by the Utah Seismic Safety Advisory Council)

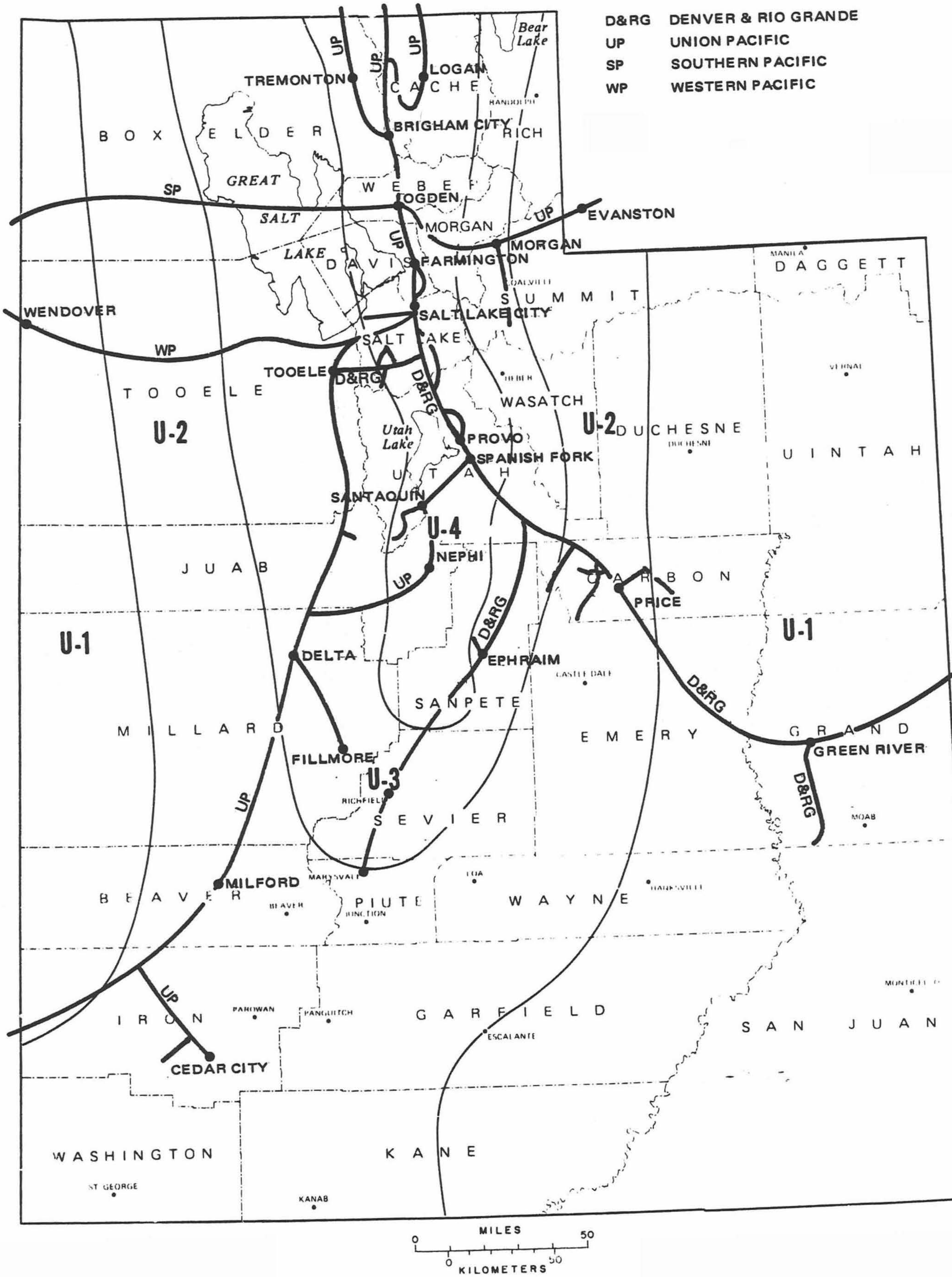


Figure 3

PRIMARY RAILROADS
STATE OF UTAH

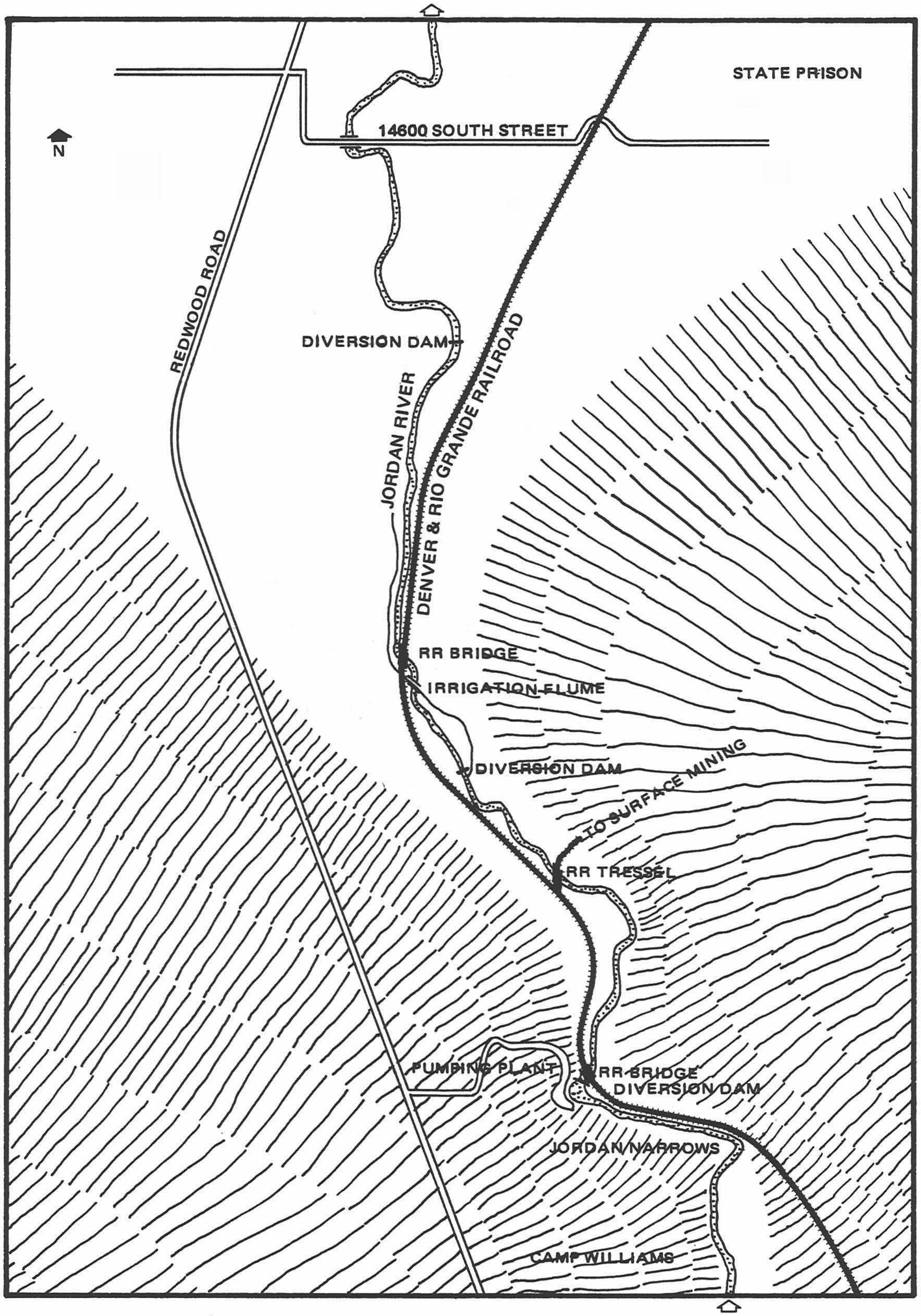


Figure 4

PROXIMITY OF THE DENVER & RIO GRANDE RAILROAD TRACKS TO THE JORDAN RIVER THROUGH THE SOUTHERN PORTION OF SALT LAKE COUNTY

Source: Provo-Jordan River Parkway Authority, State of Utah

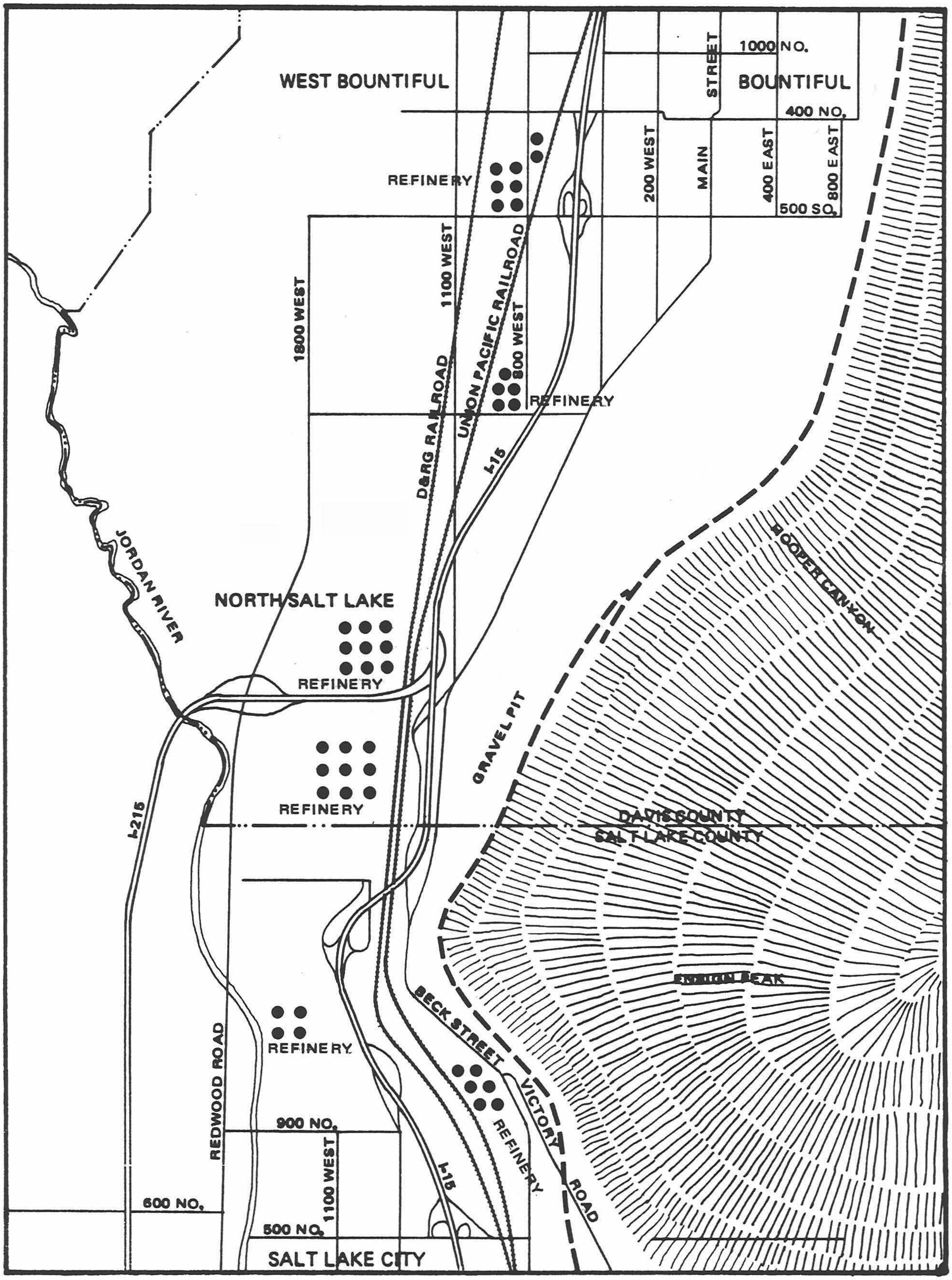


Figure 5

LOCATION OF RAILROADS NEAR REFINERIES
IN THE DAVIS-SALT LAKE COUNTY AREA IN RELATION TO FAULTS

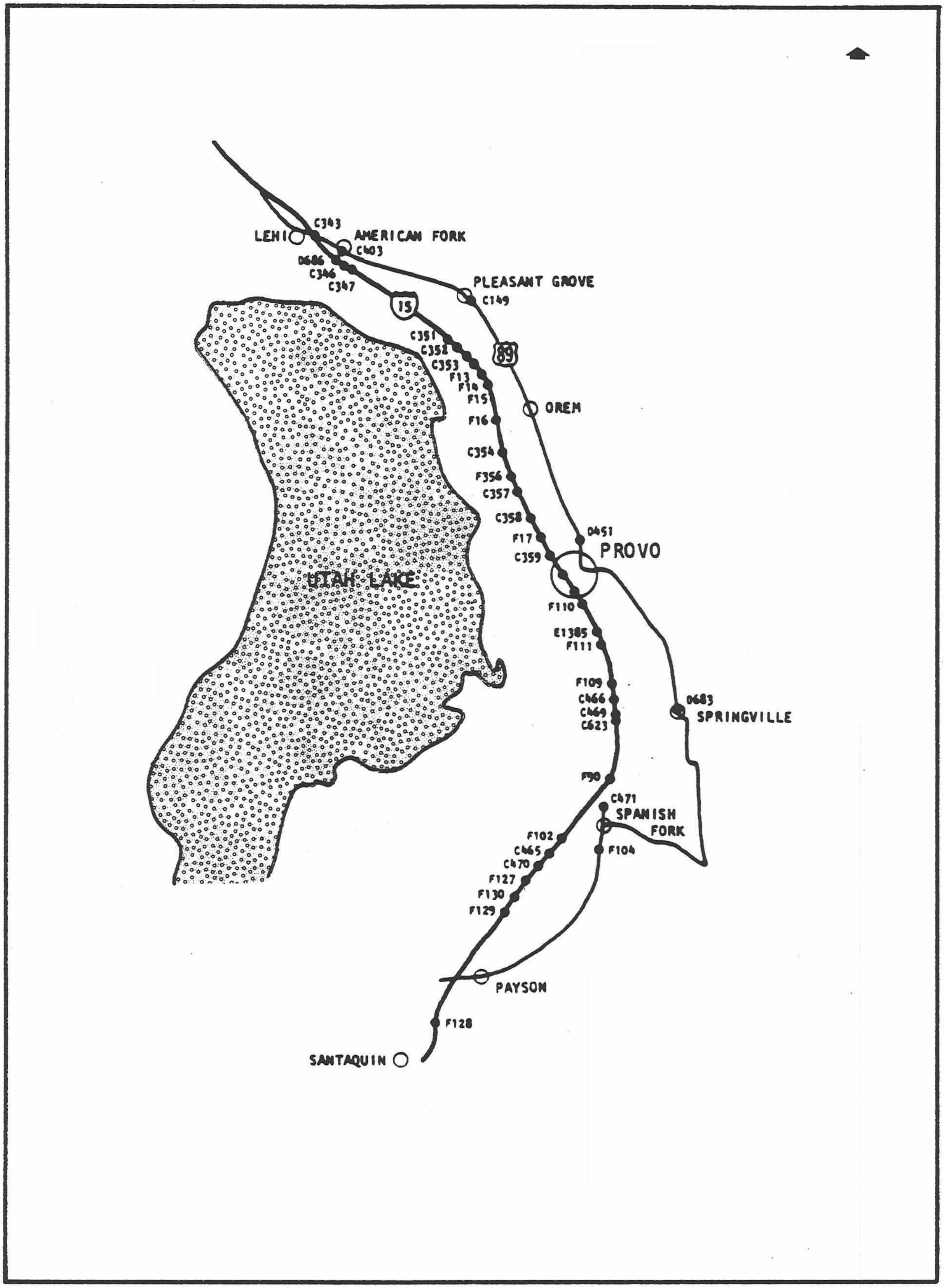


Figure 6
LOCATION OF HIGHWAY BRIDGES SAMPLED IN UTAH COUNTY

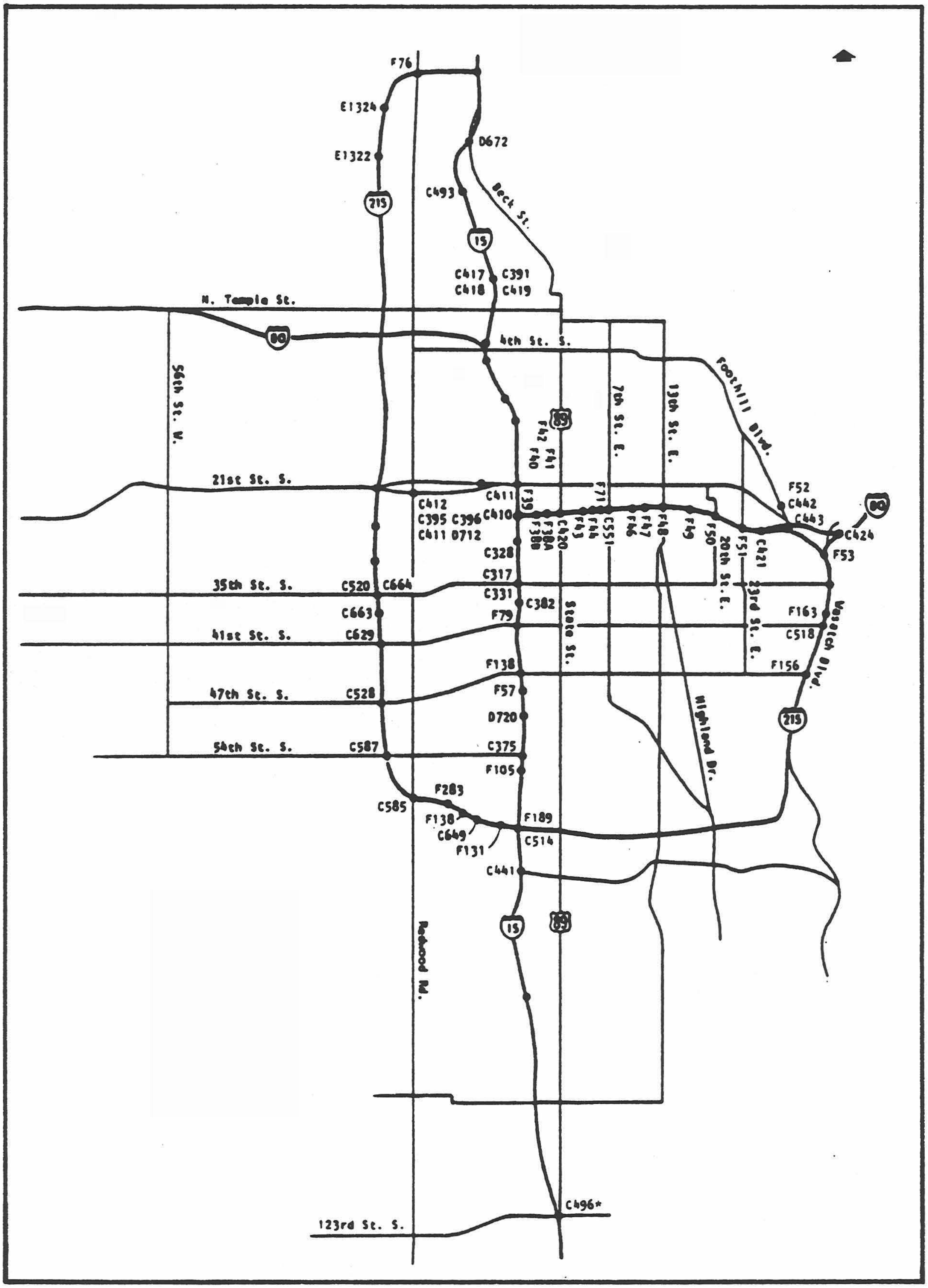


Figure 7

LOCATION OF HIGHWAY BRIDGES SAMPLED IN THE SALT LAKE CITY AREA

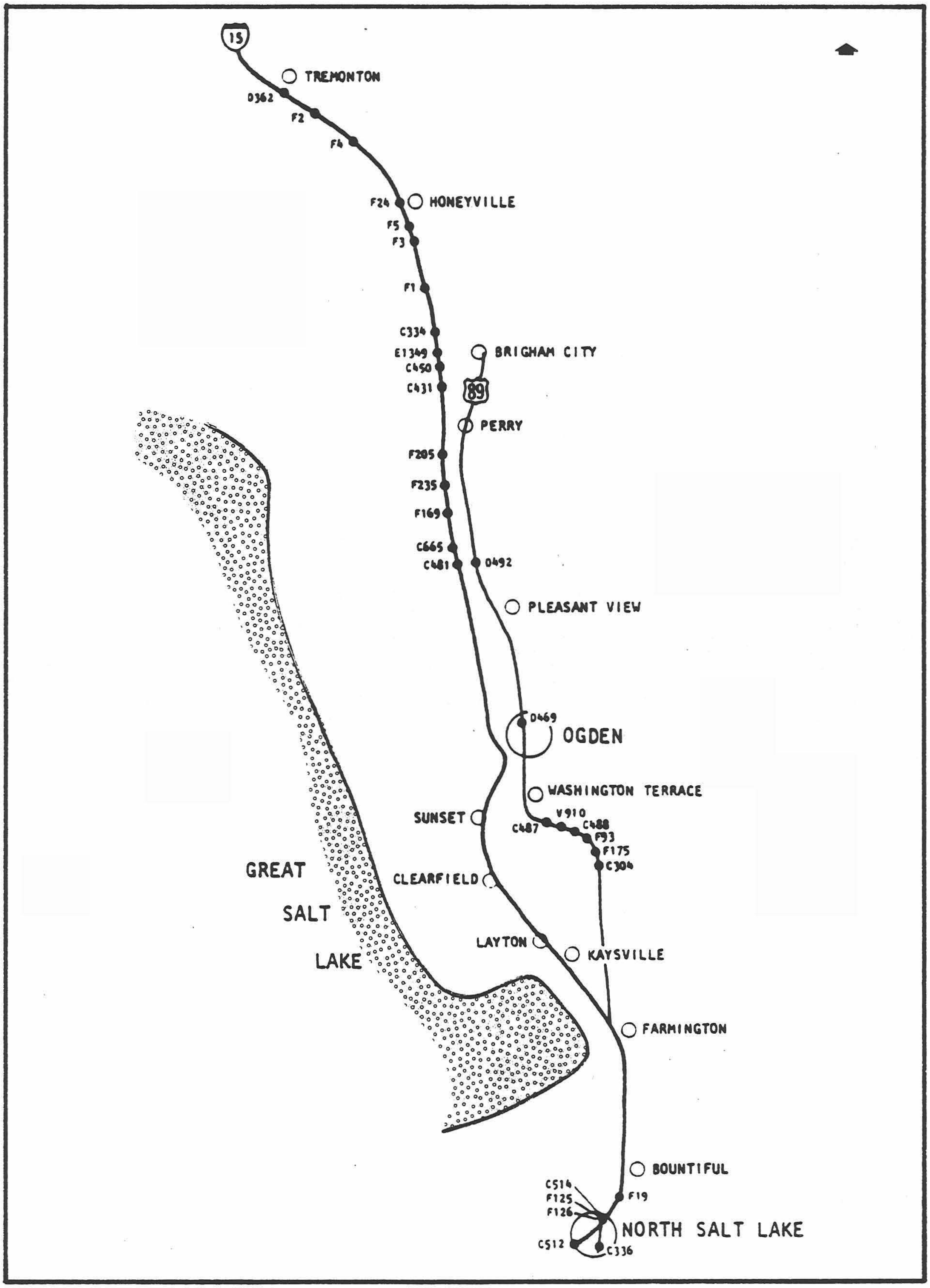


Figure 8

LOCATION OF HIGHWAY BRIDGES SAMPLED IN NORTHERN UTAH

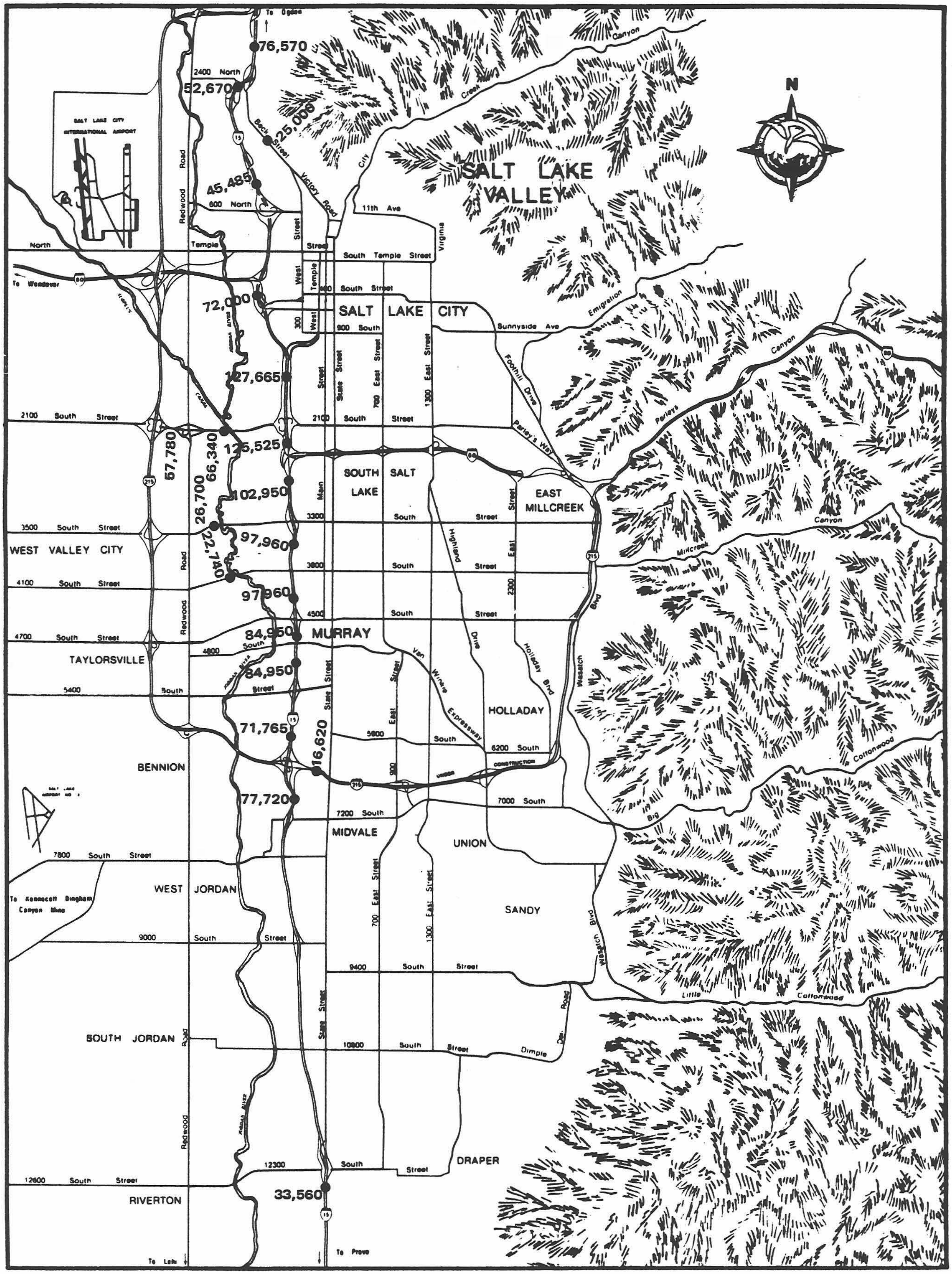


Figure 9

AVERAGE DAILY TRAFFICE ON I-15 IN THE SALT LAKE CITY AREA
Source: Reference [23].

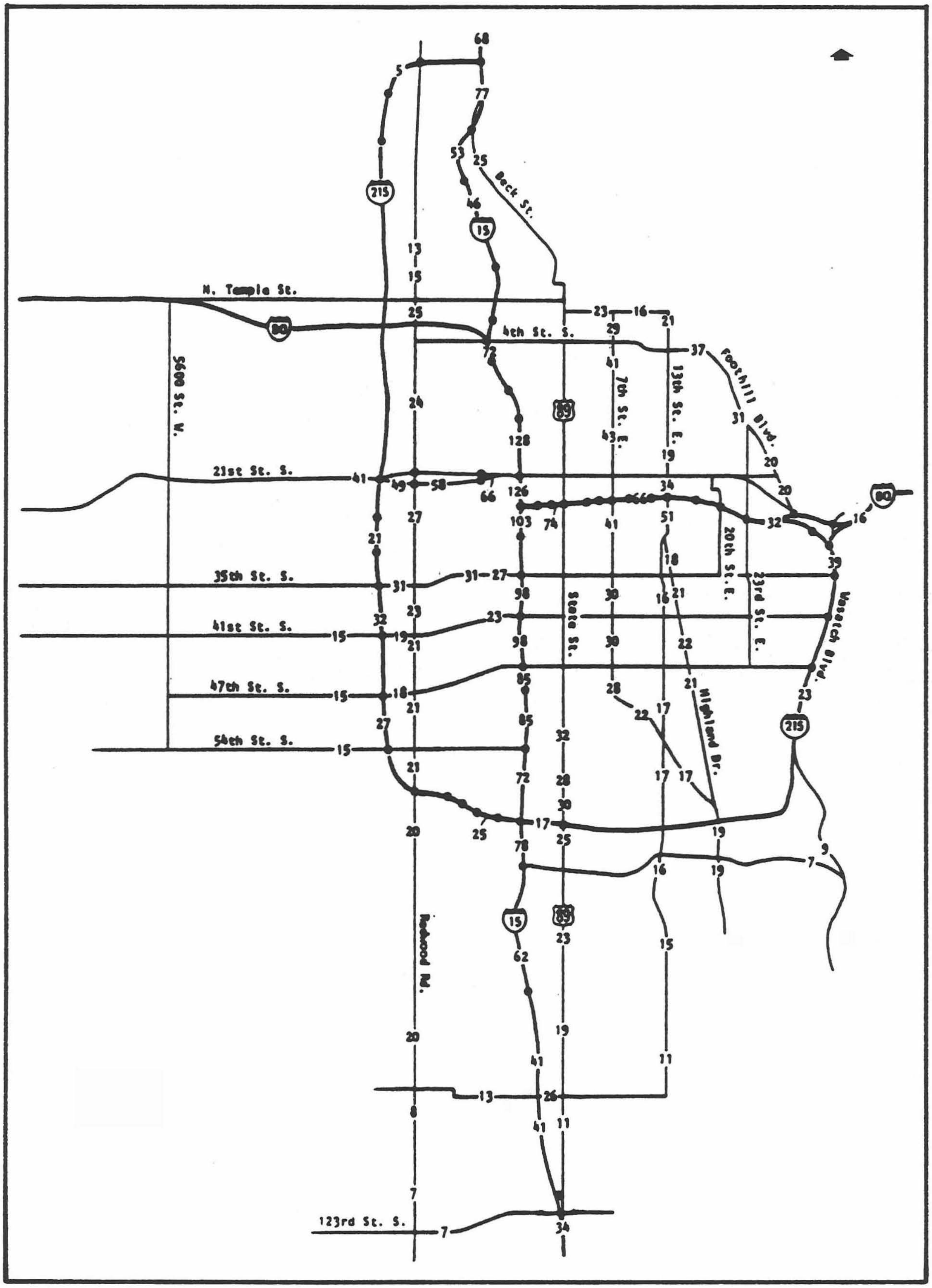


Figure 10

AVERAGE DAILY TRAFFIC ON MAJOR HIGHWAYS AND STREETS IN THE SALT LAKE CITY AREA (1978 Data, In Thousands)

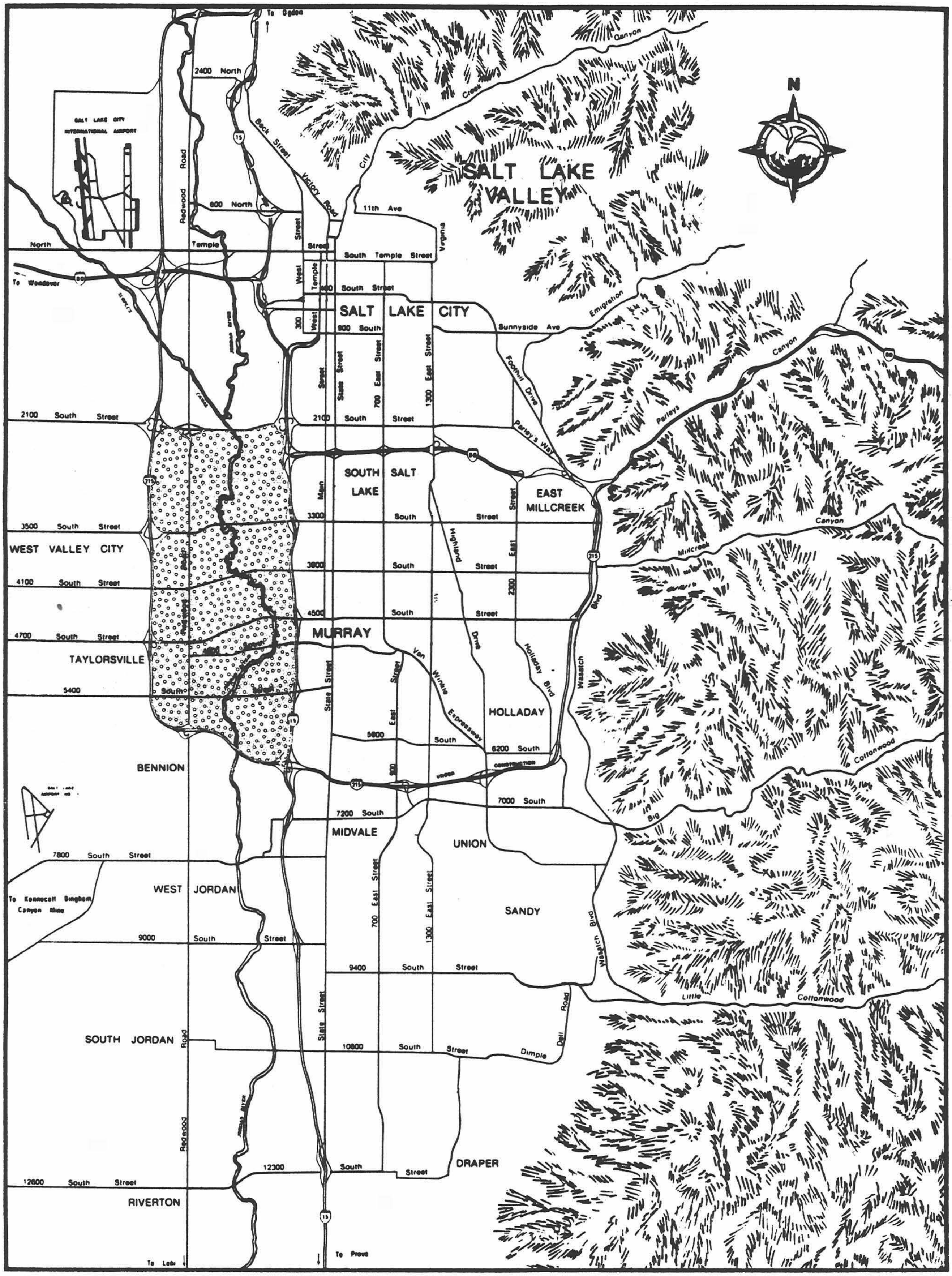


Figure 11

LOCALE SURROUNDED BY A FREEWAY LOOP IN THE SALT LAKE CITY AREA

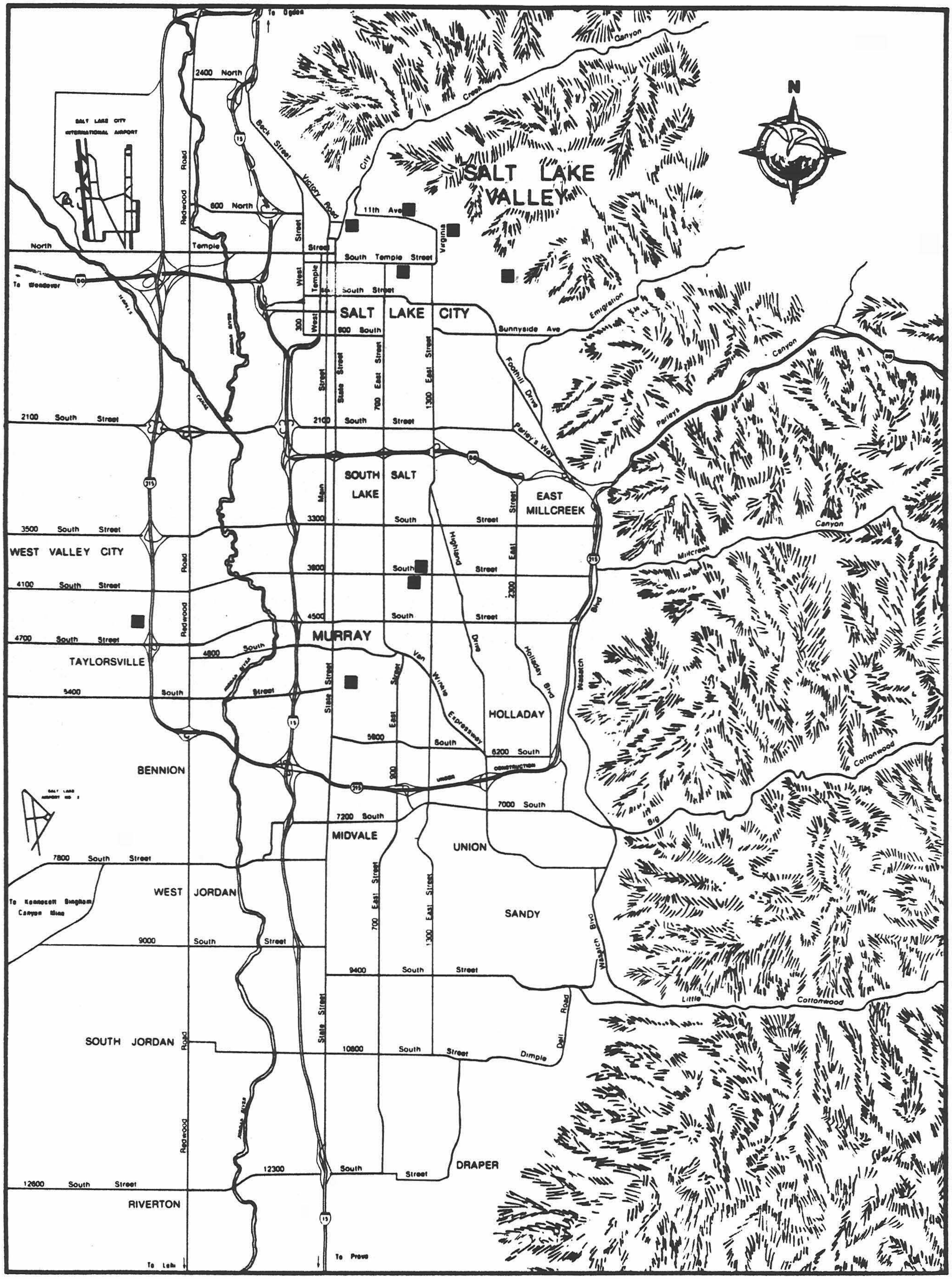


Figure 12

LOCATION OF HOSPITALS IN SALT LAKE COUNTY IN RELATION TO MAJOR TRAFFICWAYS

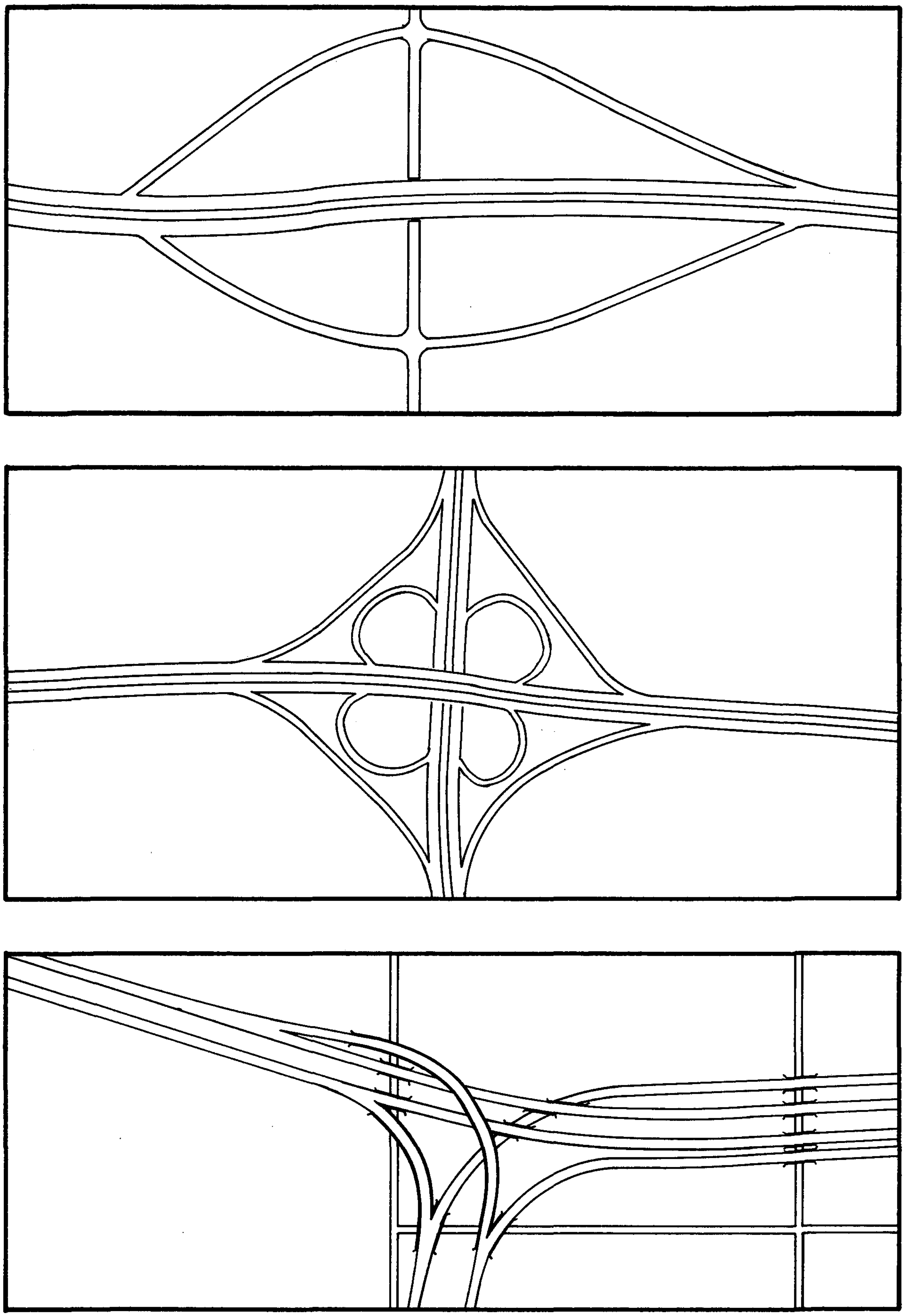


Figure 13

THREE INTERCHANGE PLAN VIEWS– INTERSTATE HIGHWAY SYSTEM
Source: Transportation Planning Division, Utah Department of Transportation.

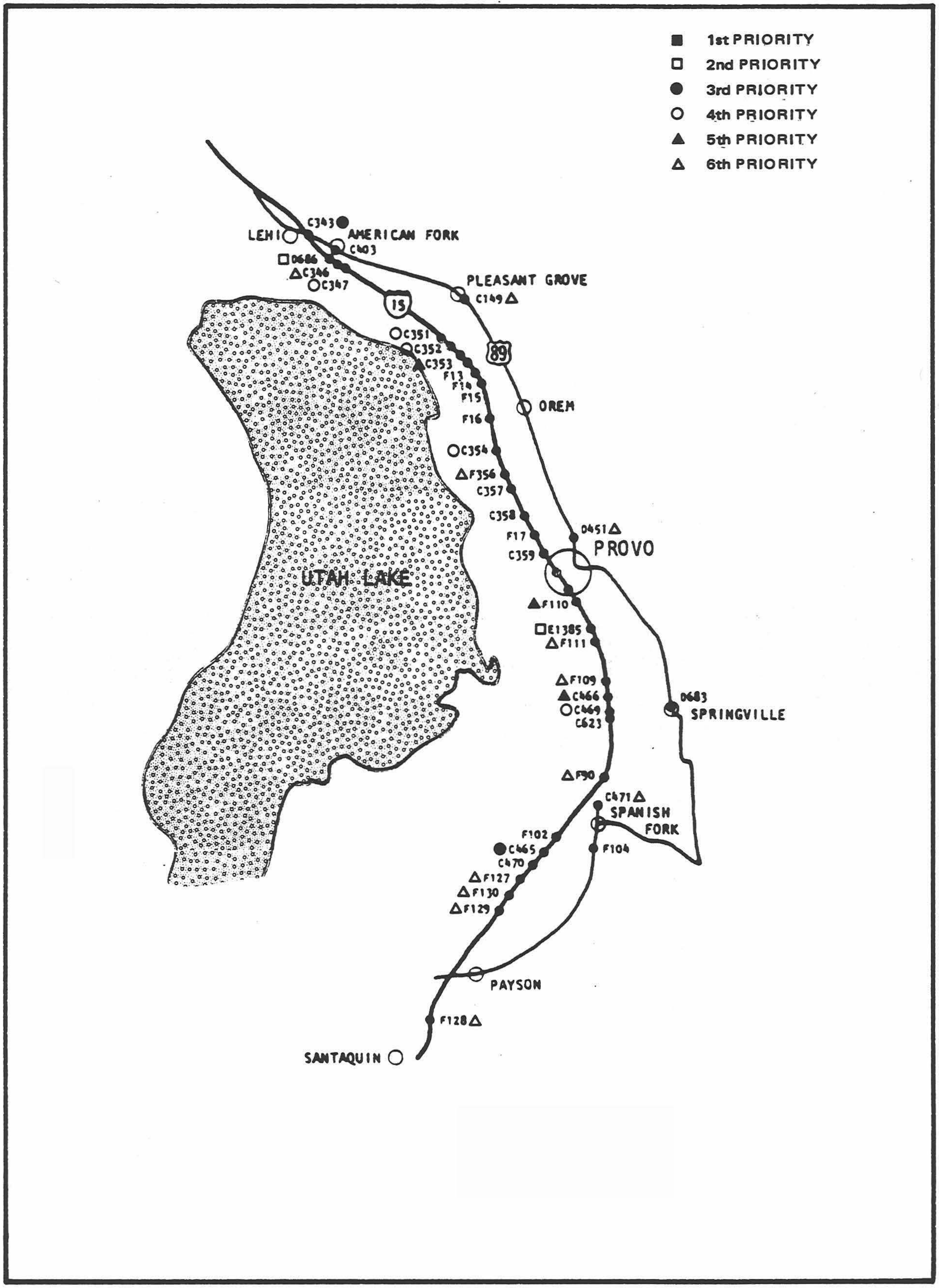


Figure 14

PROVISIONAL PRIORITY FOR SEISMIC INSPECTION, REVIEW, AND POSSIBLE RETROFIT OF HIGHWAY BRIDGE STRUCTURES IN UTAH COUNTY

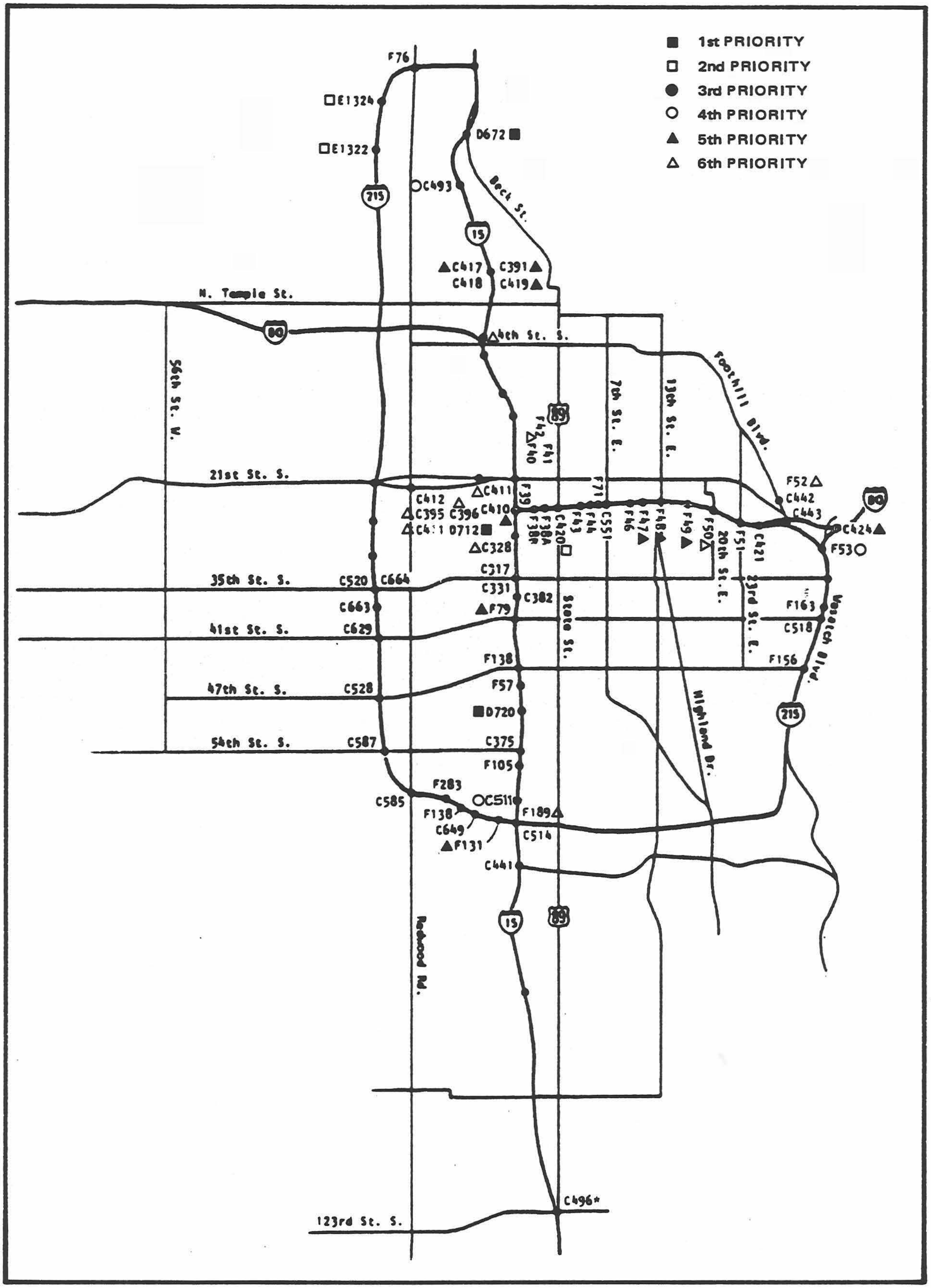


Figure 15

PROVISIONAL PRIORITY FOR SEISMIC INSPECTION, REVIEW, AND POSSIBLE RETROFIT OF HIGHWAY BRIDGE STRUCTURES IN THE SALT LAKE CITY AREA

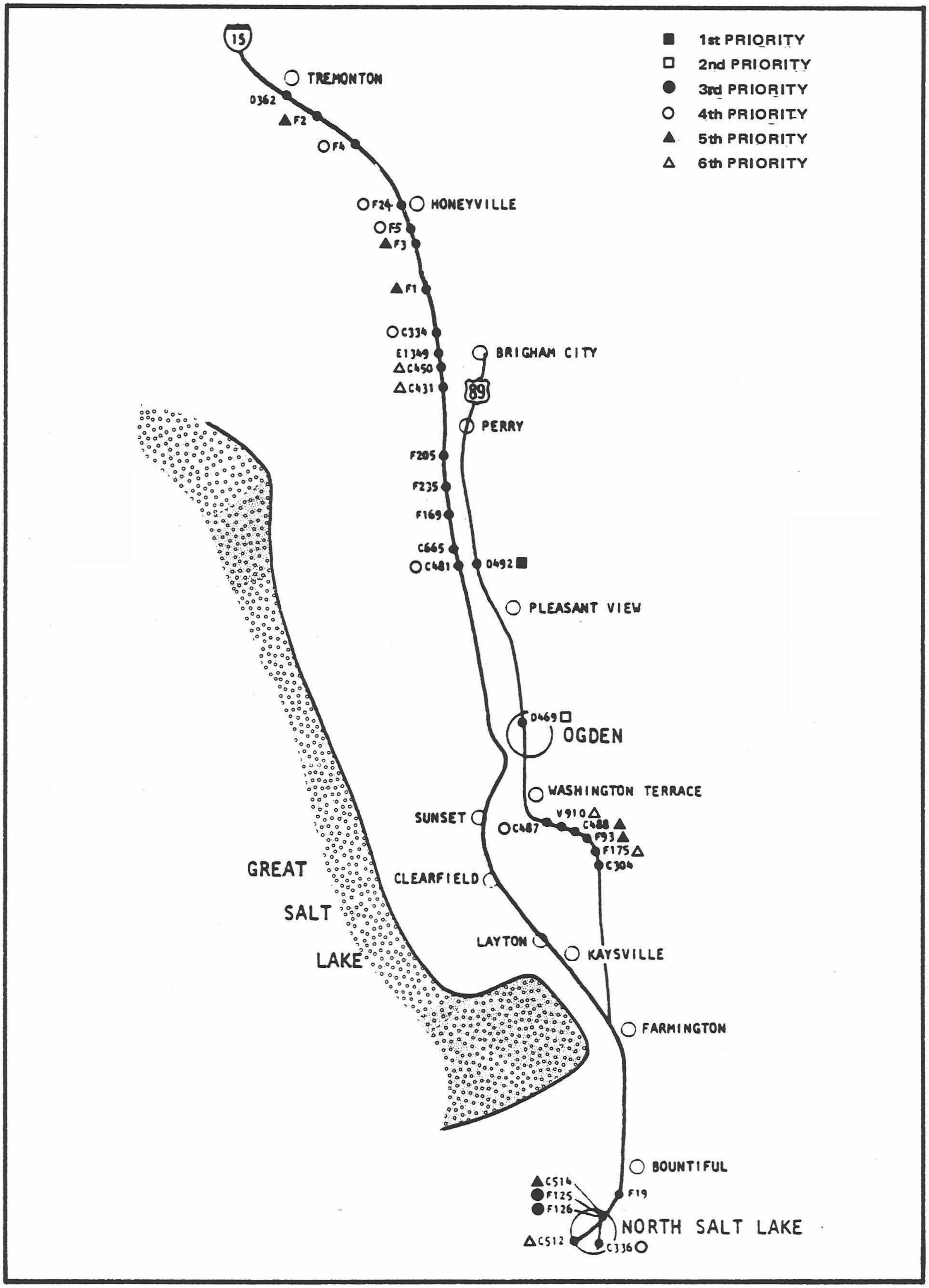


Figure 16

PROVISIONAL PRIORITY FOR SEISMIC INSPECTION, REVIEW, AND POSSIBLE RETROFIT OF HIGHWAY BRIDGE STRUCTURES IN NORTHERN UTAH

TABLE 1

ELEVEN MAJOR EARTHQUAKES CAUSING DAMAGES TO HIGHWAY BRIDGES IN JAPAN

NO.	DATE	NAME	M[1]	NO. OF DAMAGED BRIDGES	NO. OF FALLEN BRIDGES	AMOUNT OF LOSS OF BRIDGES[3]	REMARKS
1	SEPT. 1, 1923	KANTO	7.9	1,785[2]	17[4]	UNKNOWN	
2	DEC. 21, 1946	NANKAI	8.1	346	1	95,605	
3	JUNE, 1948	FUKUI	7.3	243	7	207,651	
4	DEC. 26, 1949	IMAICHI	6.4	1	0	MINOR	
5	MAR. 4, 1952	TOKACHI-OKI	8.1	128	0	200,000	
6	APR. 30, 1962	NORTHERN MIYAGI	6.5	187	0	43,000	
7	JUNE 16, 1964	NIIGATA	7.5	98	3	1,470,000	
8	FEB. 21, 1968	EBINO	6.1	10	0	50,000	
9	MAY 16, 1978	TOKACHI-OKI	7.9	101	0	421,046	
10	JAN. 14, 1978	IZU OHSHIMA KINKAI	7.0	7	0	39,000	
11	JUNE 12, 1978	MIYAGI-KEN-OKI	7.4	108	1	4,000,000	AS OF DEC., 1978
TOTAL				3,014	29[4]	--	

[1] Magnitudes are on the Richter scale, after either Annual Report of Science or Japan Meteorlogical Agency.

[2] The number includes bridges damaged by fires (roughly 400 bridges).

[3] Amounts of loss are estimated at the time of each earthquake occurrence, shown in thousands of yen.

[4] The numbers include 9 bridges fallen due to fires.

Source: [24]

TABLE 2

EXPECTED RECURRENCE INTERVALS IN YEARS
OF EARTHQUAKES WHOSE EPICENTER EQUALS
OR EXCEEDS THE GIVEN INTENSITY SOMEWHERE
IN THE GIVEN ZONE

Seismic Zone	Intensity Equalled or Exceeded				
	X+	IX+	VIII+	VII+	VI+
Zone U-1	3,300	770	200	56	16
Zone U-2	900	190	50	14	4
Zone U-3	1,250	260	65	11	4
Zone U-4	450	133	39	12	4
Cumulative For All Four Zones	223	56	15	4	1

TABLE 3

RECURRENCE INTERVALS IN YEARS FOR
INTENSITIES EQUALLED OR EXCEEDED
AT SITES RANDOMLY CHOSEN WITHIN
GIVEN SEISMIC ZONES

Seismic Zone	Intensities Equalled Or Exceeded				
	X+	IX+	VIII+	VII+	VI+
Zone U-1	--	--	1.7×10^5	29×10^3	6,300
Zone U-2	10^6	67×10^3	10×10^3	2,000	450
Zone U-3	5×10^5	90×10^3	8,200	1,300	221
Zone U-4	15×10^3	2,400	620	180	54

TABLE 4

SUMMARY OF TYPICAL CHARACTERISTICS FOR 138 HIGHWAY BRIDGE STRUCTURES IN UTAH

(A) YEAR BUILT

Year	No. of Struc-tures	Year	No. of Struc-tures	Year	No. of Struc-tures	Year	No. of Struc-tures	Year	No. of Struc-tures
1979	--	1969	8	1959	--	1949	--	1939	--
1978	--	1968	7	1958	1	1948	--	1938	--
1977	1	1967	22	1957	--	1947	--	1937	1
1976	11	1966	19	1956	--	1946	--	1936	--
1975	2	1965	6	1955	1	1945	1	1935	1
1974	--	1964	21	1954	--	1944	--	1934	1
1973	1	1963	8	1953	1	1943	--	1933	2
1972	1	1962	4	1952	--	1942	1	1932	--
1971	5	1961	7	1951	--	1941	--	1931	1
1970	--	1960	2	1950	--	1940	1	1930	--

(B) OVERPASS/UNDERPASS

Number of Lanes		1	2	3	4	5	6	7	8	9
No. of Structures	Carried	5	59	44	18	2	4	0	0	1
	Under	1	37	2	37	5	24	0	2	0

(C) SKEW

Skew, degrees	0	1-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
No. of Structures	35	22	18	12	16	15	11	4			1

TABLE 4
(continued)

(D) TYPE OF SERVICE

Service		Hwy	RR	Ped.	Hwy/RR	Hwy/Ped	Overpass 2d level	Overpass 3d level	Overpass 4th level
No. of Structures	Carried	124	5	--	--	1	5	--	--
	Under	98	12	--	8	19	--	1	--

(E) CONSTRUCTION MATERIAL

CONCRETE

Type of Construction	Slab	Stringer/Multibeam, or Girder	Tee Beam	Box Beam or Girders
No. of Structures	2	6	2	1

CONCRETE CONTINUOUS

Type of Construction	Slab	Tee Beam	Box Beam or Girders	Frame	Culvert
No. of structures	1	2	1	2	4

STEEL

Type of Construction	Stringer/Multibeam or Girder	Culvert
No. of Structures	29	1

TABLE 4
(continued)

STEEL CONTINUOUS

Type of Construction	Stringer/Multibeam or Girder
No. of Structures	29

PRESTRESSED CONCRETE

Type of Construction	Stringer/Multibeam or Girder
No. of Structures	57

(F) SPANS

No. of Spans	1	2	3	4	5	6	7	8	9
No. of Structures	10	16	70	31	6	2	1	--	1

TABLE 5

PROVISIONAL PRIORITY LIST
FOR SEISMIC INSPECTION, REVIEW, AND POSSIBLE RETROFIT
OF HIGHWAY BRIDGE STRUCTURES IN UTAH

CONCRETE AND CONCRETE "CONTINUOUS" STRUCTURES

Priority 1: Those having all four seismic rating characteristics (4 or more spans, skew exceeding 20°, vertical clearance over 20 ft., structure length over 200 ft.).

D 493	D 711	D 672	D 720

Priority 2: Those having one of four seismic rating characteristics.

C 420	D 469	E 1324	D 686	E 1385
E 1322	D 551			

STEEL, STEEL CONTINUOUS, AND PRESTRESSED-CONCRETE STRUCTURES

Priority 3: Those with all four seismic rating characteristics.

F 125	F 126	C 343	C 465

Priority 4: Those with three seismic rating characteristics.

C 336	C 493	C 511	C 332	C 334
C 481	F 4	F 5	F 24	C 487
F 53	C 347	C 351	C 352	C 354
C 364	C 462			

Priority 5: Those with two seismic rating characteristics.

C 514	C 417	C 391	C 419	C 410
F 47	F 48	F 49	F 79	F 1
F 2	F 3	C 488	F 93	F 131
C 424	C 353	F 124	F 110	C 466
F 104				

Priority 6: Those with one seismic rating characteristic.

C 420	F 50	F 40	C 411	C 395
C 396	C 328	C 411	F 52	C 346
C 149	C 356	D 451	F 111	F 109
F 90	C 431	C 450	V 910	F 175
C 512	F 189	C 471	F 103	C 470
F 127	F 130	F 129	F 128	

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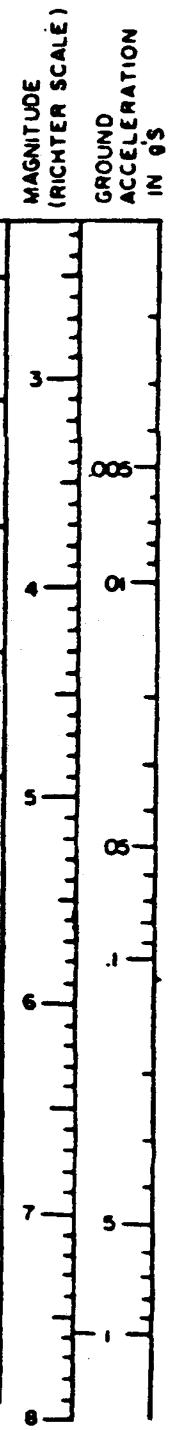
APPENDIX A

MODIFIED MERCALLI INTENSITY SCALE APPROXIMATE RELATIONSHIP WITH MAGNITUDE AND GROUND ACCELERATION

ABRIDGED MODIFIED MERCALLI INTENSITY SCALE

I	Not felt except by a very few under especially favourable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.



Modified Mercalli Intensity Scale after Wood and Neumann, 1931. (Intensities XI and XII not included).

Magnitude and acceleration values taken from Nuclear Reactors and Earthquakes, TID-7024, United States Atomic Energy Commission.

APPENDIX B

BRIDGES OF THE UNION PACIFIC RAILROAD LOCATED IN HIGH SEISMIC RISK ZONES--STATE OF UTAH

A. Bridge U.P. Main Line, M.P. 960.41, near Morgan, Utah, consists of two steel bridges on concrete piers and abutments. Each bridge consists of one 50' deck plate girder on each end of a 146' Warren truss span.

B. Bridge U.P. Main Line, M.P. 979.58, near Gateway, Utah, consists of two steel bridges on concrete piers and abutments. West bound bridge consists of one 127'-1" and one 145'-3" truss span. The east bound bridge consists of two 137'-0" truss spans.

C. Bridge U.P. Main Line, M.P. 981.01, near Gateway, Utah, consists of two steel bridges on concrete piers and abutments. Each bridge consists of one 90' deck plate girder, one 135' deck truss center span and one 50' deck plate girder.

D. Bridge Utah Division, Provo Subdivision, M.P. 790.56, near Sandy, Utah, is a steel bridge on concrete piers and abutments. Bridge consists of one 40', one 36' and one 93' through plate girders.

E. Bridge Utah Divison, First Subdivision, M.P. 45.05, near Wheelon, Utah, is a steel bridge on steel bents and concrete piers, with concrete abutments. Bridge consists of three 31'-6" and six 63' deck plate girders.

Source: W.A. Ridge, Superintendent, Transportation Divison UP, Omaha.