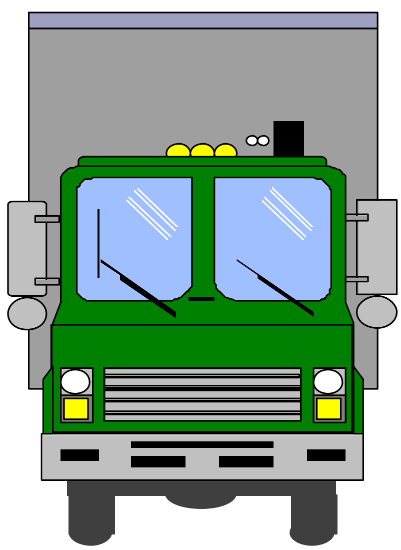
CHAPTER VI

Bridge



Introduction

The Department, in its report to Congress on the *1997 Status of the Nation's Surface Transportation System*, found that 11.7 percent of the bridges on the Nation's arterial (including Interstate) and collector highway systems are structurally deficient and 15.2 percent are functionally obsolete (see Figure VI-1). The estimated annual cost to maintain current bridge structural and functional conditions is $5.6 billion (1995 dollars). This leads to the question: How much would various changes in truck size and weight (TS&W) limits affect current and future bridge investment requirements?

This study estimates changes in costs to correct structural bridge deficiencies that could result from TS&W policy changes. The study does not address functional obsolescence, since factors that affect functional obsolescence are largely independent of truck size and weight limits.

Basic Principles

Truck-Bridge Interaction

The impact of trucks on bridges varies primarily by the weight on each group of axles on a truck and the distances between axle groups. The number of axles in each group is less important than the distance between adjacent groups. Generally, except for some continuous bridges with long spans, the longer the spacing between two axle groups, the less the impact. Figure VI-2 illustrates the two principal types of bridges, simply supported bridges and continuously supported bridges.

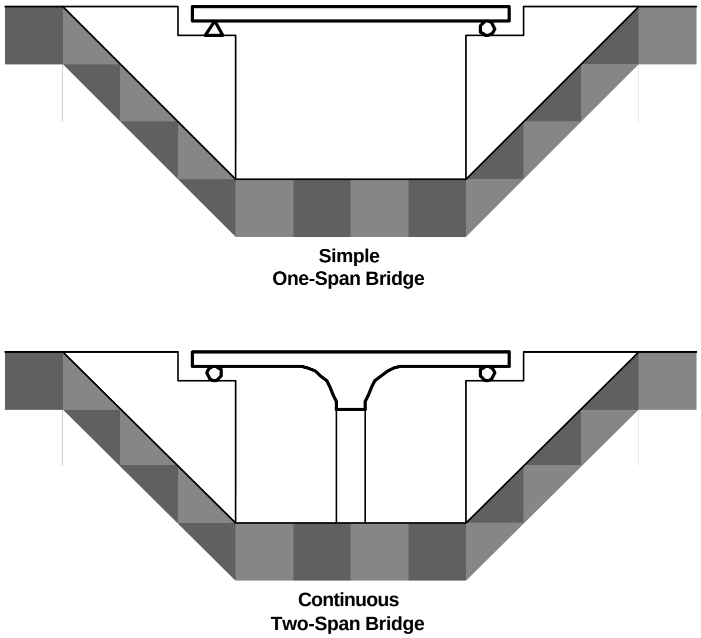
An increase in vehicle loads stretches bridge girders or beams. However, the maximum stress generally can be reduced by spreading axles and axle groups farther apart or, to a much lesser extent, by spreading the load across more axles (see Figure VI-3).

The relationship between axle loads, axle spacing, and bridge stress described above holds true for all simply supported span bridges and many continuously supported spans. However, depending on the length of continuous spans, longer axle spacings can increase stresses at the bridge inside piers. Continuous span bridges are designed to take advantage of the interactions that occur when axle groups are on the opposite side of the fixed

Figure VI-1. Structurally Deficient versus Functionally Obsolete Bridges

There are two types of deficient bridges, structurally deficient (SD) and functionally obsolete (FO). An SD bridge, as defined by the Federal Highway Administration, is one that (1) has been restricted to light vehicles only, (2) is closed, or (3) requires immediate rehabilitation to remain open. An FO bridge is one in which the deck geometry, load carrying capacity (comparison of the original design load to the State legal load), clearance, or approach roadway alignment no longer meets the usual criteria for the highway of which it is an integral part.

Figure VI-2. Simple and Continuous Span Bridges



beam connection on the central pier. This allows the use of smaller beams or girders to reduce bridge costs. However, if the two-axle loads are far enough apart and the two spans long enough, the beneficial effects will be negated.

The bridge impact analysis for this study considers both simple and continuous span bridges. The Federal Bridge Formula (FBF), which is designed to limit loads and groups of axles at different spacings to protect bridges from overloads, was based only on consideration of stresses on simple span bridges. Consequently, the FBF allows trucks to operate that could overstress certain continuous spans. Likewise, an alternative bridge formula developed by the Texas Transportation Institute (TTI) also considered only stresses on simple span bridges.

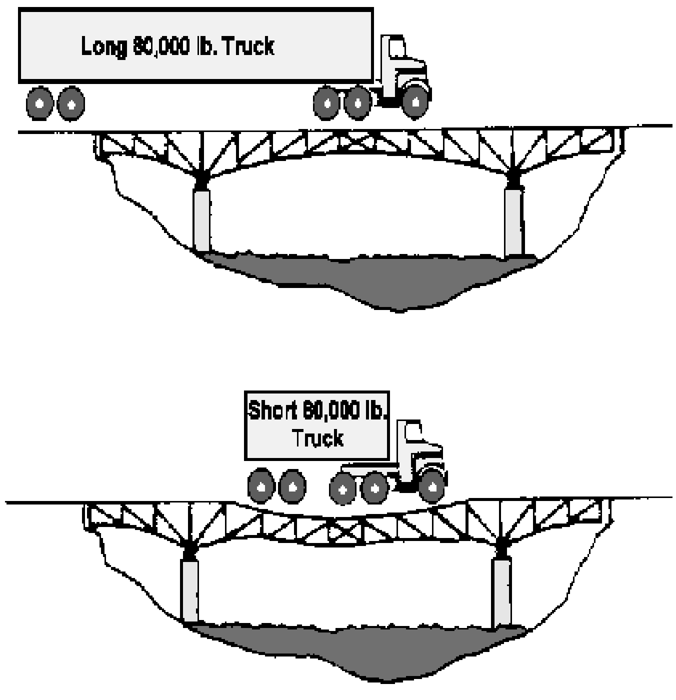
For short bridge spans, axle weights (live loads) and the weight of the span components (dead loads) are important. For longer spans,

Figure VI-3. Moments

One way to think of a moment is as two forces that tend to rotate a body, such as a bridge beam. This tendency is one source of stress in a bridge beam (the major one in a long bridge span) as the material properties and beam connection resist the rotational tendency. Further, this rotational tendency becomes stronger the farther the two forces are spread.

One of these forces results from an axle load and the other from the support at one end of the beam. One force acts in the opposite direction of the other giving rise to the rotational tendency of the two acting together. As these two forces are moved closer together, their rotational tendency is reduced. Consequently, when axle or axle groups are spread farther apart, for any given position of the truck on the bridge, the axle loads are closer to the supports which reduces the maximum moment induced by the vehicle load and the stresses in the beam.

Figure VI-4. Interaction of Bridge Span Length and Spacing of Truck Axle Groups



axle spacing becomes important in addition to the axle loads (see Figure VI-4). For spans longer than the overall length of the truck, the gross weight of the truck and its length are important along with the dead load of the span. For very long spans, the weight of the traffic is much less significant than the weight of the bridge span itself (that is, the dead load).

Bridge Impact Criteria

Previous TS&W studies have used bridge ratings as the basis for estimating whether bridges were structurally adequate to handle heavier truck loads expected under alternative truck size and weight scenarios (see Figure VI-6). Two ratings traditionally have been used by bridge engineers to rate the structural capacity of bridges, the "operating rating" which is set at 75 percent of the yield stress, and the "inventory rating", which is set at 55 percent of the yield stress. There are several methods to rate bridges. In the past the Working Stress Design or Allowable stress rating methods were used. In recent years bridge engineers have developed new bridge rating techniques based on "load factor design" and "load and resistance factor design" principles. The rating technique used by a State in reporting its bridge ratings is not directly relevant to this analyses conducted for this study since analyses are based on comparison of moments produced by scenario vehicles to those produced by the rating vehicle, regardless of how the latter were determined.

This study, with some modifications, uses the "overstress criteria" underlying Bridge Formula B -- 30 percent overstress for H-15 bridge designs and 5 percent overstress for HS-20 bridge designs. The overstress terms are defined in Figure VI-6. Also, see Figure VI-5, "H-15 and HS-20 Bridge Loading. The study used the FBF overstress criteria because they reflect current truck weight regulation policy.
If a truck (given its weight, number of axles, and the spacing of these axles) conforms to the FBF, it is not considered overweight under current weight regulations, nor does it result in an expedited program to replace H-15 bridges.

Developing an alternative bridge formula was beyond the scope of this study. As noted above, TTI, in research supported by the Federal Highway Administration, developed an alternative bridge formula in the late 1980s that was based only on the gross weight and length of the vehicle. The American Association of State Highway and Transportation Officials considered this new bridge formula, but did not accept it over the current FBF. The TRB recommended a variation of the TTI bridge formula in its Special Report 225.

Analytical Approach

The Bridge Analysis and Structural Improvement Cost (BASIC) model was used to estimate bridge impacts. This model was specifically designed to evaluate alternative national TS&W policy options. Accordingly, it was designed to analyze quickly tens of thousands of bridges using readily available data from the National Bridge Inventory (NBI). BASIC is not a bridge rating program that requires detailed section properties and other data normally only available from the "as built" construction drawings. The program uses only data available in the NBI and a table of live load/dead load ratios for different types of bridges. It determines which bridges are overstressed by comparing the computed moment of the scenario vehicles to the computed moment of the rating vehicle. If any scenario vehicle produces a moment greater than the rating vehicle times the overstress criterion, the bridge is assumed to require replacement. Once it determines the bridges that require replacement, BASIC estimates the replacement cost based on reported unit bridge costs for each Sate. It also applies a queuing theory-based construction zone model to estimate delay and related dollar costs incurred by users while bridges are being replaced.

Bridge structural impact is a function of a particular bridge loading condition and not an accumulation of loads as is the case for pavements. Bridge deck deterioration may be related to axle load repetitions similar to pavements, but there was insufficient data to analyze potential nationwide impacts of the illustrative truck size and weight scenarios on bridge deck costs.

Changes to the vehicle fleet may also cause changes in levels of fatigue damage to the bridge superstructure and damage to bridge decks. Once a critical stress range is exceeded, the added fatigue damage due to the scenario vehicles relative to the current truck fleet is not significant, because fatigue damage is a function of both repetitions and axle loads, not gross weights. Most scenario vehicles do not have greater axle loads than vehicles of the current fleet. Also, although fatigue damage can be significant, most damage to bridge components is inexpensively corrected. A further consideration is the impact of truck size and weight scenarios on bridge deck costs. If total truck VMT decreases and axle loads do not increase as the result of TS&W limit changes, bridge deck deterioration may be reduced somewhat. No direct relationships currently exist between truck traffic, axle loads, and bridge deck deterioration, but research currently is underway to develop such relationships.

Figure VI-5. H-15 and HS-20 Bridge Loadings

Most bridges in the United States were designed to accommodate either an H-15 or HS-20 loading. An H-15 loading is represented by a two-axle single unit truck weighing 30,000 pounds (15 tons) with 6,000 pounds on its steering axle and 24,000 pounds on its drive axle. An HS-20 loading is represented by a three-axle semitrailer combination weighing 72,000 pounds with 8,000 pounds on its steering axle and 32,000 pounds on its drive axle and 32,000 pounds on the semitrailer axle. The "20" in HS-20 stands for 20 tons (4 tons on the steering axle and 16 tons on the drive axle). The "S" stands for semitrailer combination which adds in the additional 16 tons for the third axle to give a total of 36 tons or 72,000 pounds.

Overview

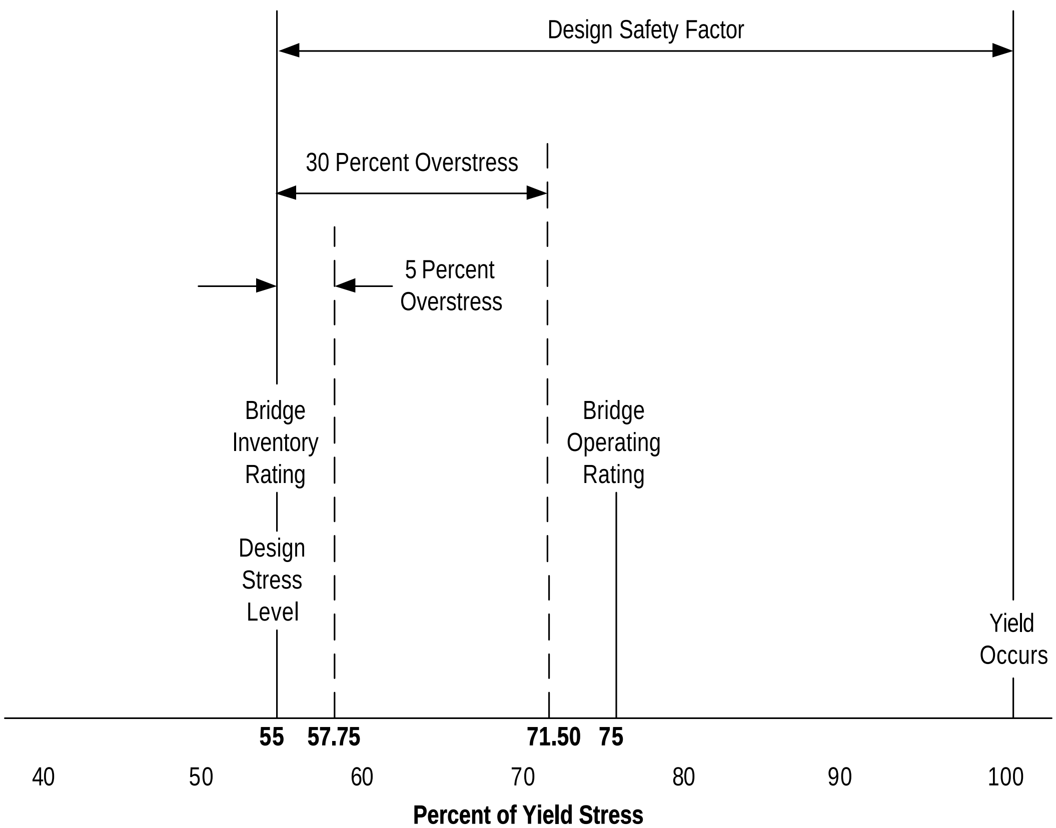
The bridge analysis for this study examines impacts of TS&W scenarios on all bridges in a sample of States from different regions of the country. For each bridge, BASIC requires data on the bridge type, bridge length, length of the main span, and the inventory rating. The inventory rating provides the safe-load carrying capacity of the bridge (see Figure VI-6). For each bridge, BASIC computes the bending moment for the rating vehicle, the base case vehicles, and the scenario vehicles. The bending moment calculations are based on both the live and dead loads for the bridge. "Dead load" refers to the weight of the bridge span components; the "live load" refers to the weight of the traffic on the span. Seven or eight truck configurations are analyzed for each scenario.

Based on the allowable overstress levels, bridges requiring replacement are identified. If the criterion for the bridge design type is exceeded, the bridge is assumed to require replacement. The cost of replacing each bridge is estimated and summed to estimate total bridge replacement costs. The user costs associated with replacing the deficient bridges are also calculated.

Like previous TRB studies, this study assumes that all deficient bridges would be replaced rather than being posted to limit maximum loads (thereby excluding some of the scenario vehicles) or strengthened. In practice it may be possible to strengthen some bridges, especially ones not expected to carry large volumes of the vehicles overstressing the bridge. There was no basis for estimating on a nationwide basis how many bridges might be strengthened rather than being replaced or what the cost to strengthen various types of bridges might be, so it was assumed that all bridges would have to be replaced. However, because in practice States might be able to strengthen some bridges rather than replacing them, cost estimates in this analysis may overestimate actual bridge costs associated with each illustrative scenario.

Figure VI-6. Relationship of Overstress Criteria to Design Stress and Bridge Ratings

The terms "overstress criteria," "design stress," " inventory rating," and "operating rating" are often used when discussing or evaluating impacts of TS&W options on bridges. These terms relate to the point at which a structural member (a load-carrying component) of a bridge undergoes permanent deformation, that is, the bridge member does not return to its original size or shape after the load is removed. The level of stress at which this permanent deformation occurs is called the "yield stress." Each of the related terms can be expressed as a percentage of this stress level. It is useful to do this to observe how each of the terms relate to each other as well as to the yield stress. Also, it is important to observe that, depending on the type of steel, a bridge member ruptures after considerable deformation relative to that which occurs at its initial point of yielding.



Relationship of Overstress Criteria to Design Stress and Bridge Ratings (Cont.)

It can be noted in the sketch that the standard stress level for the design of bridge members is 55 percent of the stress at which yield occurs. This safety factor provides a contingency for weaknesses in materials, poor quality of construction, noncompliance with vehicle weight laws, and future increases in bridge loads.

Bridges are rated by the States at either of two yield stress levels: the inventory rating, which is 55 percent of the yield stress (the same as the design stress) or the operating rating, which is 75 percent of the yield stress. These ratings are used to post bridges and for inventory purposes.

Past truck size and weight (TS&W) studies have used either of these two ratings to determine when a bridge should be replaced, given alternative TS&W policy options. A 1991 study of TS&W policy impacts on bridges used a 65-percent criterion to identify bridges needing replacement. It can be seen that bridge replacement needs would vary considerably depending on which rating was used.

The Federal Bridge Formula (FBF) is based on stress levels (overstress criteria) related to the design stress. When the FBF was formulated, a decision was made to allow loads to stress bridges designed for an H-15 loading at levels up to 30 percent over the "design stress." This type of design was used for bridges prior to the Interstate Highway Program, and these bridges are primarily located on lower functional class highways. Their early replacement was anticipated such that some shortening of bridge life could be tolerated. Bridges expected to have heavy truck traffic were designed with an HS-20 loading. The decision to allow loads no more than 5 percent over the design stress was intended to ensure that these bridges would function satisfactorily for their expected service life, 50 or more years, without the need for replacement.

This study used the FBF overstress criteria, rather than either the inventory or operating rating used in past studies, to indicate the need for bridge replacement, but with two exceptions. First, the criteria were applied to the <u>rating</u> stress level, and second the loads were permitted to exceed the inventory stress levels on H-17.5 (or higher H rating) bridges by only 15 percent versus the FBF's 30 percent. In terms of the yield stress, the 30 percent "overstress" is 71.5 percent, the 15 percent overstress is 63.5 percent, and the 5 percent overstress is 57.75 percent of the yield stress (see sketch). These criteria fall between the two bridge rating stress levels, and further they replicate the FBF criteria, which today allow a truck to exceed a bridge's inventory rating and not be considered overweight, that is, be found illegal or required to obtain an overweight permit. Whereas most bridges were designed using the HS-20, H-15 and H-20 design vehicles, recently several States have chosen to use the HS-25 design vehicle. Nonetheless, the bridge ratings in the NBI, as reported by the States, should generally not be the same as the original design ratings. The rating process should account for deterioration, strengthening, and the like. Also, a bridge may have been designed using an older Working Stress or Allowable Stress Design method, but now is rated by the Load Resistance Design rating method. Whereas bridge design and bridge rating is very dependent on which design method is used, it is not relevant to the concept of overstress as used in this study.

Figure VI-7. National Bridge Inventory

The National Bridge Inventory contains records of 581,862 bridges. The database is updated continuously and includes detailed information about all highway bridges in the country, on all functional systems. This information is used in the monitoring and managing of the Highway Bridge Replacement and Rehabilitation Program, as well as to provide the condition information presented in the biennial *Status of the Nation's Surface Transportation Report to Congress*.

Bridge Replacement

Model Inputs

To assess which bridges would be structurally inadequate to carry vehicle weights and dimensions assumed in each scenario, an 11-State sample of bridges was drawn from the National Bridge Inventory (NBI) (see Figure VI-7). The States, which were selected from various regions of the country, were Alabama, California, Colorado, Connecticut, Missouri, North Dakota, South Carolina, Texas, Virginia, Washington, and Wisconsin. Analytical results for the sample bridges, which include almost 30 percent of all bridges in the NBI, were expanded to reflect bridges in all States based on the deck area of the bridges in the sample States and the deck area of the bridges in the remaining States.

Questions were raised concerning whether bridges in States chosen to reflect each region of the country were truly representative of all bridges in those regions. No statistical analysis was conducted to verify that bridges were indeed representative, but because of the large overall sample size and the fact that no results are reported below the national level, the estimates of nationwide bridge costs in this analysis are not believed to be significantly affected by the choice of States in the sample.

Dead loads for the bridges were estimated based on detailed design information for 960 bridges of different types and span lengths. Given the type and span length of a bridge of interest, the dead load may be estimated from a table lookup feature in the model. While dead loads for specific bridges may vary from those estimated in this analysis, the methods used for the study's nationwide analysis are believed to be satisfactory.

This is the first nationwide TS&W study to consider both live and dead bridge loads. Previous studies have considered only live loads. However, with bridges of longer span length, the dead load becomes increasingly important, and in fact, the significance of the live load is reduced. In other words, the portion of total stress in a beam that results from the traffic load is less important than the portion of the stress resulting from the weight of the bridge span components.

Overstress Criteria

As noted above, this study assumed that bridges subjected to stresses that are not allowed under the FBF would have to be replaced. Thus bridges rated up to H-17.5 subjected to stresses that exceed 71.5 percent of the yield stress (1.3 times the design stress level of 55 percent of yield) are assumed to be structurally deficient to accommodate scenario vehicles. Bridges with a rating greater than H-17.5 are assumed to be deficient when stressed over 63 percent of yield. Bridges with an HS-20 rating that are subjected to stresses by scenario vehicles that exceed 57.5 percent of their yield stress (1.05 times the rating stress level of 55 percent of yield) are assumed to be structurally deficient to accommodate scenario vehicles.

Analytical Parameters

Available Routes

For the Longer Combination Vehicles (LCVs) Nationwide Scenario, Rocky Mountain Doubles (RMDs) and Turnpike Doubles (TPDs) were assumed to be restricted to a 42,500-mile system; only bridges on that system were tested to determine whether they are structurally adequate, based on the criteria described above, to carry those configurations. Other truck configurations in the scenario combinations were evaluated on all bridges in the sample States as they have the potential to use all the non-posted bridges in the NBI for access to terminals, places for loading and unloading, and places for food, fuel, rest, and repairs.

Specifications

Table VI-1 presents the weights, dimensions, and highway networks available to the truck configurations tested and the TS&W policy scenarios in which they are included. The GVWs are the weights for which the impacts were estimated. The maximum weight for no impact is given to show the difference in weight between the configurations as tested and the weight at which there would be no bridge impacts for each configuration.

Three-axle single unit trucks evaluated in the Uniformity Scenario could operate at the scenario weight without additional bridge impacts. Four-axle single unit trucks could operate at near the lower of the two North American Trade Scenario weights without additional bridge impacts, but the higher weight is considerably greater than the no impact weight. Five-axle semitrailers and STAA doubles could operate at the Uniformity Scenario weights with no bridge impacts. The six-axle semitrailer could operate at the lower of the two North American Trade Scenario weights without causing bridge impacts, but not at the higher weight. All of the LCVs would require bridge improvements, and with the exception of the seven-axle Rocky Mountain Double, the scenario weights are considerably above the no impact weight.

User Costs

In addition to the capital cost to replace bridges, the analytical approach estimates delay and excess vehicle operating costs accruing to users from traffic congestion during bridge replacement. The assumptions for accommodating traffic through the workzone are: (1) for twin bridges typically found on freeways, one bridge is taken out of service and all traffic uses the other; (2) for multilane bridges, one or two lanes are closed while traffic uses the remaining lanes with perhaps one being reversible to accommodate the predominant direction of the travel for the time of day; and (3) for a bridge with one lane in each direction, the procedure assumes either the new bridge is constructed before the old one is closed, a temporary bridge is provided while the bridge being replaced is built, or that there are adequate bypass

Table VI-1. Truck Configuration Parameters for Analysis of Bridge Impacts

Configuration	Scenarios	Gross Vehicle Weight (pounds)	Trailer Lengths (feet)	Outside Axle Spread (feet)	Highways Assumed Available	Maximum Weight for ANo Impact@ (pounds)
Three-Axle Truck	Uniformity	54,000	C	24.0	All	54,000
Four-Axle Truck	North American Trade	64,000	C	24.5	All	63,500
		71,000	C		All	63,500
Five-Axle Semitrailer	Uniformity	80,000	40	54.3	All	80,000
Six-Axle Semitrailer	North American Trade	90,000	40	54.8	All	90,300
		97,000	40	54.8	All	90,300
Five-Axle STAA double	Uniformity	80,000	28, 28	64.3	All	92,000
Seven-Axle Rocky Mt. Double	LCVs Nationwide	120,000	53, 28	94.3	42,500-mile System	115,300
Eight-Axle B-Train Double	North American Trade and LCVs Nationwide	124,000	33, 33	79.3	All	111,600
		131,000	33, 33	79.3	All	111,600
Nine-Axle Turnpike Double	LCVs Nationwide	148,000	40, 40	119.3	42,500-mile System	122,200
Seven-Axle C-Train Triple	LCVs Nationwide and Triples	132,000	28, 28, 28	97.2	65,000-mile System	116,100

opportunities and consequently no significant change in user costs.

Assessment of Scenario Impacts

The estimated costs, in 1994 dollars, for replacing bridges that would be stressed at levels above one of the three overstress thresholds discussed earlier and the user costs during bridge reconstruction are given in Table VI-2. Also shown are estimated costs to bring existing bridges up to standard to accommodate Base Case vehicles.

It is important to note that bridge costs are one time costs, not annual or recurring costs. For all scenarios, the user costs are at least as high as the capital costs, and for the scenarios with significant increases in GVWs, the delay costs are much higher.

The scenario analysis assumes that no bridges are posted or otherwise unavailable for the scenario vehicles. In practice State officials would have several options for bridges that might be structurally inadequate to accommodate vehicles that might be allowed under revised truck size and weight limits. One option would be to replace the bridge immediately if it was anticipated to carry substantial volumes of more damaging vehicles. A second option would be to postpone replacement if anticipated overstress was determined to be acceptable for a limited time. A third option would be to strengthen deficient bridges that would be expected to carry loads that could not safely be accommodated without improvements but which did not need immediate replacement. A fourth option would be to post bridges that were not economically important or were not required to carry large volumes of larger vehicles. Costs estimated in this analysis thus may be somewhat overstated and certainly not all costs would have to be incurred before heavier loads could be allowed to operate. Even if some bridges can be strengthened in the short run, many might have to be replaced sooner than otherwise would have been the case had there been no change in truck size and weight limits.

The Uniformity Scenario (see Table VI-2) would reduce current bridge investment requirements (by $20 billion). Savings result from the rollback of State weight limits that apply to the NO, which includes Interstate highways, that are higher than the Federal limits.

The bridge impacts of the North American Trade Scenarios are dominated by the weight (44,000 pounds and 51,000 pounds) allowed on the tridem-axle for the noted configurations. The bridge impacts are $51 billion and $65 billion for capital costs and $203 billion and $264 billion for user delay costs for the scenarios with the 44,000-pound and 51,000-pound tridem limit, respectively.

The bridge impact for the Longer Combination Vehicles Nationwide Scenario is $53 billion in capital costs and $266 billion in user delay costs. It is dominated by the nine-axle TPD at 148,000 pounds distributed across a length of 119.3 feet, and the eight-axle B-train double-trailer combination at 131,000 pounds distributed over 69.3 feet.

Theoretically, the H.R. 551 Scenario might increase bridge impacts as the lengths of some semitrailer combinations would be reduced as semitrailers longer than 53 feet would be phased out of service. Decreasing the length of a truck at a given weight increases the stress on bridges. This effect is very small for two reasons. First, the number of trucks affected is very small and second, the commodities carried in extra-long semitrailers are generally very light such that they have no impact on bridges. Therefore, this scenario has virtually no impact on bridges.

For the Triples Nationwide Scenario bridge costs ($16 billion in capital and $101 billion in user costs) result from the use of the seven-axle triple-trailer combination at a GVW of 132,000 pounds distributed over a length of 97.2 feet.

Table VI-2. Scenario Bridge Impacts

Analytical Case		Costs ($Billion)			Change from Base Case ($Billion)		
		Capital	User	Total	Capital	User	Total
1994 Base Case		154	175	329	0	0	0
2000 Base Case		154	175	329	0	0	0
SCENARIO							
Uniformity		134	133	267	-20	-42	-62
North American Trade	44,000-pound tridem axle	205	378	583	51	203	254
	51,000-pound tridem axle	219	439	658	65	264	329
LCVs Nationwide		207	441	648	53	266	319
H.R. 551		154	175	329	0	0	0
Triples Nationwide		170	276	446	16	101	117