Impact of Turnpike Doubles and Triple 28s on the Rural Interstate Bridge Network

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Much truck research undertaken during the 1980s has been directed toward measuring the impact of longer and heavier vehicles on the highway infrastructure. However, bridge costs have been neglected, principally because of the technical difficulties involved in measuring realistic impacts from the available data bases. Recent TRB studies on truck weight limits and Turner vehicles attempt to resolve the issue of bridge costs by including estimates of bridge damage attendant on the operation of various large-truck configurations. At present, these TRB studies constitute the most important sources of information currently available to researchers and policymakers. Yet the assumptions concerning mechanisms for determining bridge deficiencies seem worthy of further investigation, particularly because the TRB findings suggest that productivity benefits substantially overwhelm infrastructure costs. Impact on the rural Interstate bridge system of two long-combination vehicle (LCV) configurations that, although attractive to truckers, were not included in the terms of reference for the TRB studies, is examined. These are double 48-ft trailers (turnpike doubles) and triple 28-ft trailers, both of which use the considerable investment made by the trucking industry in these trailer types. It is estimated that LCV operations on the rural Interstate system result in greater bridge damage than predicted when using the TRB methodology, and that user costs—not reported by the TRB authors—are likely to be extremely high on key rural structures, resulting in cost predictions that could exceed direct agency costs.

During the 1980s, a considerable body of truck research measured the impact of longer and heavier vehicles on the highway infrastructure (*1*). Such truck types are now more commonly termed "long-combination vehicles" (LCVs). Issues investigated have focused primarily on tradeoffs between productivity gains, geometric design, and pavement damage (*2–4*). Truck performance (*5*) and trailer configurations (*6,7*) have received attention as well, leading to useful knowledge regarding the operational implications of LCV units from the trucking industry's perspective. Safety has also been a recurring objective (*8,9*), though the results have frequently been inconclusive and difficult to interpret. Yet bridge damage from LCV trucks has been relatively neglected, in part because of the complex nature of the analysis and paucity of data.

Recent TRB studies have reported on truck weight limit options and issues (*10*), as well as on Turner trucks (*11*), which are configured to lessen pavement damage while increasing gross vehicle mass. In particular, the study on Turner trucks, which includes an estimate of bridge damage attendant on the operation of various larger trucks, represents for researchers and policymakers an important source of information. The mechanism and assumptions made to determine TRB bridge deficiencies seem worthy of further investigation, particularly because the findings suggested that Turner productivity gains overwhelm net infrastructure costs. Notably, these TRB authors did not report user costs incurred during any extensive bridge replacement program—costs that are likely to be extremely high on many structures.

The impact on the rural Interstate bridge system of two LCV configurations that, although favored by truckers, were not part of the terms of reference for the TRB studies, is examined. These are double 48-ft trailers (turnpike doubles) and triple 28-ft trailers, both using the considerable investment made by the trucking industry in these trailer types. In addition, the basic TRB bridge deficiency methodology used to predict bridge failures is broadened and replacement costs are estimated. Finally, some preliminary user cost estimates are associated with the replacement of deficient bridges.

METHODOLOGY

From a U.S. Department of Transportation copy of the latest National Bridge Inventory (NBI) data base (*12*), all Interstate bridges in the system, excluding those located within cities having more than 50,000 inhabitants, were identified. This first-stage exercise produced a data base containing approximately 29,700 structures.

Data from each NBI structural record were next categorized into simple and continuous spans to permit the calculation of bending moments for selected truck types and loads. Load configurations were developed for twin 48-ft and triple 28-ft trailer trucks, on the basis of fully loaded conditions constrained by the uncapped federal bridge formula. A program to predict vehicle moments was then written and applied to all individual rural Interstate structures, with the results for each vehicle configuration compared with the inventory rating on a bridge-by-bridge basis. This rating, originally developed to issue multiple-trip permits, is a more conservative and safer limit (55 percent yield stress) than the operating rating (75 percent yield stress) used in the TRB studies. TRB authors preferred the latter because staff in the bridge divisions in 26 of the 46 states responding to a 1988 survey indicated that they then used operating ratings to post or limit bridge access (*13*). A computer model determined bridge deficiencies. That

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is, a bending moments model was run that compared the benchmark standardized rating truck moments for each structure with those induced by the two LCV types—first separately, then operating together. This approach was similar to that reported by the Arizona DOT in 1987 (*14*). Structures that failed to meet the inventory rating load (plus a 5 percent allowance) were identified. In addition, their deck areas were noted to enable a replacement cost estimate to be made from 1989 FHWA unit cost data. Finally, average daily traffic figures for each of the deficient structures were noted and then aggregated to provide an estimate of user cost impacts associated with the state and national replacement programs for such bridges.

SCOPE AND ASSUMPTIONS

General

The impact of operating double 48-ft and triple 28-ft trucks over the continental U.S. Interstate rural bridge network system was investigated under the uncapped (no total vehicle weight limit of 80,000 lb) Federal Bridge Formula (Formula B) limit. The resulting gross loads, axle weights, and dimensions for each LCV type are shown in Figure 1. Although the ability of the current federal bridge formula to protect the infrastructure and permit efficient truck operations has been reviewed in recent research (*15*), the uncapped Formula B is an extension of current legal limits; as such, it remains the best benchmark for this LCV impact study. For each deficient bridge, the deck area and average daily traffic (ADT) were recorded by state, enabling the numbers of deficient bridges to be determined for LCV operations, together with deck surface area and traffic data, first by state, then for the entire national rural bridge network.

Inventory and Operating Ratings

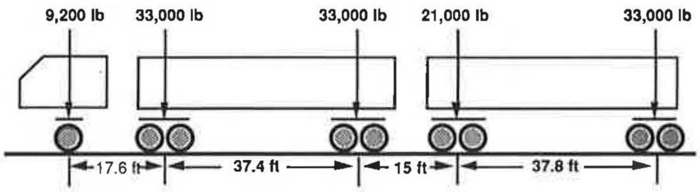
Inventory and operating ratings, originally specified by AASHTO (*16*), are important concepts associated with bending moment models and bridge distress. The inventory rating is defined as the load that produces a stress in the critical bridge element 0.55 times the yield stress (*17*). Generally, the inventory rating is used to issue multiple-trip permits, because the load is designated as what can be used over the design life of a structure without appreciable bridge deterioration.

The operating rating, frequently used to issue single-trip permits and bridge postings, is defined as the load that produces a stress in the critical bridge element 0.75 times the yield stress. As with the previous rating, stresses from the designated vehicle type are compared with the benchmark operating rating figure while a load exceeding the inventory rating—but not the operating rating—will not cause a bridge to collapse; it will shorten the life of the structure by an unknown, and possible significant, amount.

NBI Data Base

Presently, the NBI data base consists of 661,481 records, with each record representing a structure—from culverts to bridges—in the nation's road network. This study addressed the intercity use of LCVs where most LCV ton-miles accrue and ignored the costly process of assimilating them into the urban Interstate networks. This makes the study costs conservative, because urban impacts are likely to be nontrivial. In developing the rural Interstate bridge data base, the basic 661,481 records were reduced to 36,388. In addition, the study disregarded all structures classified as culverts, further reducing the data set to 29,731 bridge structures. For each of the orig-

DOUBLE 48
Total length 107.8 ft., total weight 129,200 lbs.



TRIPLE 28
Total length 94.9 ft , total weight 114,200 lbs

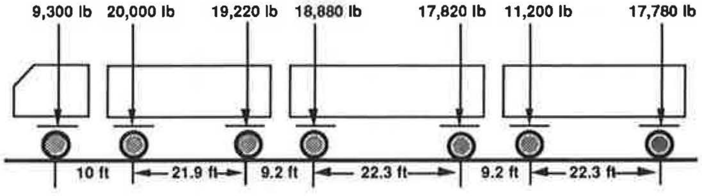


FIGURE 1 Gross loads axle weights and dimensions for double 48-ft and triple 28-ft LCVs.

inal 36,388 structures, selected data were first retrieved from the NBI data base and then sorted by state. Table 1 presents the nationwide distribution of the rural Interstate bridges classified by structure type.

The inventory rating vehicles used by a majority of states for determining operating and inventory ratings are H and HS trucks (*17*). Approximately 80 percent of the Interstate bridge rural subset studied are rated using the HS truck type, while about 11 percent are rated using the H type. For the remainder of the subset, some states (e.g., Kansas and New Jersey) rely on Types 3, 3S2, and 3–3 (*16*) to rate their bridges. Ohio, where all the Interstate rural bridges studied are rated for gross load only, represents a special case. For these bridges, the reported gross inventory rating load was assumed to be distributed over the original design load axle configuration, which turned out to be an HS truck for 96 percent of the structures in the state.

Limitations of the NBI Data Base

The NBI data base is currently the only source of national bridge data available for examining LCV operational policy. Unfortunately, this data base contains transcription errors and inconsistencies in rating procedures between states. Moreover, the NBI, though containing 90 information fields for each bridge on the national network, lacks sufficient engineering detail to determine an accurate analysis of individual bridge capacity. Consequently, several assumptions must be made when studying truck weight and axle configuration impacts. The NBI limits the description of the structural geometry (which directly affects the live-load bending moments calculations) to the number of spans, the structure length, and the length of the maximum span. Such descriptions may be sufficient for modeling a simply supported structure, but they are inadequate with respect to a continuous structure.

TABLE 1 DISTRIBUTION BY STRUCTURE TYPE NATIONWIDE

		Concrete		Steel		Prestress			Bridges+	
State	Concrete	Continuous	Steel	Continuous	Prestress	Continuous	Timber	Culverts	Culverts	Bridges
Alabama	154	113	57	106	7	42	1	205	685	480
Alaska	1		73	23	30		2	2	131	129
Arizona	30	316	9	101	139	9	1	935	1,540	605
Arkansas	137	8	156	24	3			65	393	328
California	387	1,863	152	21	508	264	2	275	3,472	3,197
Colorado	200	131	52	96	54	42	1	105	681	576
Connecticut	7	2	75	6	20			15	125	110
Delaware										
Dist Columbia		2							2	2
Florida	17	21	28	25	573	6		142	812	670
Georgia	144	13	184	106	60	15		170	692	522
Idaho	224	10	18	7	144	1		0	404	404
Illinois	46	93	33	579	140	33		182	1,106	924
Indiana	55	317	190	526	16	18		16	1,138	1,122
Iowa	12	61	2	111	182			81	449	368
Kansas	7	341		189		4	1	118	660	542
Kentucky	88	108	35	117	22	12		76	458	382
Louisiana	374	44	117	74	288		2	198	1,097	899
Maine	2		64	98				26	190	164
Maryland	8	6	109	68	1	3	1	24	220	196
Massachusetts	32	8	293	14	34	6		17	404	387
Michigan	23	19	284	20	108	9		4	467	463
Minnesota	14	35	24	307	243	2		114	739	625
Mississippi	29	105	42	18	290	7	1	140	632	492
Missouri	24	62	31	269	2	29		108	525	417
Montana	56	106	36	88	526	15	1	17	845	828
Nebraska		70	20	35	60	4		45	234	189
Nevada	36	126	16	22	46	4		86	336	250
New Hampshire	38		132	97	12		1	28	308	280
New Jersey	25		338	9	156			64	592	528
New Mexico	15	110	11	74	213	19	2	352	796	444
New York	37	7	700	76	48	10	1	150	1,029	879
North Dakota	11	62	28	119	68	36		46	370	324
North Carolina	32		221	50	94	11		134	542	408
Ohio	33	370	153	1,556	10	1		117	2,240	2,123
Oklahoma	26	142	220	152	10			219	769	550
Oregon	25	333	53	18	94	14	13	0	550	550
Pennsylvania	176	26	116	164	589	5		448	1,524	1,076
Rhode Island	2	2	6	2	6				18	18
South Carolina	193	4	166	23	103			120	609	489
South Dakota		238	4	103	4	19		36	404	368
Tennessee	46	175	11	74	268	87		172	833	661
Texas	573	259	42	267	820	41	1	1,107	3,110	2,003
Utah	24	59	23	48	250	21		82	507	425
Vermont	4		148	91	2			46	291	245
Virginia	124	10	440	106	144			222	1,046	824
Washington	39	171	23	8	116	104		3	464	461
West Virginia	3	7	34	330	14	6		34	428	394
Wisconsin	4	208	12	141	66	103		54	588	534
Wyoming	7	622	15	224	4		4	57	933	876
Totals	3,544	6,785	4,996	6,782	6,587	1,002	35	6,657	36,388	29,731

Two bridges with the following NBI information—one simply supported and the other continuous—can be used as examples:

1. Structure length: 180 ft.
2. Number of spans: 3.
3. Length of maximum span: 80 ft.

Many combinations are possible for the remaining two span lengths for both the continuous and the simply supported bridge, as shown in Figure 2. In the case of the simply supported bridge structure, the modeling approach used calculates the live-load maximum bending moment for the rating vehicle, and the maximum live-load bending moments for both the double and triple LCV configurations using the 80-ft span. Comparing the benchmark moment caused by the rating vehicle with the values from the LCV configurations would then determine bridge deficiency. For such a determination, no assumptions are necessary regarding the bridge geometry as it affects the structural calculations. The critical span of a simply supported bridge is the maximum span, and no interaction exists between adjacent spans of a simply supported structure.

However, because more than half of the bridges in the rural Interstate network are continuous, their analysis requires that some assumptions be made, and questions arise when trying to model this continuous bridge with the NBI available data. For example, is the 80-ft maximum span really the middle span? Are the two remaining spans of the same length? To answer such questions, two assumptions were made: (a) the maximum span is always the middle span; and (b) the remaining spans are calculated by subtracting the maximum span from the overall structure length and dividing the result by the remaining number of spans, as described in the following equation:

$$\text{Secondary span} = \frac{(\text{structure length} - \text{maximum span})}{(n - 1)} \qquad (1)$$

where n is the number of spans in the structure. In addition, the cross section was assumed to be constant throughout the bridge.

The limitations of the NBI data base make it unsuitable for project-level analysis—for example, for determining what engineering work would correct deficiencies on a specific bridge. However, it is perfectly suitable for network evaluations and, using the previous assumptions, adequate for policy determination of the type sought in this study. Finally, because there is no other comparable national data base, such assumptions must be made for any network analytical modeling.

Structural Models

The calculations performed using NBI data compared the inventory rating bending moments induced on the bridge structure by the rating vehicles, with the bending moments induced by the LCVs under investigation. Inventory rating bending moments are defined as the moments that induce maximum stresses in the bridge superstructure (beams and girders), which are equal to the inventory rating allowable stress as previously defined. Inventory rating bending moments are a combination of the dead- and live-load effects. The type, axle configuration, allowable loading of the rating vehicle, and brief description of the structural geometry are recorded in the NBI data base, making it therefore possible to calculate inventory rating live-load moments for each one of the Interstate bridges, and to compare them with the moments induced by the LCVs under study. The maximum live-load bending moments are calculated by placing the rating vehicles and the LCVs, one at a time, on the position that generates the maximum live load bending moment—an approach similar to that used by White and Minor (*18*).

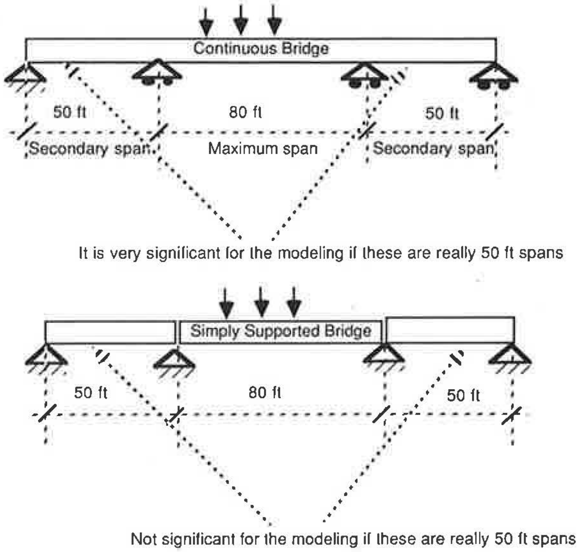


FIGURE 2 Simply supported and continuous bridge calculations as affected by limitations in the NBI data base.

For this study, a bridge was counted as deficient, and thus in need of replacement, if the maximum live-load bending moment, negative or positive, induced by the LCV, exceeded the inventory rating live-load bending moment by 5 percent, a figure reported in the TRB studies. The procedure compared the positive and the negative bending moments, one pair at a time. Now, while the combination of live-load and dead-load moments is usually critical when calculating negative bending moments, the same does not hold for positive moments, where the combination of dead-load and live-load bending moments may affect the search for the bridge cross section having the highest stress. Because dead loads are not recorded on the NBI data base, moment calculations assume that the most critical section for the live load is also the critical section for the combination of dead load and live load.

Deck area and average daily traffic (ADT) were recorded for all bridges screened as deficient. Deficient bridges are reported first by state and then for the nation for double 48s alone, triple 28s alone, and both types together. These data were categorized by two structural types, namely simply supported and continuous bridges. Of the 29,731 bridges identified, 14,569 were classified as continuous structures and 15,162 were classified as simply supported structures. Influence-line diagrams for each structure type were used in the calculations of the maximum bending moments induced by the rating and LCV configurations under study. Continuous-beam influence line diagrams were used (*19*) to calculate the critical bending moments for the rating vehicles and the LCVs under study. Influence-line diagrams were used to identify the most critical vehicle positions for both negative and positive live-load moments. At the critical positions, where maximum bending moments are induced, the critical bending moments (negative and positive) are calculated using influence-line diagrams. Either negative or positive moment comparisons between rating vehicle live-load bending moments and LCV live-load bending moments will flag a bridge as deficient. The procedures for calculating inventory rating bending moments, LCV bending moments, and deficiencies include the following:

1. Determine if the bridge is continuous or simply supported and obtain the appropriate influence-line diagram.
2. Calculate the maximum bending moments, negative and positive, for continuous bridges, induced by the inventory rating vehicle.
3. Calculate the maximum bending moments, negative and positive, for continuous bridges, induced by the double 48-ft and triple 28-ft LCVs.
4. Flag the bridge as deficient where the LCV live-load moments exceed the inventory rating live-load moments by 5 percent. Record deck area and ADT for each deficient bridge.

A flowchart of the procedure used to perform the screening of structurally deficient bridges nationwide is shown in Figure 3.

All deficient bridges are replaced, not strengthened or rehabilitated (as with the TRB studies). Reasons include the inability to determine appropriate individual bridge corrective strategies from the NBI data, problems of strengthening bridges (like strengthening concrete structures), and the federal requirement that where federal-aid bridges are being strengthened, other features related to functional deficiency must be addressed. The study assumed that all rural Interstate bridges currently met the inventory rating criteria for 80,000-lb trucks. In addition, no allowance was made for grandfathered exemptions, an approach that differed from the TRB study. Many grandfathered configurations are clear LCV types, and logic requires that their impacts be correctly accounted for when determining LCV impacts. Although fatigue costs are not reported, they are likely to be lower than the TRB estimates, because it is assumed that the most conservative of the stress levels (the inventory rating) is used to issue multiple-use permits.

RESULTS

A full summary of the results, by state, is given in Tables 2–4. These cover the number of deficient bridges triggered by triple 28s, double 48s, and both types operating together, respectively. Two categories are reported: (a) the costs of replacing deficient structures, where 1989 FHWA bridge replacement cost data (by state) are adopted; and (b) ADT data for the set of deficient structures. Costs reported are therefore in 1989 prices. The critical costs are those related to the replacement of deficient bridges, including user costs attendant on the massive reconstruction program. These are now considered.

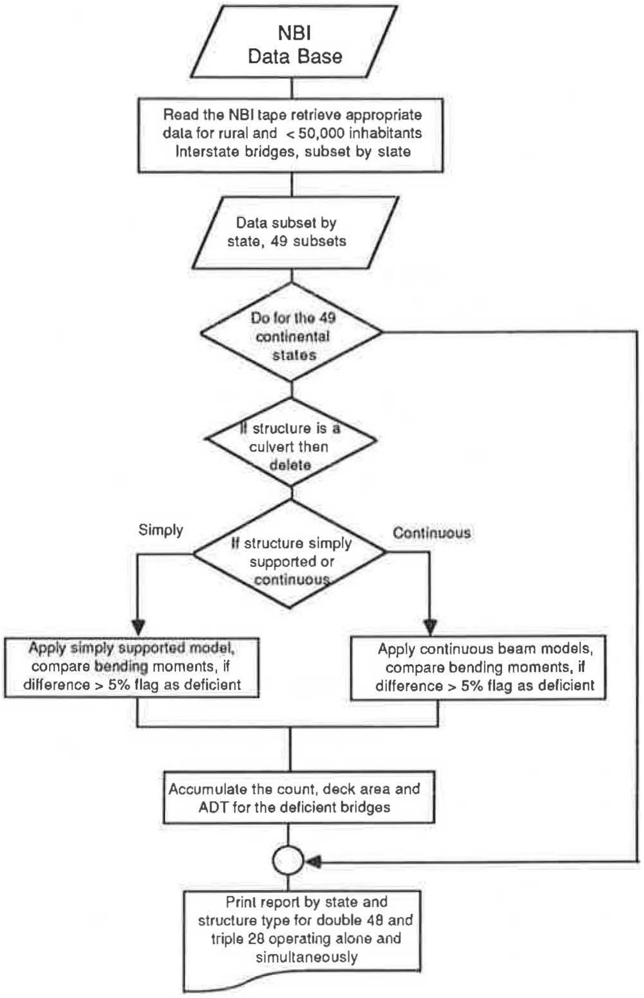


FIGURE 3 Flowchart of the calculations performed when assessing the impacts of LCVs.

Replacement Costs

Replacement costs were developed for each of the two main vehicle categories, and then both operating together. Table 5, which presents results by state, indicates that the operation of triple 28s on the rural Interstate system renders about 2,900 bridges deficient at a replacement cost of $3.9 billion. Double 48s have a much higher impact and render around 6,000 bridges deficient at a cost of $5.8 billion. Finally, both LCV types operating together are predicted to fail around 6,300 structures at an estimated replacement cost of over $6.0 billion. Direct comparisons with other LCV impact results cannot be made because of the different weights and configurations used in the various studies. However, TRB research on heavier trucks constitutes a valuable input for determining the scale of the predicted values on the rural Interstate network. The TRB Turner study nine-axle double has the same axle configuration as the double 48 but is limited to 77 ft in length and around 111,000 lb in mass. The TRB Turner estimates

TABLE 2 SUMMARY OF CALCULATIONS FOR TRIPLE 28s OPERATING ALONE (INVENTORY RATING)

State	*Simply Supported Bridges*			*Continuous Bridges*			*Continuous and Simply Supported*		
	Count	*Area*	*ADT*	*Count*	*Area*	*ADT*	*Count*	*Area*	*ADT*
Alabama	6	92	64	4	93	44	10	185	108
Alaska	12	239	51	8	130	27	20	369	78
Arizona	52	335	417	56	589	341	108	924	757
Arkansas	6	100	59	3	304	92	9	404	151
California	264	7,258	10,128	135	7,147	3,942	399	14,405	14,069
Colorado	44	351	230	47	858	284	91	1,208	514
Connecticut	2	10	9	2	106	50	4	116	59
Dist Columbia	0	0	0	0	0	0	0	0	0
Florida	17	950	151	14	1,480	152	31	2,430	302
Georgia	7	181	117	10	596	177	17	777	293
Idaho	30	258	142	1	12	0	31	270	143
Illinois	5	374	22	28	579	213	33	953	235
Indiana	4	34	15	94	1,268	505	98	1,302	519
Iowa	2	9	6	5	134	33	7	143	39
Kansas	3	11	10	276	2,264	1,210	279	2,275	1,221
Kentucky	10	129	78	35	583	442	45	712	520
Louisiana	68	1,894	1,871	15	328	364	83	2,221	2,235
Maine	9	65	38	8	155	87	17	220	125
Maryland	4	73	105	19	540	358	23	613	463
Massachusetts	26	536	1,155	5	251	49	31	787	1,204
Michigan	8	121	83	0	0	0	8	121	83
Minnesota	10	292	315	34	1,415	837	44	1,707	1,152
Mississippi	6	855	100	12	355	105	18	1,209	204
Missouri	6	59	33	82	1,942	705	88	2,000	738
Montana	2	47	5	41	1,255	203	43	1,302	208
Nebraska	8	98	73	11	177	44	19	275	117
Nevada	15	198	40	4	87	8	19	285	48
New Hampshire	13	84	109	53	806	359	66	889	468
New Jersey	96	1,789	3,295	1	24	19	97	1,813	3,315
New Mexico	3	31	10	1	9	6	4	40	15
New York	116	1,880	1,954	21	1,020	373	137	2,900	2,327
North Dakota	2	17	1	48	426	21	50	443	22
North Carolina	32	436	362	16	448	225	48	883	587
Ohio	26	1,003	696	221	2,751	5,622	247	3,754	6,318
Oklahoma	3	28	19	7	117	58	10	145	77
Oregon	20	645	236	18	342	393	38	987	629
Pennsylvania	110	1,222	997	67	1,815	753	177	3,037	1,750
Rhode Island	0	0	0	0	0	0	0	0	0
South Carolina	18	717	112	7	535	72	25	1,252	184
South Dakota	0	0	0	25	244	96	25	244	96
Tennessee	0	0	0	20	501	405	20	501	405
Texas	26	596	243	37	1,651	591	63	2,246	834
Utah	15	139	69	13	162	84	28	302	153
Vermont	6	47	10	8	156	36	14	203	45
Virginia	21	732	786	23	754	415	44	1,486	1,201
Washington	33	445	423	24	484	202	57	929	625
West Virginia	7	74	39	32	849	201	39	924	240
Wisconsin	4	36	71	24	772	212	28	808	283
Wyoming	7	48	27	72	443	165	79	491	192
Totals	1,184	24,537	24,773	1,687	36,955	20,578	2,871	61,493	45,351

Note: Units, Area (sqft) x 1000 and ADT (vehicles) x 1000.

for nine-axle double and seven-axle tractor-semitrailer impacts suggest that 7,000 Interstate and primary bridges would fail the rating criterion (operating) at a replacement cost of $2.8 billion. The TRB 11-axle double has a gross weight of 141,000 lb (near the upper limit for double 48s) but is again limited to 77 ft in length (which severely impacts on bridges), affecting 23,000 Interstate and primary bridges at an estimated cost of over $9 billion. Insofar as it is possible to compare these results, this study would seem to suggest that double-48 and triple-28 operations will have a profound impact on the Interstate bridge, requiring a much larger state replacement program that that indicated by the TRB studies.

Although agency cost considerations have thus far been foremost, any intensive program of Interstate bridge reconstruction will impact on the traveling public in the form of user costs. These costs were not estimated in the TRB document, but the system-wide implications are so great that they deserve to be studied. These implications will be considered next.

User Costs

There were insufficient resources to investigate this issue in detail, but valuable insights into the likely magnitude and impact of these costs can be estimated using only the NBI data. Each bridge record has an ADT, and when determining the characteristics of the deficient bridges, the ADT data recorded on the NBI tape were noted and subsequently aggregated by the vehicle type that rendered the bridge deficient.

The program to replace bridges for triple 28s affected an estimated 45 million vehicles per day. Double 48s affected 85 million vehicles per day, while the two types together affected

TABLE 3 SUMMARY OF CALCULATIONS FOR DOUBLE 48s OPERATING ALONE (INVENTORY RATING)

State	Simply Supported Bridges			Continuous Bridges			Continuous and Simply Supported		
	Count	Area	ADT	Count	Area	ADT	Count	Area	ADT
Alabama	14	845	165	37	453	267	51	1,298	433
Alaska	18	267	58	10	267	72	28	534	130
Arizona	68	403	583	73	682	445	141	1,085	1,028
Arkansas	18	276	183	7	407	127	25	683	310
California	335	8,299	12,687	355	10,820	7,754	690	19,119	20,442
Colorado	74	486	483	89	1,205	479	163	1,691	963
Connecticut	2	5	14	2	106	50	4	111	64
Dist Columbia	0	0	0	0	0	0	0	0	0
Florida	26	1,065	301	27	1,826	203	53	2,892	504
Georgia	13	252	198	31	1,433	462	44	1,686	660
Idaho	74	412	341	5	34	29	79	446	370
Illinois	11	453	61	101	1,104	628	112	1,557	689
Indiana	3	30	38	179	1,727	1,302	182	1,757	1,340
Iowa	5	37	16	32	342	217	37	380	233
Kansas	3	11	10	436	3,323	1,927	439	3,334	1,937
Kentucky	10	129	78	49	742	603	59	871	681
Louisiana	98	2,271	2,634	25	740	931	123	3,011	3,565
Maine	19	118	169	48	580	305	67	698	474
Maryland	5	75	117	28	695	658	33	770	775
Massachusetts	42	616	1,637	9	260	99	51	876	1,736
Michigan	7	108	69	2	12	6	9	120	75
Minnesota	16	388	375	78	2,021	1,680	94	2,409	2,055
Mississippi	15	925	185	17	604	160	32	1,529	345
Missouri	19	128	130	155	2,391	1,206	174	2,519	1,336
Montana	8	141	22	71	1,570	318	79	1,711	340
Nebraska	8	98	73	49	371	282	57	469	355
Nevada	29	456	113	31	233	168	60	690	281
New Hampshire	29	196	207	65	858	531	94	1,054	738
New Jersey	138	3,173	5,232	2	46	62	140	3,219	5,293
New Mexico	4	49	11	48	351	220	52	399	231
New York	157	2,323	2,714	33	1,202	540	190	3,525	3,254
North Dakota	21	148	6	94	662	143	115	810	149
North Carolina	36	444	427	20	459	253	56	902	680
Ohio	41	1,828	1,179	620	6,061	14,556	661	7,888	15,734
Oklahoma	17	73	96	33	477	232	50	549	328
Oregon	30	949	338	105	918	2,070	135	1,867	2,407
Pennsylvania	155	1,624	1,626	100	2,300	1,144	255	3,923	2,769
Rhode Island	0	0	0	1	5	1	1	5	1
South Carolina	35	1,066	328	7	616	60	42	1,682	388
South Dakota	0	0	0	162	995	510	162	995	510
Tennessee	0	0	0	90	1,065	1,904	90	1,065	1,904
Texas	274	2,779	3,258	125	3,562	1,690	399	6,341	4,947
Utah	22	189	87	41	337	163	63	526	250
Vermont	10	97	31	10	286	40	20	383	70
Virginia	39	1,496	1,371	33	953	470	72	2,449	1,841
Washington	58	719	592	72	936	892	130	1,655	1,484
West Virginia	9	96	48	32	849	201	41	945	249
Wisconsin	8	96	160	31	839	271	39	935	431
Wyoming	10	54	43	347	1,485	775	357	1,539	818
Totals	2,033	35,693	38,491	4,017	59,211	47,105	6,050	94,904	85,596

Note: Units, Area (sqft) x 1000 and ADT (vehicles) x 1000.

88 million vehicles. What do such data indicate? A precise answer would require a breakdown of vehicle types (particularly trucks), numbers of vehicles in each category, some measure of daily variation over the week, and time of delay at each structure. Unfortunately, no such data are available from NBI tapes (or from other readily accessible sources), and it would take a dedicated research effort to quantify these effects. In addition, information is needed on the time periods for bridge reconstruction programs. Nevertheless, some assumptions can be made to determine the scale of the impacts.

In attempting to estimate the impacts on traffic affected by the triple 28s and double 48s, whether the traffic data seem reasonable must be considered first. If 88 million vehicles per day are affected, then an average of approximately 14,000 vehicles per day per structure are involved, a figure that does not seem unduly high given the capacity and use of the rural Interstate system. Next, if we assume that half this figure is affected by the capacity constraints imposed by replacement construction activities, then a total of 44 million vehicles per day is predicted to be affected. If we further assume that 5 min are lost per vehicle—decelerating, traveling slowly through or around the construction, and accelerating back to cruising speed—we obtain a total of about 3.7 million hours per day. Now, if only one passenger per vehicle is affected, and their value of time is weighted at $5 per hour, then a total of $18 million per day is lost because of the program. Over a 300-day reconstruction cycle (a figure suggested by records in Texas), a total time delay figure of over $5 billion is thus predicted.

In addition to time costs, vehicle operating costs are affected. Assume that only fuel is affected, and that 0.1 gal is lost per bridge—about 12 cents per vehicle. Then a flow of 44 million vehicles per day produces $5.3 million per day, or $1.6 billion for the 300-day program. Thus, total time

TABLE 4 CALCULATIONS FOR TRIPLE 28s AND DOUBLE 48s OPERATING SIMULTANEOUSLY (INVENTORY RATING)

State	*Simply Supported Bridges*			*Continuous Bridges*			*Continuous and Simply Supported*		
	Count	*Area*	*ADT*	*Count*	*Area*	*ADT*	*Count*	*Area*	*ADT*
Alabama	14	845	165	37	453	267	51	1,298	433
Alaska	19	271	59	12	277	75	31	548	134
Arizona	68	403	583	74	692	454	142	1,095	1,037
Arkansas	18	276	183	7	407	127	25	683	310
California	335	8,299	12,687	361	11,017	8,175	696	19,316	20,863
Colorado	75	493	495	94	1,257	508	169	1,750	1,003
Connecticut	4	15	22	2	106	50	6	121	72
Dist Columbia	0	0	0	0	0	0	0	0	0
Florida	26	1,065	301	27	1,826	203	53	2,892	504
Georgia	13	252	198	31	1,433	462	44	1,686	660
Idaho	76	462	349	5	34	29	81	496	378
Illinois	11	453	61	108	1,177	719	119	1,630	780
Indiana	5	42	38	206	1,984	1,440	211	2,026	1,478
Iowa	5	37	16	32	342	217	37	380	233
Kansas	3	11	10	441	3,377	1,966	444	3,388	1,976
Kentucky	10	129	78	52	780	631	62	908	709
Louisiana	100	2,339	2,692	31	803	1,117	131	3,141	3,810
Maine	21	134	180	49	586	311	70	719	490
Maryland	5	75	117	29	778	683	34	854	800
Massachusetts	42	616	1,637	9	260	99	51	876	1,736
Michigan	8	121	83	2	12	6	10	133	89
Minnesota	16	388	375	84	2,073	1,763	100	2,461	2,138
Mississippi	15	925	185	19	617	169	34	1,541	354
Missouri	20	131	131	164	2,466	1,285	184	2,597	1,415
Montana	8	141	22	71	1,570	318	79	1,711	340
Nebraska	8	98	73	51	387	288	59	485	361
Nevada	29	456	113	31	233	168	60	690	281
New Hampshire	29	196	207	75	942	578	104	1,138	785
New Jersey	140	3,215	5,291	2	46	62	142	3,260	5,353
New Mexico	4	49	11	49	359	226	53	408	236
New York	161	2,355	2,760	33	1,202	540	194	3,557	3,300
North Dakota	22	158	6	114	853	152	136	1,010	158
North Carolina	39	481	471	24	495	304	63	975	775
Ohio	42	1,853	1,210	672	6,673	15,702	714	8,527	16,912
Oklahoma	17	73	96	33	477	232	50	549	328
Oregon	30	949	338	107	940	2,113	137	1,889	2,451
Pennsylvania	158	1,657	1,648	103	2,333	1,152	261	3,990	2,799
Rhode Island	0	0	0	1	5	1	1	5	1
South Carolina	35	1,066	328	9	631	86	44	1,697	414
South Dakota	0	0	0	164	1,007	519	164	1,007	519
Tennessee	0	0	0	96	1,132	2,052	96	1,132	2,052
Texas	274	2,779	3,258	125	3,562	1,690	399	6,341	4,947
Utah	22	189	87	50	418	242	72	607	328
Vermont	10	97	31	14	317	57	24	414	87
Virginia	39	1,496	1,371	35	971	504	74	2,467	1,875
Washington	58	719	592	84	1,062	959	142	1,781	1,552
West Virginia	9	96	48	32	849	201	41	945	249
Wisconsin	8	96	160	31	839	271	39	935	431
Wyoming	10	54	43	355	1,546	794	365	1,600	837
Totals	2,061	36,051	38,807	4,237	61,610	49,962	6,298	97,660	88,770

Note: Units, Area (sqft) x 1000 and ADT (vehicles) x 1000.

and fuel costs for triple 28s and double 48s are approximately \$7 billion—a substantial impact based on defensible assumptions.

Although the problem of estimating user costs is complex, this large figure suggested that further study was warranted. The financial impacts clearly transcend by a significant (but unknown) amount the agency costs reported for many vehicle configurations in the TRB studies. Concern about the broad assumptions made earlier—and about the significant costs involved—encouraged a more precise examination of the user impacts. Accordingly, the QUEWZ model (*20*), developed at the Texas Transportation Institute for measuring work zone user costs (time and vehicle operating costs) under different traffic scenarios, was selected. This model estimates both vehicle operating costs and passenger time delay costs. Not all bridges were considered, because the traffic levels over many rural Interstate bridges are low enough to enable diversions to one lane per direction without causing congestion. For example, ADT of 15,000 or less did not trigger significant user delay and operating costs when the QUEWZ model was run with a typical bridge work zone traffic strategy. Therefore, the data set was evaluated only for higher ADT levels, specifically bridges exceeding 20,000 ADT, which represent around 18 percent of the rural Interstate population. Because bridge capacity should vary with traffic levels, lane numbers were allocated to various levels of ADT for the purposes of predicting delay and user costs during construction. Two lanes were assigned to the 20,000 ADT level, three lanes to 30,000, and four lanes to the 45,000 category. When dealing with an appropriate traffic management strategy for the 20,000 and 45,000 groups, one and two lanes were closed, respectively. For the three-lane bridge, traffic handling was more complex. After experimenting with various strategies, capacity on the matching bridge was restricted to two lanes, one lane of traffic

TABLE 5 SUMMARY OF DEFICIENT BRIDGES AND REPLACEMENT COSTS FOR VARIOUS TYPES OF LARGE TRUCKS

State		*Triple 28 Operating Alone*		*Double 48 Operating Alone*		*Triple 28 and Double 48 Operating simultaneously*	
	Unit Cost ($/sqft)	*Deficient Bridges*	*Replacement Cost*	*Deficient Bridges*	*Replacement Cost*	*Deficient Bridges*	*Replacement Cost*
Alabama	44	10	8,145	51	57,119	51	57,119
Alaska	117	20	43,143	28	62,495	31	64,079
Arizona	45	108	41,568	141	48,828	142	49,264
Arkansas	47	9	18,988	25	32,094	25	32,094
California	62	399	893,094	690	1,185,374	696	1,197,619
Colorado	48	91	57,999	163	81,155	169	83,999
Connecticut	170	4	19,665	4	18,858	6	20,495
Dist Columbia	164	0	0	0	0	0	0
Florida	53	31	128,809	53	153,256	53	153,256
Georgia	41	17	31,853	44	69,117	44	69,117
Idaho	54	31	14,567	79	24,109	81	26,781
Illinois	50	33	47,673	112	77,845	119	81,501
Indiana	47	98	61,200	182	82,571	211	95,235
Iowa	43	7	6,156	37	16,327	37	16,327
Kansas	38	279	86,448	439	126,693	444	128,729
Kentucky	61	45	43,420	59	53,120	62	55,394
Louisiana	27	83	59,977	123	81,295	131	84,815
Maine	92	17	20,215	67	64,221	70	66,187
Maryland	80	23	49,073	33	61,619	34	68,311
Massachusetts	160	31	125,890	51	140,167	51	140,167
Michigan	69	8	8,331	9	8,311	10	9,177
Minnesota	52	44	88,772	94	125,283	100	127,976
Mississippi	31	18	37,490	32	47,388	34	47,785
Missouri	38	88	76,010	174	95,733	184	98,691
Montana	45	43	58,606	79	77,008	79	77,008
Nebraska	48	19	13,211	57	22,534	59	23,292
Nevada	57	19	16,229	60	39,302	60	39,302
New Hampshire	90	66	80,051	94	94,854	104	102,385
New Jersey	130	97	235,720	140	418,458	142	423,837
New Mexico	50	4	1,988	52	19,972	53	20,399
New York	114	137	330,621	190	401,854	194	405,483
North Dakota	42	50	18,593	115	34,015	136	42,435
North Carolina	42	48	37,106	56	37,900	63	40,958
Ohio	63	247	236,472	661	496,971	714	537,174
Oklahoma	33	10	4,786	50	18,127	50	18,127
Oregon	57	38	56,277	135	106,447	137	107,671
Pennsylvania	107	177	324,970	255	419,812	261	426,893
Rhode Island	79	0	0	1	428	1	428
South Carolina	33	25	41,326	42	55,511	44	56,016
South Dakota	42	25	10,238	162	41,777	164	42,307
Tennessee	36	20	18,044	90	38,330	96	40,760
Texas	33	63	74,127	399	209,240	399	209,240
Utah	42	28	12,667	63	22,077	72	25,482
Vermont	104	14	21,120	20	39,827	24	43,076
Virginia	65	44	96,619	72	159,195	74	160,384
Washington	85	57	78,998	130	140,702	142	151,408
West Virginia	91	39	84,074	41	86,026	41	86,026
Wisconsin	38	28	30,702	39	35,521	39	35,521
Wyoming	41	79	20,127	357	63,089	365	65,605
Totals		2,871	3,871,156	6,050	5,791,958	6,298	5,955,335

Notes: (1) Source for unit cost data, FHWA 1989
(2) Replacement costs in 1,000 dollars.

from the bridge under reconstruction being switched to run counterflow in the closed inside lane. Although this procedure affected users on both bridges, the user costs proved lower than those resulting from three lanes of traffic on one bridge being channeled into one lane.

The predictions for all three ADT categories presented in Table 6 total approximately $6 billion for the bridges exceeding 20,000 ADT. This figure is conservative, because it relates only to a subset of the rural bridge population and uses a truck ADT of 14 percent—lower than most Interstate values. The model also indicates that many high-ADT structures will generate such high user costs that radical planning under construction will be necessary, or their use prohibited to LCVs. This result may, in turn, affect the routing of LCVs and the productivity estimates developed as part of LCV benefits. Further work is underway to assign lane capacities to all failed bridges and to measure the user cost impacts more accurately. However, what preliminary figures clearly indicate is that system costs attendant on the operation of double 48 and triple 28 trucks, configured under uncapped Formula B constraints, of about $12 billion, are very significant, and both replacement and user costs should be compared with predicted productivity gains when attempting to determine the true economic impact.

CONCLUSIONS

Results indicate that LCVs could have a great impact on the Interstate rural bridge network—greater than those estimates obtained using the methodology developed in recent TRB studies. The key assumptions adopted are considered both

TABLE 6 PREDICTED USER COSTS[1] USING QUEWZ MODEL (*20*)

ADT	No. Lanes[2]	No. Deficient Bridges	Cost per Bridge/Day	Total[3] Cost ($ billions)
>20,000 <30,000	2	524	$4,423	0.695296
>30,000 <45,000	3[4]	297	$7,319	0.652123
>45,000	4	363	$39,847	4.339338
Totals		1184		5.686757

[1] Triple 28 and double 48 trucks both permitted to operate on the system.
[2] One lane closed for 2-lane capacity, two lanes for 4-lane capacity.
[3] Cost assumes a 300-day contract cycle per structure.
[4] Construction first rehabilitates two lanes, then the third. Two lanes always open to traffic. When only one lane is open, the matching bridge is opened to diverted traffic and both bridges are reduced to two lane travel.

realistic in terms of the LCV configurations preferred by truckers, and conservative in terms of the inventory rating for bridge fatigue and safety. Furthermore, agency costs are only part of the system impacts; when user costs are included, productivity gains do not necessarily overwhelm total system costs. Although issues related to safety and fatigue costs have not been included in this cost estimate, both are likely to be positive.

Results of this study were compared with a recent American Trucking Association (ATA) document on pavement and bridge damage (*21*). In that document, the authors performed no basic research on the NBI bridge data base, using instead TRB source material. Moreover, the ATA report concentrated only on simply supported structures and did not evaluate continuous bridges. Consequently, its results implied that LCVs were less damaging to the bridge system. The LCV configurations were limited to the uncapped Formula B, but some double-48 rigs are operating at much higher loads, for example up to 146,000 lb on the Florida tollway. Bridge deficiencies are highly sensitive to changes in loadings, and accordingly the LCV configurations were increased to test the magnitude of this change. Increasing the mass of the double 48 in this study to 134,000 lb resulted in an extra 2,000 Interstate structures (33 percent) being rendered deficient. Total replacement and user costs for these bridges were predicted to exceed $17 billion. This sensitivity has profound implications for LCV configurations and weight enforcement strategies. In terms of general policy towards increases in truck size and weight regulations, triple 28s are the least-damaging LCV type, whereas turnpike doubles are significantly more costly, particularly when user impacts are included. Although the implications for LCV user fees, which reflect the highway infrastructure damage, were not considered, they seem an important issue on which to focus additional research.

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