Allocation of Pavement and Bridge Costs in the 2010 Idaho Highway Cost Allocation Study

In the 2010 Idaho Highway Cost Allocation Study (HCAS), the cost responsibility for each vehicle class was estimated using the Federal Highway Administration (FHWA) State HCAS Model as a framework, updated to reflect Idaho's highway system and the vehicles using the system. This paper outlines the methods used to allocate the costs associated with both pavements and bridges. Further, it reports a breakdown of state construction costs allocated to broad registered gross weight (RGW) classes (i.e., 0-26,000 pounds, 26,001-80,000 pounds, and greater than 80,000 pounds) for both the full Grant Anticipation Revenue Vehicle (GARVEE) and reduced GARVEE bond scenarios of the 2010 Idaho HCAS. This report also presents a detailed discussion of the National Pavement Cost Model (NAPCOM) and a description of the procedures used to allocate each major type of bridge expenditure. These discussions, however, are at such detailed levels that they have been relegated to appendices at the back end of this report.

Pavements

The most important update of the FHWA State HCAS Model in Idaho to date has focused on vehicle characteristics. The HCAS research team used WIM data collected by ITD during 2008-2009. The WIM data contained 871,000 truck and bus observations. The research team subjected each of these observations to our updated evaluation and editing algorithm and found that slightly over 9 percent failed to pass the edit tests, leaving approximately 792,000 observations judged valid. This set of edited WIM data was used to refine weight-related HCAS model inputs. The weight observations provided distributions of vehicle operating weights for 18 truck and bus classes, as well as detailed information on axle weights and simple span bridge moments—three vital components needed for accurate allocation of pavement, bridge, and other highway costs. Like most states, Idaho screens out light vehicles when compiling WIM data. Therefore the research team had to supplement the Idaho truck and bus data with national auto and light van and truck data.

These results make use of a recent FHWA run of the latest available version of NAPCOM using 2007 highway section data reported by ITD to FHWA under the Highway Performance Monitoring System (HPMS). NAPCOM, one of the most important HCAS innovations developed by FHWA, estimates how much pavement deterioration in a given state results from each type and weight of axle for each basic type of pavement, condition of pavement, soil condition, and environmental condition.

FHWA has been using NAPCOM since it was developed and first applied in a major national study, the 1997 Federal HCAS. A primary product of its application was the development of load equivalency factors (LEFs) which have less steeply sloped pavement deterioration curves as functions of axle loadings. These LEFs are widely variable, however, and depend upon many pavement and environmental parameters.

FHWA recently ran NAPCOM on current data, including data for Idaho. Although we have not investigated our model results in these terms, we expect that they would show that the heaviest axle loads have somewhat less cost responsibility and the middle weight axles somewhat more. Our team that performed the 2010 Idaho HCAS has been using NAPCOM in all our state HCASs since it was applied in the 1997 Federal HCAS. For a more detailed discussion of how to calculate both Equivalent Single Axle Loads (ESALs) and LEFs, please review the article at http://www.pavementinteractive.org/index.php?title=ESAL. For a much more detailed discussion of NAPCOM, please review Appendix A.

NAPCOM attributes pavement rehabilitation costs to specific groups of vehicles. For each of a large number of specific highway sections, NAPCOM applies a set of pavement deterioration models to determine the expected pavement condition at the end of each year of analysis. When a pavement section reaches a condition that would trigger a need for major rehabilitation or reconstruction, NAPCOM takes note of the specific distresses and their contribution to the need to rehabilitate, the contribution of specific groups of vehicles to each of these distresses, and the year of failure. It accumulates these factors by pavement type, highway functional class, and state.

After all pavement section data have been analyzed, NAPCOM converts the tabulated arrays of failure data into vehicle cost responsibilities and relative responsibilities per mile for each vehicle configuration. It produces output files not only in the form needed for the cost allocation analysis spreadsheet, but also for such analyses as effective load equivalence factors.

NAPCOM does not use standard ESALs in its distress models. Instead, the relative effect of each axle weight varies widely depending upon type of distress, pavement thickness, and various environmental and design variables. As mentioned above, the resulting allocation factors, at least for the national sample of pavements used in the cost allocation applications of NAPCOM, charge heavy axle loads somewhat less than if ESALs had been used.

The approach outlined in this section resulted in the allocation of $2.1 million (23.6 percent) of new pavement and $2.1 million (18.7 percent) of pavement rehabilitation costs to vehicles weighing less than 26,000 pounds in the reduced GARVEE bond scenario (Tables 1.1 and 1.2). Note that the amounts presented in Tables 1.1 and 1.2 represent state construction expenditures only and exclude federal construction expenditures. Vehicles with RGWs of between 26,001 and 80,000 pounds were allocated the highest cost responsibility at $4.4 million (49.1 percent) of new pavement and $6.1 million (54 percent) of pavement rehabilitation costs under the reduced GARVEE bond scenario. Vehicles with RGWs of more than 80,000 pounds were allocated $2.4 million (27.3 percent) of the costs associated with new pavements and $3.1 million (27.3 percent) of pavement rehabilitation costs under the revised GARVEE bond scenario. Under the full GARVEE bond scenario, the pavement costs that were allocated grew while the percentage shares of allocated costs were largely unchanged.

Bridges

The bridge cost allocation procedures used in this study are based on research and methods developed by FHWA for the 1982 and 1997 Federal HCASs. Three types of bridge expenditures were considered: new bridges, bridge replacement, and bridge rehabilitation.

New bridge costs are allocated based on an incremental analysis of the costs of constructing bridges using different design loadings. These loadings are based on hypothetical vehicles for which stresses in the load-bearing members of bridges are calculated and compared with permissible stress levels. As loadings become heavier, the size of bridge members (and, consequently, bridge costs) must be increased to remain within permissible stress levels. All vehicles share the cost of the first increment (i.e., that associated with the lightest design loadings). Only heavier vehicles share the cost of subsequent increments. The determination of which vehicles share the costs of which increments depends upon a comparison of the stresses produced by the vehicles with those produced by the design loadings used in the incremental analysis.

Bridge replacement costs are allocated based on estimates of the percentage of these costs that are incurred because the load-bearing capacity of existing bridges are deficient. Those costs due to deficient load-bearing capacity are allocated to vehicles that operate at weights over the load-bearing capacities of the replaced bridges. The percentage of bridge replacement costs that are incurred as a result of deficient load-bearing capacities was estimated using FHWA's Bridge Sufficiency Rating Formula.[1] Under the Bridge Sufficiency Rating Formula, bridges lose points if their load-bearing capacity is inadequate or if they have other non-load-related problems such as scouring around piers or being too narrow for current traffic levels. For assessing which bridges need to be replaced, points lost due to inadequate load-bearing capacity are expressed as a fraction of total points lost to determine the share of bridge replacement costs to be allocated to vehicles that operate at weights over the load-bearing capacities of the bridges to be replaced.

Bridge rehabilitation costs are allocated based on estimates of the fraction of these costs associated with different types of bridge rehabilitation projects and the extent to which expenditures for each type of project are load-related. The allocation was based on information from FHWA's Bridge Needs and Investment Process and an analysis of a representative sample of bridge repair projects to determine the percentage of costs that are expected to be load-related as opposed to non-load-related. This split, broken down by functional class of street and highway, is then used to determine the split between costs that should be allocated by vehicle mile of travel broken down by weight category and the costs that should be allocated only by vehicle miles of travel for each vehicle class. For a much more detailed discussion of bridge cost allocation, see Appendix B.

In the reduced GARVEE bond scenario, roughly \$5.2 million (45.9 percent) of new bridge costs, \$10.2 million (41.0 percent) of replacement bridge costs, and \$1.0 million (53.4 percent) of bridge repair costs were allocated to vehicles weighing under 26,000 pounds. Vehicles with RGWs of between 26,001 and 80,000 pounds were assigned \$4.3 million (37.8%) of new bridge

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[1] This formula is described in Appendix A of FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges.*

costs, $10.0 million (40.1 percent) of replacement bridge costs, and $0.6 million (33.2 percent) of bridge repair costs in the reduced GARVEE bond scenario. Finally, vehicles weighing more than 80,000 pounds were assigned $1.9 million (16.3 percent) in new bridge costs, $4.7 million (18.9 percent) in replacement bridge costs, and $0.3 million (13.4 percent) in bridge repair costs under the reduced GARVEE bond scenario. As was the case with pavement-related costs, the level of costs allocated grew under the full GARVEE bond scenario but the percentage shares of costs were largely unchanged.

In addition to pavement and bridge costs, Tables 1.1 and 1.2 also present the breakdowns for grading and other construction costs. When all state construction cost categories are accounted for, $43.6 million (43.9 percent) were allocated to vehicles with RGWs of less than 26,000 pounds, $38.2 million (38.5 percent) were allocated to vehicles with RGWs of between 26,001 and 80,000 pounds, and the remaining $17.5 million (17.6 percent) were allocated to vehicles with RGWs in excess of 80,000 pounds in the reduced GARVEE bond scenario. Under the full GARVEE bond scenario, $80.6 million (41.1 percent), $78.8 million (40.1 percent), and $36.9 million (18.8 percent) of all state construction costs were allocated to vehicles weighing with RGWs of 26,000 pounds or less, RGWs of 26,001 to 80,000 pounds, and RGWs of in excess of 80,000 pounds, respectively.

Table 1.1. 2010 Idaho Highway Cost Allocation Study (Reduced GARVEE Bond Scenario - State Construction Expenditures)
(Dollars in Thousands)

	New Pavement		Pavement Rehabilitation		New Bridge		Replacement Bridge		Bridge Repair		Grading		Other Construction		Total Construction	
RGW	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)
0-26,000	$ 2,100	23.6%	$ 2,105	18.7%	$ 5,241	45.9%	$ 10,206	41.0%	$ 1,041	53.4%	$ 14,256	50.8%	$ 8,659	67.4%	$ 43,607	43.9%
26,001-80,000	$ 4,367	49.1%	$ 6,085	54.0%	$ 4,316	37.8%	$ 9,987	40.1%	$ 646	33.2%	$ 9,695	34.5%	$ 3,119	24.3%	$ 38,214	38.5%
>80,000	$ 2,432	27.3%	$ 3,071	27.3%	$ 1,862	16.3%	$ 4,697	18.9%	$ 261	13.4%	$ 4,128	14.7%	$ 1,067	8.3%	$ 17,518	17.6%

Table 1.2. 2010 Idaho Highway Cost Allocation Study (Full GARVEE Bond Scenario - State Construction Expenditures)
(Dollars in Thousands)

	New Pavement		Pavement Rehabilitation		New Bridge		Replacement Bridge		Bridge Repair		Grading		Other Construction		Total Construction	
RGW	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)	($)	(%)
0-26,000	5,811	23.4%	6,232	18.5%	9,078	45.9%	17,677	41.0%	1,802	53.4%	24,865	50.8%	15,103	67.4%	80,568	41.1%
26,001-80,000	12,264	49.3%	18,279	54.2%	7,475	37.8%	17,297	40.1%	1,118	33.2%	16,911	34.5%	5,440	24.3%	78,784	40.1%
>80,000	6,801	27.3%	9,201	27.3%	3,224	16.3%	8,136	18.9%	452	13.4%	7,201	14.7%	1,861	8.3%	36,876	18.8%

Appendix A – Allocation of Pavement Rehabilitation Costs Using NAPCOM

Overview

NAPCOM attributes pavement rehabilitation costs to specific groups of vehicles. This paper summarizes NAPCOM and its supporting data.

For each of a large number of specific highway sections, NAPCOM applies a set of pavement deterioration models to determine the expected pavement condition at the end of each year of analysis. When a pavement section reaches a condition that would trigger a need for major rehabilitation or reconstruction, NAPCOM takes note of the specific distresses and their contribution to the need to rehabilitate, the contribution of specific groups of vehicles to each of these distresses, and the year of failure. It accumulates these factors by pavement type, highway type, and state.

After all pavement section have been analyzed, NAPCOM converts the tabulated arrays of failure data into vehicle cost responsibilities and relative responsibilities per mile. It produces output files not only in the form needed for the cost allocation analysis spreadsheet, but also for such analyses as effective load equivalence factors.

NAPCOM does not use standard ESALs in its distress models. Instead, the relative effect of each axle weight varies widely depending upon distress, pavement thickness, and various environmental and design variables. The resulting allocation factors, at least for the national sample of pavements used in the cost allocation study, charge heavy axle loads somewhat less than if ESALs had been used.

The following sections describe in somewhat more detail various aspects of NAPCOM's application for highway cost allocation.

Highway Section Data Used in NAPCOM

NAPCOM uses information about specific, representative highway sections supplied by the states to FHWA's HPMS. The full national HPMS sample consists of over 100,000 pavement sections. Some states collect data on more sections than are included in the national sample in order to meet state needs. States can apply NAPCOM to their augmented section data since NAPCOM works at either a national level or a subset of the national level.

This highway section data provides information about number of lanes, type of pavement, pavement thickness, current pavement condition, average daily traffic, percentage of trucks in the traffic stream, predicted 20-year traffic levels, climatic zone, and some rudimentary information about pavement base.

Since the deterioration models used in NAPCOM (described below) require more information than the HPMS section file contains, we need to supplement the HPMS section data with such data items as freeze-thaw cycles, freezing index, Thornthwaite moisture index, modulus of subgrade reaction, average annual rainfall, and thickness of base.

In some cases, we need to use information tied to climatic zones. Examples of data that vary by climatic zone include: average maximum temperature, aggregate reactivity, and concentration of summer thermal efficiency.

We considerably enhanced the section traffic data, as described below, adjusting truck and overall traffic levels by factors necessary to ensure that the total traffic on all analyzed sections corresponded to the HCAS travel estimates described in the body of this report.

Vehicle Fleet Data Used in NAPCOM

NAPCOM uses the following fleet data: (a) estimates of annual vehicle miles travelled (VMT) by vehicle class, highway functional class, and state, (b) operating weight distributions for each vehicle class on groups of highway types in groups of states, and (c) axle weights for the midpoint of each weight group for each vehicle class.

As mentioned above, we calculated the annual VMT for all vehicles, for single unit trucks, and for combination trucks implied by expanding the average daily traffic in the HPMS data file for all sections on a given functional class in a given state. We compared this implied VMT with the actual estimated VMT for the same grouping of vehicle classes, and derived a calibration factor for each state, functional class, and year of analysis. We needed this step to ensure that allocated costs corresponded exactly to estimated travel levels used throughout the cost allocation study.

Further, because we derived national attributed shares by aggregating state shares for each highway functional class, we needed to account for the missing five states. We did this by accumulating VMT by vehicle class on each type of highway, then multiplying vehicle shares for each vehicle class and weight group by a ratio of total estimated VMT to total VMT accumulated on the analyzed sections.

We derived estimated allocated shares for the three functional classes not included in HPMS (Rural Minor Collector, Rural Local, and Urban Local) by a similar procedure: multiplying shares for the closest corresponding functional class by a ratio of total VMT estimates by vehicle class and weight group.

Since we did not use ESALs, we applied the deterioration model for each distress on each pavement section to each axle in each weight group of each vehicle class. We calculated the proportional deterioration caused that year by all the travel by this axle, then accumulated the total deterioration by all axles of a distress type.

Pavement Deterioration and Rehabilitation Triggering Logic

The HPMS section data contains each pavement section's pavement serviceability rating (PSR) and/or its international roughness index (IRI). We used this information to calculate a pavement's age by applying our model for PSR to the pavement section. We then estimated the current levels for each other pavement distress based on the accumulated years and traffic loadings.

We calculated the current overall pavement condition score (OPCS) based on weighting the distress levels by corresponding "deduction point" maxima, and subtracting from 100. We added one year's worth of traffic at a time and repeated our calculation of PSR and OPCS. When a pavement deteriorated to a PSR level of 2.5 or less or an OPCS of 10 or less, we deemed the pavement ready for major rehabilitation and stopped analyzing it.

At this point, NAPCOM tabulates the specific distresses and their contribution to the need to rehabilitate and the contribution of specific groups of vehicles to each of these distresses. It accumulates the expanded lane miles and vehicle shares by pavement type, highway type, and state.

We used the following deduction point maxima:

Flexible Pavements:

PSR Loss	50
Cracking	25
Rutting	30
Skid Resistance Loss	20

Rigid Pavements:

PSR Loss	50
Faulting	30
Skid Resistance Loss	20
Cracking	30
Spalling	10
Swelling and Depression	20

In each case, we converted the physical distress measurement to an index that varied from zero (for a newly-installed, distress-free pavement) to a value of one at the critical distress level. We then multiplied this normalized deterioration value to the maximum deduction points for that particular distress.

When a pavement deteriorated to the point of needing major rehabilitation, we first divided each distress into load-related and non-load-related portions (as described below), then distributed the load related share to each vehicle group based on its accumulated equivalent loadings. We weighted each distress share by its contribution to the loss in the OPCS at the time of failure.

Pavement Deterioration Models in NAPCOM

NAPCOM includes some models newly derived from mechanistic-empirical analysis, as well as some developed earlier as part of the 1982 Highway Cost Allocation Study. NAPCOM includes the flexible pavement distresses (1) traffic-related PSR loss, (2) expansive-clay-related PSR loss, (3) fatigue cracking, (4) thermal cracking, (5) rutting, and (6) loss of skid resistance. Distresses for rigid pavements consist of (1) traffic-related PSR loss, (2) faulting, (3) loss of skid resistance, (4) fatigue cracking, (5) spalling, and (6) soil-induced swelling and depression.

The newly-developed and most of the older models use environmental descriptors directly in their model form and equations. Only the older model for flexible pavement traffic-related PSR loss has separate equations for each of four climatic zones.

Flexible Pavement Traffic-Related PSR Loss

NAPCOM's flexible pavement PSR loss model uses the general form:

Damage = (LEFS / RHZ) ^ (BEZ / (LEFS / RHZ)

where: LEFS = summation of accumulated load equivalents, RHZ / RH(ax)
RHZ = number of applications to failure of standard axle
RH(ax) = applications to failure of axle load "ax"
BEZ = coefficient of exponent (beta)
^ = an operator that raises the first quantity to the power of the second

Each of the factors RHZ, RH(ax), and BEZ derive from various environmental and design factors, as described below. RHZ follows from the equation for RH(ax), using a single axle of 18 kips (18,000 pounds). The equations for RH(ax) and BEZ vary by climatic zone: (1) wet freeze, (2) dry freeze, (3) wet no-freeze, (4) dry no-freeze.

RH(ax) and BEZ derive from the following equations:

RH(ax), zone 1 = 0.000780 * (Lx + L2) ^ (-5.2007 -0.179700 * thk) *
L2 ^ 4.5084 * subm ^ 2.7631 * strn ^ 3.6271 * thk ^ 7.1145

zone 2 = 0.005665 * (Lx + L2) ^ (-4.5847 -0.239900 * thk) *
L2 ^ 4.3140 * subm ^ 2.3364 * strn ^ 3.8468 * thk ^ 8.1663

zone 3 = 0.000536 * (Lx + L2) ^ (-6.4275 -0.004884 * thk) *
L2 ^ 4.7937 * subm ^ 3.8685 * strn ^ 5.1466 * thk ^ 0.4485

zone 4 = 0.148400 * (Lx + L2) ^ (-6.4900 +0.015640 * thk)
* L2 ^ 4.9571 * subm ^ 3.5203 * strn ^ 5.9548 * thk ^ (-0.96679)

BEZ, zone 1 = 0.0865 + 0.06180 * 19.0 ^ (0.497 - 0.159 * thk +.0135 * thk2) *
subm ^ 0.295 * strn ^ (-2.805) * thk ^ 0.541

zone 2 = 0.0820 + 0.15500 * 19.0 ^ (0.700 - 0.223 * thk + 0.0184 * thk2) *
subm ^ 0.107 * strn ^ (-2.072) * thk ^ 0.631

zone 3 = 0.0703 + 0.00963 * 19.0 ^ (0.645 - 0.219 * thk + 0.0160 * thk2) *
subm ^ 0.333 * strn ^ (-2.872) * thk ^ 1.646

zone 4 = 0.0760 + 0.01830 * 19.0 ^ (0.739 - 0.197 * thk + 0.0139 * thk2) *
subm ^ 0.229 * strn ^ (-2.909) * thk ^ 1.685

where: Lx = axle load in thousands of pounds (kips)
L2 = indicator of axle type (1 for single axle, 2 for tandem)
thk = thickness of asphalt surface layer (inches)
thk2 = thk * thk
subm = subgrade modulus (psi)
strn = structural number of pavement and base (as in ***AASHTO Pavement Design Guide***)

In the application of these models, we assumed that PSR moved from 4.5 for new pavements to 2.5 for ready-for-rehabilitation pavements. The damage equations represent proportional PSR loss, so that a damage value of zero represents a PSR value of 4.5 and a damage value of 1.0 represents a PSR value of 2.5. Further, tridem axles were given no special treatment and were assumed to have an RH(ax) value equal to 1.5 times a tandem having the same weight per tire.

NAPCOM treats this portion of PSR loss as entirely traffic related. Also, the form of the equations shows that design and soil parameters influence the rate of deterioration, but only through their interaction with traffic loads.

Expansive-Clay-Related PSR Loss

NAPCOM's expansive-clay PSR loss model has the following equation:

$$\begin{aligned}\text{Damage} &= 0.087 * \text{exsp}^{0.13} * \text{clay}^{3.05} / (\text{dpth}^{0.20} * \text{cexc}^{1.22} \\ &\quad * \text{acpi}^{1.31} * \text{rnge}^{1.32}) * \text{age}^{0.53}\end{aligned}$$

where:
exsp = exchange sodium capacity
clay = percent clay (grain size less than 0.002 mm) in subgrade
dpth = effective depth of asphalt layer (equivalent to 2.3 times its thickness)
cexc = cation exchange capacity of subgrade
acpi = activity (plasticity index / percent clay)
rnge = range of values of Thornthwaite moisture index for a 20-year period
age = number of years since pavement construction or reconstruction

Because expansive clays occur in specific geographic bands, we assigned a probability of occurrence to each state, then randomly assumed expansive clay conditions for highway sections in each state according to that probability. We combined the traffic-related and the expansive-clay PSR losses and prorated the responsibility for the loss in pavement rating between the two component contributors to PSR loss.

NAPCOM treats this portion of PSR loss as entirely non-load-related.

Fatigue Cracking

NAPCOM's fatigue cracking model starts by calculating the number of repetitions to failure (20 percent fatigue cracking) of each axle load. Rather than using a standard axle reference as a basis for load equivalence, we simply used the reciprocal of the number of cycles to failure as the load equivalence factor. A sum of the LEFS directly states the progression toward failure, from zero to one.

NAPCOM used the Asphalt Institute's equation for predicting the number of stress cycles to failure:

N(ax) = 18.4 * 10 ^ M * 0.004325 * ep(ax) ^ (-3.291) * easc ^ (-0.854)

where:
N(ax) = number of applications to failure for an axle load of a given weight and type
M = 4.84 * (Vb / (Vb + Vv) - 0.6875)
Vb = percent volume of asphalt in mix
Vv = percent volume of air voids in mix
ep(ax) = tensile strain at bottom of asphalt layer (see below)
easc = asphalt modulus of elasticity (psi)

NAPCOM calculates the tensile strain at the bottom of the asphalt layer by calculating the strains for 3, 12, and 30-kip single axle weights and for 6, 24, and 60-kip tandem axle weights, then interpolating between the applicable values. Tridems are treated as 1.5 tandems, effectively, as for PSR loss. To calculate the strains at the representative axle loads, NAPCOM used the following equations:

ES3 = 0.00029 - 1.032e-10 * easc - 0.00004681 * thk - 7.87e-10 * ebse + 8.39e-11 * ebse * thk + 1.03e-11 * thk * easc + 0.000002057 * thk2

ES12 = 0.000753 - 2.87e-07 * easc - 0.00008643 * thk - 4.415e-6 * ebse - 3.405e-6 * tbse - 1.350e-6 * esub + 1.485e-8 * easc * thk + 1.535e-9 * easc * ebse + 2.6e-7 * thk * ebse + 3.140e-6 * thk * thk + 7.7728e-9 * ebse * ebse

ES30 = 0.001126 - 3.263e-7 * easc - 0.00007256 * thk - 6.6103e-6 * ebse - 2.441e-5 * tbse - 8.461e-6 * esub + 2.9e-9 * easc * ebse + 4.866e-7 * thk * ebse +1.6221e-6 * thk * tbse + 6.444e-7 * esub * tbse

ET6 = 0.000267 - 7.15e-8 * easc - 0.00004146 * thk - 1.065e-6 * ebse - 7.48e-7 * tbse - 2.114e-6 * thk * thk + 4.8317e-10 * ebse * easc + 8.392e-8 * thk * ebse

ET24 = 0.00066 - 1.95e-7 * easc - 8.80995e-5 * thk - 3.375e-6 * ebse -2.935e-6 * tbse - 3.376e-6 * thk * thk + 1.4894e-9 * ebse * easc + 2.610e-7 * thck * ebse

$$\mathrm{ET60} = 0.001084 - 3.19\mathrm{e}{-7} * \mathrm{easc} - 1.01\mathrm{e}{-4} * \mathrm{thk} - 6.443\mathrm{e}{-6} * \mathrm{ebse} - 1.6634\mathrm{e}{-5} * \mathrm{tbse} + 2.2229\mathrm{e}{-6} * \mathrm{thk} * \mathrm{thk} + 2.758\mathrm{e}{-9} * \mathrm{ebse} * \mathrm{easc} + 4.880\mathrm{e}{-7} * \mathrm{thk} * \mathrm{ebse} + 1.599\mathrm{e}{-6} * \mathrm{tbse} * \mathrm{thk}$$

where: ES3 = strain at bottom of asphalt layer for 3-kip single axle
ES12 = " for 12-kip "
ES30 = " for 30-kip "
ET6 = " for 6-kip tandem axle
ET24 = " for 24-kip "
ET60 = " for 60-kip "
easc = asphalt modulus of elasticity (psi)
thk = thickness of asphalt surface layer (inches)
ebse = elastic modulus of base layer (psi)
tbse = thickness of base layer (inches)
esub = elastic modulus of subgrade (psi)

NAPCOM uses the following equations to interpolate between the characteristic axle loads:

$$\mathrm{EP(ax)} = (\mathrm{Lx}/3.) * \mathrm{ES3} \qquad [\mathrm{L2} = 1, \mathrm{Lx} < 3.0]$$

$$\mathrm{EP(ax)} = \mathrm{ES3} + ((\mathrm{ES12} - \mathrm{ES3}) / 1.732) * (\mathrm{Lx} \wedge 0.5 - 1.7321) \qquad [\mathrm{L2} = 1, 3.0 < \mathrm{Lx} < 12.0]$$

$$\mathrm{EP(ax)} = \mathrm{ES12} + ((\mathrm{ES30} - \mathrm{ES12}) / 2.0131) * (\mathrm{Lx} \wedge 0.5 - 3.4641) \qquad [\mathrm{L2} = 1, 12.0 < \mathrm{Lx} < 30.0]$$

$$\mathrm{EP(ax)} = (\mathrm{Lx}/30.) * \mathrm{ES30} \qquad [\mathrm{L2} = 1, \mathrm{Lx} > 30.0]$$

$$\mathrm{EP(ax)} = (\mathrm{Lx}/6.) * \mathrm{ET6} \qquad [\mathrm{L2} = 2, \mathrm{Lx} < 6.0]$$

$$\mathrm{EP(ax)} = \mathrm{ET6} + ((\mathrm{ET24} - \mathrm{ET6}) / 2.4495) * (\mathrm{Lx} \wedge 0.5 - 2.4496) \qquad [\mathrm{L2} = 2, 6.0 < \mathrm{Lx} < 24.0]$$

$$\mathrm{EP(ax)} = \mathrm{ET60} + ((\mathrm{ET60} - \mathrm{ET24}) / 2.84698) * (\mathrm{Lx} \wedge 0.5 - 4.8990) \qquad [\mathrm{L2} = 2, 24.0 < \mathrm{Lx} < 60.0]$$

$$\mathrm{EP(ax)} = (\mathrm{Lx}/60.) * \mathrm{ET60} \qquad [\mathrm{L2} = 2, \mathrm{Lx} > 60.0]$$

where: EP(ax) = strain at bottom of asphalt layer for a given axle load and type
Lx = axle load (kips)
L2 = axle type (1 = single, 2 = tandem)

NAPCOM treats all fatigue cracking as load related.

Thermal Cracking

NAPCOM uses the following equation to predict thermal cracking:

STHR = -2.66 + 3.06 * (0.25 * peni + 0.5) ^ 0.257 * (rbsp / 125.6) ^
0.122 * 0.519 * vcoa ^ 24.5 * (aasr / 240.) ^ 1.97 / (thk / 8.) ^
0.410 * ((tpmm + 20.) / 55.7) ^ 7.43 * (age / 10.) ^ 1.16

where: sthr = percentage of thermal cracking
peni = penetration index of asphalt
rbsp = ring and ball softening point (def F)
vcoa = volumetric concentration of the aggregate
aasr = average annual solar radiation (Langleys per day)
thk = thickness of asphalt layer (inches)
tpmm = minimum monthly temperature
age = number of years since construction or reconstruction

NAPCOM treats thermal cracking as entirely non-load related.

Rutting

NAPCOM's rutting model first calculates the number of repetitions to failure (1.5 inch rut depth) of each axle load. As with fatigue cracking, rather than using a standard axle reference as a basis for load equivalence, we simply used the reciprocal of the number of cycles to failure as the load equivalence factor. A sum of the LEFS directly states the progression toward failure, from zero to one.

Unlike for fatigue cracking, however, we had to use an iterative procedure to solve for the number of passages to a given rut depth, based on the following equation:

rutd = 0.286 * age ^ 0.13 * (thk * (n * CSac(ax) ^ (1/(1-a1))) ^ (1-a1) +
tbse * (n * CSbase(ax) ^ (1/(1-a2))) ^ (1-a2) + 12.0 * (n * CSsubg(ax)
^ (1/(1-a3))) ^ (1-a3))

where: rutd = rut depth (inches) for a given number of load applications of a given axle
age = number of years since pavement construction or reconstruction
thk = thickness of asphalt layer
n = number of applications of axle load of interest
tbse = thickness of base layer (inches)
a1 = 0.6
a2 = 0.7
a3 = 0.7

CSac = compressive strain at top of asphalt layer
= abs[(Lx / (18 * L2)) * (-0.000182 + 4.56e-7 * easc –
2.217e-5 * thk + 4.26e-8 * ebse - 4.64 e-7 * tbse - 2.123e-6 *
esub - 2.56e-10 * easc * easc + 1.778e-6 * thk * thk +
6.009522e-8 * esub * esub)]

CSbase = compressive strain at top of base layer
= (Lx/18) * exp(-4.6588 - 0.00186 * easc - 0.38 * thk - 0.0157 *
ebse - 0.124 * tbse - 0.0123 * esub + 0.00217 * Tmb * Tmb
+ 1.02e-5 * easc * ebse + 0.0172 * easc / ebse + 3.10e-5 * easc *
tbse + 0.680e-4 * thk * ebse + 0.006924 * Tmb * Tmb * thk) [L2 = 1]

= (Lx/36.) * exp(-4.6386 - 0.001853 * easc - 0.396 * thk -
0.015684 * ebse - 0.12622 * tbse - 0.01492 * esub + 0.002198
* Tmb * Tmb + 1.0241e-5 * easc * ebse + 0.017392 * easc /
ebse + 3.288e-5 * easc * tbse + 0.683e-4 * thk * ebse +
0.008305 * Tmb * Tmb * thk) [L2 = 2]

CSsubg = compressive strain at top of subgrade
= (Lx/18.) * exp(-3.98533 - 8.7e-4 * easc - 0.331 * thk -
0.0078 * ebse - 0.13671 * tbse - 0.0958 * esub + 2.87e-5 *
easc * tbse + 3.81e-4 * ebse * thk + 6.76e-3 * thk * tbse +
1.58e-4 * ebse * esub + 0.006149 * thk * thk + 0.001814
*esub * esub) [L2 = 1]

= (Lx/36.) * exp(-3.83746 - 8.3e-4 * easc - 0.37066 * thk -
0.00789 * ebse - 0.14805 * tbse - 0.10899 * esub + 3.97e-5 *
easc * ebse + 4.78e-4 * ebse * thk + 8.956e-3 * thk * tbse +
1.46e-4 * ebse * esub + 0.008688 * thk * thk + 0.002188 *
esub * esub) [L2 = 2]

Lx = axle load (in kips)
L2 = axle type (1 for single, 2 for tandem)
exp = exponential operator
easc = elastic modulus of asphalt layer
ebse = elastic modulus of base
esub = elastic modulus of subgrade
Tmb = thk + 0.5 * tbase

Because of the form of the equation for rut depth, unlike for other distresses, NAPCOM cannot calculate rut depth for a combination of axle loads by simply summing the LEFs. Instead, it sums the product of number of applications of each axle load times the individual compressive strains for each layer raised to the corresponding exponents in the equations above, then calculates rut depth from the following equation:

rdpth = 0.286 * age ^ 0.13 * (thk * sum1 ^ (1-a1) + tbse * sum2 ^
(1-a2) + 12. * sum3 ^ (1-a3)) ^ 0.765

where: rdpth = rut depth for mixed traffic
sum1 = summation of (n * CSac(ax) ^ (1/(1-a1))) across all axles
sum2 = summation of (n * CSbase(ax) ^ (1/(1-a2))) across all axles
sum3 = summation of (n * CSsubg(ax) ^ (1/(1-a3))) across all axles

NAPCOM treats rutting as entirely load related.

Loss of Skid Resistance

NAPCOM's loss-of-skid-resistance model predicts loss of skid resistance based on the total weight of all axles passing over the pavement's most heavily-travelled lane. Thus the equivalence factor for each axle is proportional to its load.

skid = -1.781 - 1.199 * plsh + (0.290 + 0.152 * plsh) * log10(0.11 * sum)

where: skid = skid resistance damage (zero at new pavement to 1.0 at full loss of skid resistance)
plsh = dummy variable (1 = polish-susceptible aggregate, 0 = not)
sum = total weight of all axles

NAPCOM treats skid resistance loss as entirely load related.

Rigid Pavement PSR Loss

NAPCOM's rigid pavement PSR loss model uses the general form:

Damage = LEFS / RHZ

where: LEFS = summation of accumulated load equivalents, RH(ax)
RHZ = number of applications to failure of standard axle
RH(ax) = applications to failure of axle load "ax"
BEZ = coefficient of exponent (beta)
RHZ, BEZ, and RH(ax) derive from the following equations:

RHZ = 1.e6 * exp(1.333 * styp - 0.009024 * frzi + btyp * (1.156 * slbt - 6.966) + jlts * (0.6556 * slbt + 1.763) + 0.803) [JPCP]

= 1.e6 * exp(0.4593 * slbt - 0.01167 * thmi + 0.6758 * btyp - 1.709) [JRCP]

BEZ = max(0.0006076 * frzi + btyp * (-0.01435 * slbt - 0.0683) + jlts * (-0.09997 * slbt + 0.7107),0) + 0.544 [JPCP]

= 7.656 / jtsp + 0.04152 * tobl + 0.43516 [JRCP]

RH(ax) = esal(Lx,L2) ^ BEZ

where: exp = the exponential operator
styp = type of subbase soil (0 = granular, 1 = coarse)
frzi = freezing index (32 deg F-- CE method)
btyp = type of base (0 = nonstabilized, 1 = stabilized)
slbt = slab thickness (inches)
jlts = joint load transfer system (0 = undowelled, 1 = dowelled)
thmi = Thornthwaite moisture index
max = a function that selects the listed expression with the highest value
jtsp = average joint spacing (feet)

tobl = thickness of base layer (inches)
esal(ax) = standard AASHTO ESALs for specified axle load and type

NAPCOM treats all rigid pavement PSR loss as load related.

Faulting

As with flexible pavement fatigue cracking, NAPCOM's rigid pavement faulting model starts by calculating the number of repetitions to failure (defined as 0.1 inches) of each axle load. As before, we used the reciprocal of the number of cycles to failure as the load equivalence factor. A sum of the LEFS directly states the progression toward failure, from zero to one.

NAPCOM used the following equation for predicting the number of stress cycles to failure:

N(ax) = 10 ^ (6.27 - 1.6 * log10(DE - 0.002) [DE > 0.002]
= 10 ^ 25.47 [DE = < 0.002]

where: N(ax) = number of applications to failure for an axle load of a given weight and type
DE = differential energy of subgrade deformation
= 0.5 * ksub * (wl + wul) * (wl - wul)
ksub = modulus of subgrade reaction
wl = loaded corner deflection
= wl0 + (wl36 - wl0) / 3.
wul = unloaded corner deflection
= wul0 + (wul36 - wul0) / 3.
wl0 = wul0 / LTE0
wl36 = wul36 / LTE36
wul0 = wfe0 * LTE0 / (1 + LTE0)
wul36 = wfe36 * LTE36 / (1 + LTE36)
lte0 = 0.01 / (0.01 + 0.012 * aggkl ^ (-0.849))
lte36 = 0.01 / (0.01 + 0.003483 * aggkl ^ (-1.13677))
aggkl = 2. * exp(1 + 0.2 * dodb ^ 2 - 0.17 * jtsp / l)
dodb = diameter of dowel bars (inches)
jtsp = average joint spacing (feet)
l = (Ecnc * 1000. * (thk ^ 3) / (12 * (1-mu) * ksub)) ^ 0.25
Ecnc = concrete modulus of elasticity
thk = thickness of slab
mu = Poisson's ratio
wfe0 = (0.0000864 * lsq + 0.002824 * l + 0.29530) * 1000. * Lx / (ksub * lsq) [single axle]

= (1.0023 - 0.0337002 * axsp + 0.000308639 * axsp * axsp - 0.043436 * l + 0.00178717 * axsp * l - 0.0000168611 * axsp * axsp * l + 0.000796801 * lsq - 0.0000265334 * axsp * lsq + 2.41667e-07 * axsp * axsp * lsq) * 1000. * Lx/ (ksub * lsq) [tandem axle]

= (0.43246 - 0.0138288 * axsp + 0.000135903 * axsp * axsp - 0.01548 * l + 0.000634833 * axsp * l - 0.0000063333 * axsp *

axsp * l + 0.000649091 * lsq - 0.0000196378 * axsp * lsq +
1.70800e-07 * axsp * axsp * lsq) * 1000. * Lx/ (ksub * lsq)
[tridem axle]

wfe36 = (0.0000648 * lsq + 0.003934 * l - 0.02548) * 1000. * Lx /
(ksub * lsq) [single axle]

= (-0.142828 + 0.00360675 * axsp - 0.0000174028 * axsp *
axsp + 0.00909779 * l - 0.000251908 * axsp * l +
0.000001473 * axsp * axsp * l - 0.0001004 * lsq +
0.000006225 * axsp * lsq - 5.13889e-08 * axsp * axsp * lsq) *
1000. * Lx/ (ksub * lsq) [tandem axle]

= (-0.572713 + 0.0215153 * axsp -0.000187292 * axsp *axsp
+ 0.0313199 * l - 0.00122083 * axsp * l + 0.0000109722 *
axsp * axsp * l - 0.000423601 * lsq + 0.0000190917 * axsp *
lsq - 1.79167e-07 * axsp * axsp * lsq) * 1000. * Lx/ (ksub *
lsq) [tridem axle]

lsq = l * l
axsp = axle spacing for tridems and tandems (inches)
Lx = axle load (kips)

NAPCOM treats all faulting damage as load-related.

Loss of Skid Resistance

NAPCOM's rigid loss-of-skid-resistance model predicts loss of skid resistance based on the total weight of all axles passing over the pavement's most heavily-travelled lane. Thus the equivalence factor for each axle is proportional to its load.

skid = sum / 1.11e9

where: skid = skid resistance damage (zero at new pavement to 1.0 at full loss of skid resistance)
sum = total weight of all axles in lane (kips)

NAPCOM treats skid resistance loss on rigid pavements as entirely load related.

Fatigue Cracking

NAPCOM's rigid pavement fatigue cracking model uses the general form:

Damage = LEFS / RHZ

where: LEFS = summation of accumulated load equivalents, RH(ax)
RHZ = number of applications to failure of standard axle
RH(ax) = applications to failure of axle load "ax"
BEZ = coefficient of exponent (beta)

RHZ, BEZ, and RH(ax) derive from the following equations:

RHZ = 1.e6 * exp(jlts * (4.872 + 0.0435 * (slbt - 7) ^ 3) + btyp * (0.0535 * slbt * slbt - 0.2745 * slbt) + 1.698 * styp - 0.105 * tdif + 2.386) [JPCP]

= 1.e6 * exp(79.51 / aarf - 0.5949 * slbt + 0.7 * drnt -0.0011546 * frzi + 0.550745 * btyp + 2.805 + 0.053188 * slbt * slbt) [JRCP]

BEZ = 1.510 + 0.16 * btyp [JPCP]

= -0.003513 * thmi + 1.324 [JRCP]

RH(ax) = esal(Lx,L2) ^ BEZ

where: exp = the exponential operator
jlts = joint load transfer system (0 = undowelled, 1 = dowelled)
slbt = slab thickness (inches)
btyp = type of base (0 = nonstabilized, 1 = stabilized)
styp = type of subbase soil (0 = granular, 1 = coarse)
tdif = difference between average maximum and monthly temperatures
aarf = average annual rainfall (cm)
drnt = drainage type (0 = no underdrains, 1 = yes)
frzi = freezing index (32 deg F-- CE method)
thmi = Thornthwaite moisture index
esal(ax) = standard AASHTO ESALs for specified axle load and type

NAPCOM treats all rigid pavement fatigue cracking as load related.

Spalling

NAPCOM's spalling model for jointed plain concrete pavement (JPCP) has the form:

spall = (0.00257 * age ^ 0.6 * (ftcy * thk) ^ 1.2) / 40

where: spall = spalling damage (zero at new pavement to 1.0 at existence of 40 percent spalling)
age = number of years since slab placement
ftcy = average number of annual freeze-thaw cycles
thk = slab thickness (inches)

NAPCOM treats all JPCP spalling as non-load related. On the other hand, NAPCOM's model for JRCP spalling has a load-related component and a non-load-related component, each of which it adds to a constant term to predict total spalling. NAPCOM prorates spalling damage between the load-related and the non-load-related components in assessing cost responsibility, and uses ESALs to distribute the load-related portion, following the model form.

spall = (79.66426 + nlsp - lrsp) / 40

where: spall = spalling damage (zero at new pavement to 1.0 at existence of 40 percent spalling)
nlsp = non-load-related spalling
= jtsp * (1.565966 * pref - 0.004343 * ftcy) + aari * (0.035802 * age - 1.311778) - thkb * (10.422486 * pref + 0.029727 * thkb) - 0.00119 * ksub * frzi
lrsp = 2.439e-9 * lefs * frzi
jtsp = average joint spacing (feet)
pref = presence of preformed joint sealant = 1, other types = 0
ftcy = average number of annual freeze-thaw cycles
aari = average annual rainfall (inches)
age = number of years since slab placement
thkb = thickness of base layer (inches)
ksub = modulus of subgrade reaction
frzi = freezing index (32 deg F-- CE method)
lefs = summation of standard ESALs for all traffic

<u>Soil-Induced Swelling and Depression</u>

NAPCOM uses the following equations to predict damage from swells and depressions:

sdas = age * (0.000159 * thmi - 0.00004515 * cbrs - 0.0155 * btyp + 0.027746) [JPCP]

= age * (0.000350 * aarf - 0.007427 * btyp - 0.01785) [JRCP]

where: sdas = swell/depression damage (zero at new pavement to 1.0 at maximum swelling)
age = number of years since slab placement
thmi = Thornthwaite moisture index
cbrs = California bearing ratio of foundation soil
btyp = base type (0 = nonstabilized, 1 = stabilized)
aarf = average annual rainfall (cm)

NAPCOM treats swelling and depression as entirely non-load related.

Appendix B – Allocation of Bridge Costs

Overview

The cost allocation spreadsheet handles four bridge cost categories: new bridges, bridge replacement, bridge repair, and special bridge costs. Special bridge costs are a “wildcard” category that can be used by the analyst to represent unique bridge costs such as retrofitting existing bridges for earthquakes. The special bridge category was not used in the 2010 Idaho HCAS. Expenditures for each highway cost allocation category, including the four bridge categories, should be entered in the 1A Expenditures sheet of CostAlloc.xls. The spreadsheet contains representative values which the user will have to replace with current or projected estimates for the state.

The following additional inputs are required for bridge cost allocation, all of which have default values provided in the model:

- Assignment of vehicles to bridge increments based on their live-load moments
- An allocation of the cost of various types of new bridges to bridge increments
- Information on the types of material and span lengths for new and replacement bridges
- Inventory ratings of bridges that are to be replaced
- An estimate of the percentage of bridge replacement costs due to structural deficiencies in existing bridges
- An estimate of the percentage of bridge repair costs that are load-related
- An estimate of the percentage of special bridge costs that are load-related.

The spreadsheet provides default values based on the 1997 Federal HCAS for the rest of the required information. Default values for the assignment of vehicles to bridge increments based on their live-load moments are found on sheet 4G MomentDist. Other default values are found on sheet 4B BridgeData. The following sections provide guidelines for modifying these default values.

Assignment of Vehicles to Bridge Increments

Vehicles are assigned to bridge increments based on a comparison of their live-load moments[2] and the live-load moments used in bridge design. The H15 loading is a 30,000 pound two axle truck with 6,000 pounds on the first axle, 24,000 on the second axle, and a distance of 14 feet between the two axles. The HS20 loading is a 72,000 pound three axle truck with 8,000

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[2] Live-load moment is the principal determinant of the amount of stress induced by a vehicle in load-bearing members of a bridge. As live-load moments increase, thicker (and, hence, more costly) load-bearing members are required to keep stresses within acceptable limits.

pounds on the first axle, 32,000 pounds on the second axle, and 32,000 pounds on the third axle, with both axle spacings being 14 feet. For other H and HS loadings, weights are proportional to the index (e.g., the H10 is a 20,000 pound two axle truck with 4,000 pounds on the first axle, 16,000 pounds on the second axle, and a distance of 14 feet between the two axles.

Live-load moments for a vehicle or a design loading depend upon gross weight, axle spacings, and the distribution of weight among the axles, as well as the length of the span for which the moments are being calculated.

Sheet 4G MomentDist provides the fraction of vehicles falling into each bridge design increment, as a function of vehicle configuration and operating weight. This information is provided for short and long span bridges. The fractions were developed based on an analysis of axle weight distributions and spacings from weigh-in-motion data. In calculating live-load moments, a span length of 40 feet was assumed for short span bridges and 110 feet for long span bridges.

Allocation of New Bridge Costs to Bridge Increments

The allocation of new bridge costs to bridge increments is based on an analysis of the increases in cost that occur when the live-loads used in bridge design are increased. To develop this information, various types of bridges[3] were designed using each of the design loadings (from H2.5 up to HS25). Costs were estimated then for each of these bridges. Costs for each of the lighter design loadings were expressed as a fraction of the cost for the HS25 design loading. All vehicles are assumed to be responsible for the fraction of costs accounted for by the H2.5 design. Only vehicles whose live-load moments exceed those of the H2.5 design vehicle are assumed to be responsible for the added cost associated with moving from the H2.5 to the H5 design loading. Similarly, only vehicles whose live-load moments exceed those of the H5 design vehicle are assumed to be responsible for the added cost associated with moving from the H5 to the H10 design vehicle, and so on.

Redoing the allocation of new bridge costs to bridge increments would be a time-consuming and expensive process. For this reason, and because we would not expect large state-to-state variations, we recommend against a state's redoing these allocations. It should be noted, however, that these allocations are based on the assumption that new and replacement bridges are being designed with HS25 loadings. For those states still using HS20 design loadings for new and replacement bridges, the allocation of new bridge costs to bridge increments should be adjusted to account for this fact. To make this adjustment, the allocation of new bridge costs to the HS20+ increment should be set to zero, and the remaining entries in the column should be factored up so that they sum to 1.0. For example, the default allocation of new bridge costs for steel bridges with a maximum span length of 55 feet or less is as follows:

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[3] Six types of bridges are considered in the spreadsheet, based on two span classes (less than 55 feet and greater than 55 feet) and three types of material (steel, prestressed concrete, and reinforced concrete).

Increment	Percent Allocation
All Vehicles	79.67
H2.5+	4.01
H5+	2.31
H10+	2.91
H15+	2.34
HS15+	4.53
HS20+	4.24
Total	100.00

For a state that uses HS20 design loads for new and replacement bridges, the percent allocations would be revised as follows:

Increment	Percent Allocation
All Vehicles	83.19%
H2.5+	4.19%
H5+	2.41%
H10+	3.04%
H15+	2.44%
HS15+	4.73%
HS20+	0.00
Total	100.00

Note that each of the percentages (except for HS20+) is divided by the quantity 1-0.0424.

Types of Material and Span Lengths for New and Replacement Bridges

In the spreadsheet, bridges are classified by type of material (steel, prestressed concrete, and reinforced concrete) and length of longest span. If this information is not available for planned new bridge and bridge replacement projects, it is possible to develop estimates for recently built bridges from the state's bridge inventory data.

According to the most recent edition of the Coding Guide[4] for the bridge inventory, data on type of material is found in Item 43 (Structure Type, Main). The ten codes for this data item are:

1. Concrete
2. Concrete continuous
3. Steel

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[4] Office of Engineering, Bridge Division, Federal Highway Administration, *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, Report No. FHWA-PD-96-001, December 1995.

4. Steel continuous

5. Prestressed concrete

6. Prestressed concrete continuous

7. Wood or timber

8. Masonry

9. Aluminum, wrought iron, or cast iron

0. Other

For the purpose of developing distributions for input to the spreadsheet, Codes 1, 2, and 8 should be grouped under “Reinforced Concrete”, Codes 3, 4, 7, 9, and 0 should be grouped under “Steel”, and Codes 5 and 6 should be grouped under “Prestressed Concrete”.

The length of the maximum span is Item 48. We use 55 feet as a breakpoint in separating short span and long span bridges.

Construction cost is the ideal measure to use in developing percentage distributions by type of material and span length for input to the spreadsheet. However, construction cost is not available as part of the standard bridge inventory data. As a second best measure, we recommend using square feet of deck area for each category, since unit costs for bridges are usually expressed as cost per square foot of area, rather than cost per lane or cost per bridge. Area can be calculated as the product of Item 49 (Structure Length) and Item 52 (Deck Width, Out to Out).

Inventory Ratings of Replaced Bridges

Inventory ratings (Item 65 in the bridge inventory data) are a measure of the load-carrying capacity of a bridge[5]. According to the latest (1995) edition of the Coding Guide, these ratings are to be expressed in metric tons for an MS loading. An HS20 loading corresponds to an inventory rating of 32.8 and an HS15 loading corresponds to an inventory rating of 24.6. The factor for converting inventory ratings to H loadings depends on span length. Following the approach used in earlier editions of the Coding Guide, we recommend applying a factor of 1.25 to convert H loadings to their HS equivalent. With this assumption, an H15 loading corresponds to an inventory rating of 17.08 in metric tons for an MS loading. The inventory ratings for other H loadings vary in proportion; e.g., the inventory rating for an H5 is 5.69 (17.08*5/15).

Bridge Replacements Due to Structural Deficiencies

The percentage of bridge-replacement costs due to structural deficiencies in existing bridges can be estimated using the sufficiency rating procedure described in Appendix B of the 1995 Coding Guide. In this procedure, a bridge in perfect condition will receive a sufficiency rating of 100%. Bridges lose sufficiency rating points if they have inadequate load-carrying capacity or

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[5] The inventory rating defines the load level that can safely use the bridge for an indefinite period of time.

suffer from other deficiencies. In calculating the loss of sufficiency rating points due to inadequate load carrying capacity, the bridge's inventory rating is used, i.e.,

$$B = 0.3254\,(32.4 - IR)^{1.5} \qquad \text{for } IR < 32.4$$

$$B = 0 \qquad \text{otherwise}$$

where

- B is the loss of sufficiency points due to inadequate load-carrying capacity
- IR is the inventory rating

For existing bridges that are to be replaced, the loss of sufficiency rating points due to inadequate load carrying capacity divided by the total loss of sufficiency points for all reasons is an estimate of the percentage of bridge-replacement costs due to structural deficiencies.

Load-Related Bridge Repair and Special Bridge Costs

The spreadsheet user specifies the percentages of bridge repair and special bridge costs that are load-related and non-load-related. Load-related bridge costs are allocated in the same way that new bridge costs are allocated. Non-load-related bridge costs are allocated using the residual allocators specified by the user.

Default values for the percentage of bridge repair costs that are load-related are based on results from the 1997 Federal HCAS. If bridge repair costs account for a significant portion of all costs (e.g., over five percent), we recommend that these default values be over-ridden based on a more in-depth investigation of the types of activities carried out as part of bridge repair.

The spreadsheet user should (1) develop a set of subcategories for bridge repair costs based on the state's bridge-repair program categories, (2) for each category, estimate the percentage of costs that are load-related, and (3) take a weighted average of these percentages, depending on expenditures for each bridge-repair subcategory.

In determining the percentage of cost that are load-related for a given program subcategory and highway class, the analyst should estimate the fraction by which costs for the program category would be reduced if all vehicles on the highway class were automobiles or other very light vehicles. If costs for a program category would be reduced by, say, 10 percent if all vehicles were automobiles, then 10 percent of the costs are load-related and 90 percent are non-load-related. In making these judgments, inputs from individuals who are knowledgeable about the role of traffic, weather, and other factors affecting costs should be sought.

The 1997 Federal Highway Cost Allocation Study used the following estimates of percentages of bridge repairs that are load-related:

- Rehabilitate or replace deck—20 percent

- Rehabilitate or replace deck and superstructure—30 percent

- Rehabilitate substructure—15 percent

- Minor rehabilitation—0 percent

As additional guidance, the following are estimates from the 1999 Oregon Highway Cost Allocation Study of percentages of bridge repair expenditures that are load-related:

- Bridge raising—0 percent
- Bridge rail replacement and modifications—0 percent
- Cathodic protection—0 percent
- Deck replacement and bridge strengthening—50 percent
- Deck joint repair and replacement—70 percent
- Deck overlays—70 percent
- Other repairs and rehabilitation—0 percent

For special bridge costs, 50% are assumed to be load-related. If special bridge costs account for anything more than a trivial part of total bridge costs, this default value should be replaced with one that reflects the characteristics of the special bridge expenditures.