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# BRIDGE NETWORK COSTS VS. TRUCK WEIGHT LIMITS: METHODOLOGY AND COMPUTER SOFTWARE DEVELOPMENT

**Paul D. Thompson[1], Dr. Gongkang Fu[2], Jihang Feng[2], Waseem Dekelbab[2], Dr. Fred Moses[3], Dr. Harry Cohen[4], and Dr. Dennis Mertz[5]**

[1]2425 Hawken Drive, Castle Rock, CO 80104, USA, pdt@pdth.com

[2]Department of Civil and Environmental Engineering, Wayne State University
5050 Anthony Wayne Drive, Room 2172, Detroit, MI 48202, USA, gfu@ce.eng.wayne.edu

[3]Department of Civil Engineering, University of Pittsburgh, Pittsburgh, PA, fmoses@engrng.pitt.edu

[4]4507 Mustering Drum, Ellicortt City, MD 21042, harrycohen@home.com

[5]Department of Civil engineering, University of Delaware, Newark, DE, ztrem@ce.udel.edu

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**Abstract.** *The US National Cooperative Highway Research Program is developing, under project 12-51, a new methodology and decision support tool to be used by highway agencies to estimate the network-level bridge costs due to changes in truck weight limits. Combined with other tools for pavements and other affected assets, the system will help agencies to assess the full costs and benefits of allowing heavier trucks to use the highway network, or even restricting the network to lighter trucks.*

*Using bridge inventory data, the methodology addresses four cost impact categories: steel fatigue consumption, deck fatigue consumption, overstress deficiencies, and higher new bridge design loads. For the first two categories, it quantifies the change in the number and magnitude range of loading cycles and assesses the probability of fatigue damage for cost estimation. For the latter two categories, it estimates the change in load rating requirement and design load requirement, respectively. Then the impact costs are estimated based on these requirements.*

*To enable practical application of the methodology, a decision support tool is being developed in Microsoft Excel and Visual Basic. The system consists of a connected set of workbooks for preparing inventory data, describing scenarios of weight limit changes, and analyzing the impacts.*

## 1 INTRODUCTION

Transportation decision makers worldwide are under increasing pressure to allow heavier trucks to use the highway network. Per unit of payload, a heavier truck reduces labor and fuel costs, and reduces the number of vehicles in the traffic stream. However, heavier trucks may have negative impacts on safety, infrastructure damage, and facility construction costs. Several studies have been conducted to quantify positive and negative consequences due to weight limit changes for various highway networks, to enable more informed decisions.

The study conducted in the US National Cooperative Highway Research Program (NCHRP) described in this paper addresses the possible negative consequences on the maintenance and construction of bridges. The following specific types of cost impacts were investigated:

- Fatigue damage on steel superstructures leads to repair or bridge replacement costs.
- Fatigue damage on concrete decks also causes repair or deck replacement costs.
- Overstress of existing bridges leads to strengthening or bridge replacement costs.
- Higher design requirements for new bridges increase the new bridge construction cost.

The first phase of the study, completed in 2000, developed damage and cost models for these categories of cost impacts.

All four categories are based on a prediction model for the truck weight distribution in the traffic stream. Truck weights are represented by a truck weight histogram (Figure 1). Such histograms may be derived from data on vehicle-miles traveled in each functional class, by each type of heavy truck.

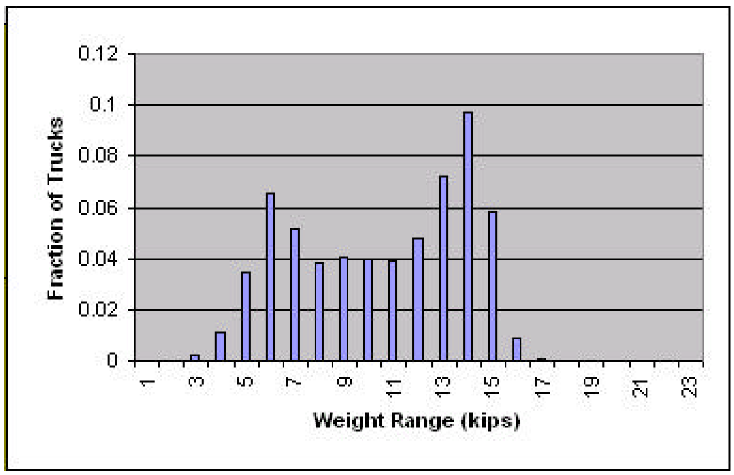


Figure 1: Truck weight histogram

An increase in allowable weight is modeled to cause shifts in truck traffic to larger truck types and higher weight ranges. If payload is kept constant, this shift lowers the number of fatigue loading cycles due to traffic reduction. However, the net effect may be an increase in fatigue damage to bridge structural members. This may increase fatigue repair costs on steel superstructures and concrete decks. Further, on certain bridges, higher weight limits may decrease the rating factor below 1.0, causing the need for strengthening.

A software system, written in Microsoft Excel and Visual Basic for Applications, was developed in phase 2 of the study, and scheduled to be completed in 2002. The software provides tools for compiling input data for the models, supports the analysis of scenarios of truck weight limit change, and presents the results in a flexible way. The outputs are to be used to inform decision makers of the economic consequences of considered weight limit changes, as well as to identify specific bridges where new repair or replacement needs may arise.

## 2 TRUCK WEIGHT HISTOGRAM PREDICTION MODEL

A direct impact of truck weight limit change is the change in truck load spectra applied to bridges. This includes changes in truck weight histograms (TWHs) and wheel weight histograms (WWHs). The former represents the load to the entire bridge, affecting the bridge's relative strength demand. It also influences steel bridge fatigue accumulation. The latter is the load to bridge decks that transfer wheel loads to the supporting frame. A new method is developed in this project for predicting the TWHs and WWHs under a change in truck weight limits.

Changes in TWHs due to truck weight limit changes may be classified into the following three types of freight shifting. 1) Load shifts without changing truck types (truck configurations), referred to as truck load shift hereafter. 2) Load shifts with changing of truck configuration, referred to as truck type shift below. 3) Exogenous shifts, such as economic growth and mode shift (e.g., from and to rail) due to competition. These shifts are individually dealt with in this study. The term "Base Case" used below refers to the condition before the considered change in truck weight limits, while "Alternative Scenario" represents the condition after the change.

It is assumed that TWHs for the Base Case are available for each type of vehicle, except automobiles and 4-tire light trucks. These two types of vehicles are considered irrelevant to issues related to trucks and to bridge strength and fatigue.

For assessing reinforced concrete (RC) deck fatigue, truck wheel weight distributions are needed to estimate the cost effects of changes in truck weight limits. It is suggested that predicting WWHs be based on GVW, assuming that there is a correlation between the wheel weights and the gross weight. This assumption is particularly valid for trucks loaded to the limits, which are dominant in RC deck fatigue. When a TWH is available, the wheel weights can be estimated using the following empirical relation:

$$\text{Wheel Weight} = E + F \times GVW \qquad (1)$$

where E and F are model coefficients for each axle. They can be obtained using WIM data and a regression analysis. In a 2000 study by Fu et al[1], examples of E and F were obtained using data from the State of California. It is recommended that agencies use their own WIM data to obtain those coefficients for typical truck types within the jurisdiction.

## 3 DAMAGE AND COST MODELS

### 3.1 Fatigue on steel superstructures

Fatigue of steel bridge components has been extensively investigated[2]. The vast majority of highway agencies have experience with fatigue damage. Under an increase in truck weight limits, fatigue accumulation is expected to increase due to load (and thus stress range) increase, although the truck traffic is expected to decrease if the total payload remains constant.

The following procedure is suggested to estimate the impact cost due to additional fatigue accumulation. 1) Identify possibly vulnerable bridges. 2) Decide to analyze all or a sample of possibly vulnerable bridges. 3) For the analysis of each bridge, generate the TWH under the Base Case and predict the TWH under the Alternative Scenario. 4) Estimate remaining safe life and remaining mean life for both the Base Case and Alternative Scenario. 5) Select responding action for treating possible fatigue failure. 6) Estimate the costs for the selected action. 7) Sum the costs for all bridges. 8) Perform a sensitivity analysis to understand possible controlling effects of the input data.

### 3.2 Fatigue on reinforced concrete decks

Based on previous studies on RC deck fatigue under wheel load[3,4,5], the following procedure is recommended for assessing fatigue accumulation using a similar format to that for steel fatigue:

$$Y_d = \frac{K_d K_p}{(T_a/T)TC_d\left(R_d I P_s\, P/P_u\right)^{17.95}} \tag{2}$$

where $Y_d$ is the service life of the deck. $Y_d$ will be the mean service life for the reliability factor $R_d$ set equal to 1 and the evaluation life for $R_d$ equal to 1.35. $T_a$ and T are the life average daily truck traffic and current annual average daily truck traffic. $C_d$ is the average number of axles per truck. $P/P_u$ is the equivalent stress ratio caused by wheel load P:

$$P\Big/P_u = \left[\sum_i f_i\left(P_i/P_u\right)\left(P_i/P_u\right)^{17.95}\right]^{1/17.95} \tag{3}$$

where $P_u$ is the ultimate shear capacity of the deck, and $P_i$ is the mid-interval value of the $i^{th}$ interval of the wheel weight histogram. Eq.3 uses the same linear damage accumulation assumption (the Miner's Law) as for steel fatigue. $K_d$ is a coefficient that covers model uncertainty (with respect to the assumed Miner's Law). $K_p$ addresses the difference between the state of deck failure recognized in the laboratory and the state of real decks when treatment is applied[1].

### 3.3 Overstress of existing bridges

Currently in the US highway system, there are a number of bridges that are inadequate in load carrying capacity. This is indicated by their load rating factor lower than 1, according to the AASHTO requirement[6,7]. When higher truck loads are legalized or permitted, more bridges will become inadequate. Costs to correct the additional inadequacy are covered in this cost impact category. The new rating factor is recommended to be calculated as follows:

$$RF_{AS} = \frac{RF_{BC}\left(M_{BC}/M_{AS}\right)}{AF_{rating}} \tag{4}$$

where $RF_{AS}$ is the rating factor for the Alternative Scenario, and $RF_{BC}$ is the rating factor for the Base Case (likely the existing rating factor). $M_{BC} / M_{AS}$ is the ratio between the maximum load effects due to the rating vehicle under the Base Case and due to the new rating vehicle under the Alternative Scenario. The new rating vehicle is a model representing the practical maximum load permissible under the changed weight limits. It could be a set of vehicles. $AF_{rating}$ is the ratio between the live load factors for the Base Case and the Alternative Scenario, representing the load spectrum change. Subscripts BS and AS respectively refer to the Base Case and the Alternative Scenario. This approach is consistent with the concept of load and resistance factor rating under development[8] for AASHTO.

For cost estimation, those bridges that are inadequate with $RF_{BC}<1$ under the Base Case should be excluded, because they do not contribute to the cost impact (additional costs). When a bridge is found to be inadequate or overstressed under the Alternative Scenario but adequate under the Base Case (i.e., $RF_{BC} \geq 1$ and $RF_{AS}<1$), an action needs to be selected as the basis for cost estimation. It can be, for example, posting, strengthening, replacing, or a combination thereof. Note that, in reality, the decision making process requires information on a number of other factors, not only the load rating.

### 3.4 Higher load requirements on new bridges

The bridge design load is supposed to envelope current and expected future loads for the bridge life span. When higher loads are legalized or permitted, the design load needs to be adjusted to assure relatively uniform safety of the bridges. The costs caused by this adjustment are covered in this cost impact category. The analysis requires the following steps. 1) Identify the new bridges to be constructed in the future within the planning period. 2) Estimate the required design load for each of these bridges under the Alternative Scenario. 3) Estimate the additional costs for each of these bridges under the new design load.

Step 1) may be approximated using the bridges constructed in recent years and averaged to an annual population of new bridges. It can be done using the agency's bridge inventory. Step 2) is to be accomplished using the following formula for the amount of design load change:

$$\text{DLCF} = (M_{\text{AS design vehicle}} / M_{\text{BC design vehicle}})\ AF_{\text{design}} \tag{5}$$

where DLCF stands for design load change factor indicating the ratio between the design load effects under the Base Case and the Alternative Scenario. $M_{\text{AS, design vehicle}} / M_{\text{BC, design vehicle}}$ is the ratio of the maximum load effects due to the design vehicle under the Base Case and the same under the Alternative Scenario. Practically, it should not be lower than 1. $AF_{design}$ is the ratio between the live load factors under the Base Case and the Alternative Scenario. It is an adjustment factor for the design load used to cover the change in uncertainty associated with the considered Alternative Scenario. It plays a similar role as $AF_{rating}$ in Eq.4 for additional deficiency in existing bridges.

DLCF in Eq.5 indicates the relative increase in the design load effect. The incremental cost can be accordingly calculated as the impact cost. A set of default cost data have been prepared for this purpose, if no more specific data are available[1]. A cost database was established to estimate the cost increase due to a design load increase.

## 4 SCENARIO ANALYSIS SOFTWARE

The software system is designed to be a platform for testing the models, as well as a practical policy analysis decision support tool. Excel was considered to be an ideal environment for developing such a system. Construction of the data management and reporting features was relatively quick, permitting a focus on the analytical models. All of the damage and cost models were implemented as Excel worksheet formulas, making them easily visible and modifiable by researchers and analysts. For decision support, a few relatively simple screens support defining the policy scenarios, keeping track of multiple alternatives, and reporting the results.

### 4.1 Data preparation

With relatively complex input requirements, the software provides a separate data preparation activity that can be conducted by relatively technical personnel in advance of any scenario analysis. The input data needed are related to existing bridge inventories and statistics of current condition. Because such inputs change infrequently in practice, many scenario analyses can be completed before the need arises to repeat the data preparation step. The following inputs are required:

- Bridge inventory data, including lists of decks and fatigue-prone details
- A base case truck weight histogram
- A number of background model parameters

Some of the required inventory data are typical of bridge management systems worldwide: identification, location, structure type, gross geometry (length, width, maximum span), year built, load rating, functional classification, truck volume, and number of lanes. The software can automatically import these data from AASHTO's Pontis® bridge management system, and can also be configured to import them from any other modern relational database.

Other inventory items are infrequently found in automated form, and might have to be collected and entered manually. These include fatigue-prone details and deck thickness. The software provides a stratified sampling methodology to minimize the cost of new data collection.

For US agencies, a base case truck weight histogram is provided in the software. This database resulted from Federal Highway Administration truck weight studies. This information is stored as an Excel worksheet and therefore can readily be imported from any other source, such as processed weigh-in-motion data.

The models require a number of parameters, many of which were empirically calibrated and provided as products of the study. These are mostly quite generic and would not have to be modified by user agencies. However, a few of the parameters would typically be customized, including unit costs of repairs, strengthening, and replacement; a choice of metric or US Customary output; discount rate for the time value of money; and the base year of the analysis.

## 4.2 Preparing alternative policy scenarios

To execute a scenario analysis, the end-user provides information about the changed weight limits, and hypothesized shifts among truck types and weight categories. Typically an analysis would entail a search through reasonable assumptions about truck traffic shifts, to derive an envelope of likely economic impacts.

The software provides worksheets to define the anticipated truck traffic shifts, and then runs the prediction model to derive an alternative scenario truck weight histogram. Each of the four cost categories then compares the alternative scenario with the base case to quantify the damage and/or resulting cost that arises from the weight limit changes. Simplified worksheets present the results for individual bridges (Figure 2) and for the network as a whole (Figure 3). A filtering feature allows scenarios to be developed for any defined sub-network of the bridge inventory, such as a planned truck route.

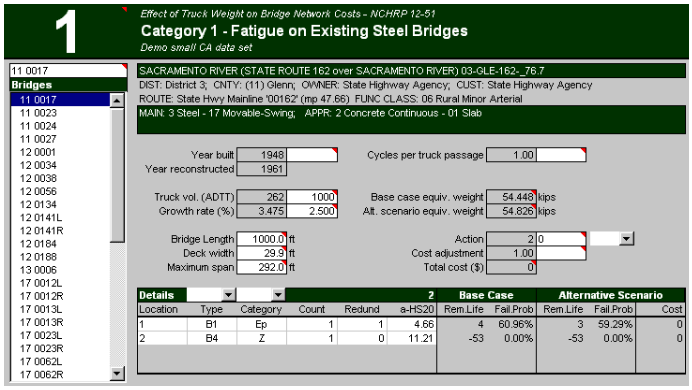


Figure 2: Example results at bridge level

## 4.3 Output capabilities

The Excel worksheets are all formatted to print conveniently as presentable reports, allowing the analyst to report final results, input data, or intermediate results. In addition, there is a generic report writer to consolidate data from multiple worksheets into focused presentations for each of the cost categories. A sensitivity analysis worksheet makes it easy to systematically vary an input parameter

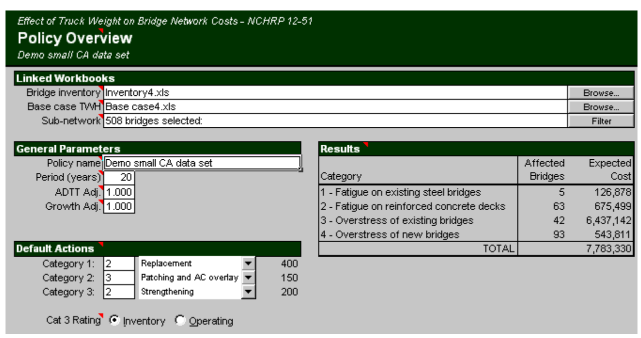


Figure 3: Example network-level results

to see the effect on model results.

## 5 CONCLUSIONS

The new policy analysis models and software system will be very helpful to decision makers when considering increases in truck weight limits, for either the entire network or any sub-network under its jurisdiction. Initial case studies for Michigan and Idaho were carried out for realistic scenarios of truck weight limit changes. These were calculated using the new software as well as by alternative means. The results showed that the largest economic impact is strengthening or replacement caused by overstress of existing bridges. The fatigue impacts certainly did not exceed the overstress impacts under the considered scenarios.

The software system demonstrates a very cost-effective way to implement analytical software of this type, where the underlying models are research products subject to further revision, but user-friendly execution is desired.

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