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Detect and charge: Machine learning based fully data-driven framework for computing overweight vehicle fee for bridges

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ABSTRACT

This study develops a fully data-driven framework for computing overweight vehicle fee that combines historical bridge data from National Bridge Inventory (NBI) and weigh-in-motion (WIM) data. In this framework, information regarding vehicle weight distribution on bridges was obtained using Gaussian mixture model (GMM) based interpolation. Using this interpolation approach, the vehicle weight distribution on each bridge could be estimated from WIM data based on their location. Later, these estimated distributions were combined with the NBI for developing a machine learning-based prediction model that inputs bridge characteristics (e.g., age and traffic) and outputs deck condition. The model was employed to calculate the expected bridge service life under two scenarios to compute a bridge life reduction per damaging load. Finally, the bridge life cycle cost was conducted to convert the calculated service life difference into a fee. Integration of this framework with existing geographical information system based online permit issuing tools will allow for detection of bridges on vehicles' routes and charge them a fee considering their weight and the load capacity of the bridges they will pass over. Therefore, fees will be calculated more accurately and efficiently. Additionally, the proposed framework has the flexibility of being converted into a table for conforming to the conventional permit fee calculation scheme.

1. Introduction

The U.S. population and economy exhibited a significant growth between 2000 and 2014. According to the U.S. Department of Transportation Freight Fact reports [1], while the population grew by 13% during that time, climbing to an estimated 319 million in 2014, gross domestic product increased by 24.9% in real terms (inflation adjusted), reaching $15,773,516 (millions of chained dollars). This expansion in the economy and population caused a concurrent increase in truck freight transportation which carried 69.6% (by ton) of total goods moved in 2013. Moreover, a total of 13,732 million of tons of goods valued at $11,444 million shipped by trucks in 2013, representing 9.21% and 6.16% increase over the estimates of 2007 by ton and value, respectively [1].

Well-maintained and functional transportation infrastructures are instrumental to sustain this growth in economy and to provide safer mobility for the increasing truck traffic. Nevertheless, with 20% of roadway miles in poor or mediocre conditions and 9.1% of bridges being structurally deficient or functionally obsolete [2], state departments of transportation (DOTs) face a major challenge in meeting their infrastructure needs. Therefore, DOTs have become more interested in initiating and supporting research projects that try to address challenges in transportation infrastructure management.

This research addresses one of these challenges under a project supported by Illinois Department of Transportation: quantification of the damage on bridges caused by overweight vehicles. In this research, a fully data-driven framework, “Detect and Charge”, is developed to assess the economic impact of the vehicles that violate federally defined weight limits. Thereby, a permit fee that compensates for the damage imparted on bridges by such vehicles can be established.

In the State of Illinois, the overweight limits for a group of two or more consecutive axles are calculated by the following formula (Eq. (1)):

$$W = 500\left(\frac{LN}{N-1} + 12N + 36\right) \tag{1}$$

where

W, overall gross weight of any group of two or more consecutive axles, to the nearest 500 lb.

L, distance in feet between the extreme of any group of two or more consecutive axles

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N, number of axles in the group under consideration

This formula, known as the federal bridge (FB) formula, was enacted by Congress in 1975 and updated in 2006. In addition to Illinois, the majority of U.S. states use the FB formula to legislate and enforce legal truck weight limits on interstate highways. Trucks that violate these limits have to buy a permit to travel through the states. A recent study, Comprehensive Truck Size and Weight Limits Study [3], investigated the possibility of modifying the overweight limits determined by the FB. In that study, six different trucks (i.e., scenarios) that would currently be classified as overweight/oversize (OW/OS) trucks were simulated. A comprehensive set of measures including bridge/pavement damage, highway safety, compliance, and modal shift was selected for a holistic evaluation of the potential impacts of allowing these OW/OS trucks to travel on highways. Although several advantages of increasing the limits were noted, the study does not recommend any changes to existing limits.

Although OW/OS limits are set by federal government, each state can develop its own permit fee structures. U.S. Department of Transportation [3] reported that the number of permits increased to approximately 4.2 million from 2.1 million between 2008 and 2012. This increase in OW/OS traffic has motivated DOTs to revise their permit fee structures. Ahmed et al. [3] used an incremental damage approach to assess the damage caused by OW vehicles. Chowdhury et al. [4] developed a finite element model of selected bridges where specific OW vehicles were analyzed. The reduction in fatigue life due to the simulated OW vehicles was computed by analyzing the stresses developed within the bridges. Ghosn et al. [5] compared the overweight vehicles with HS-20 load to quantify their impact on bridge fatigue life. Chowdhury et al. [4] linked the structural analysis results to the fee by exploiting bridge life-cycle cost assessment (BLCCA). Ghosn et al. [5] used unit cost prices from literature to compute the final fee. It should be noted that these studies also present the fee computation for pavement. However, the pavement fee is not included herein; it is out of the scope of this paper.

Because of the high computational cost, a number of representative bridges were selected out of thousands to analyze and develop a fee [4,5]. This approach was criticized in a review written by Transportation Research Board National Academies of Sciences [6] to U.S. Department of Transportation [3] for introducing bias to the decision-making process since it depends on selective bridges.

This limitation can be overcome using data-driven approaches. Lou et al. [7] used weigh-in-motion (WIM) data to compute the fee for overweight vehicles. Vehicle loadings extracted from WIM data were correlated to the service life of bridges and the fee was computed by employing BLCCA. In Lou et al. [7], it was assumed that bridges on the same highway are exposed to similar traffic characterization. The framework developed in this study, "Detect and Charge", also exploits a data-driven approach for computing the fee for OW vehicles considering all the bridges in Illinois. Although the results of the framework were specific to bridges in Illinois, the framework can be extended to any state as long as the corresponding data are utilized in the framework as inputs.

2. Detect and charge

In a broad sense, the objective of this study is defined as an economic assessment of overweight vehicle loading on bridges. Many research topics in the area of infrastructure management build on similar objectives where the impact of a variable (e.g., construction material type or traffic) on a type of infrastructures (e.g., buildings, bridges) is quantified economically. In order to perform such quantification, one needs to have an input-output tool that computes the service life of the infrastructure of interest considering the variable of interest along with other significant variables.

Traditionally, in civil engineering, such performance prediction tools are developed using mechanistic approaches, such as finite element analysis, which are generally computationally expensive. Therefore, using such approaches for the aforementioned type of research problems requires subset selection of infrastructures to reduce the number of simulations which, as previously mentioned, may introduce bias to the decision process. Additionally, these approaches have to be built on assumptions that simplify or neglect variables that are too complicated to be represented in mechanistic equations. Alternatively, this study employs a machine-learning algorithm for simulating the performance of bridges over time, based on historical inspection data that captures the actual field behavior of bridges. In other words, this study substitutes mechanistic approaches with the machine-algorithm to provide a computationally efficient approach while producing a realistic bridge performance prediction.

Development of such a prediction model requires addressing some challenges in data preprocessing (e.g., data cleaning and filtering) to ensure the presence of a comprehensive set of inputs (e.g., material properties, applied load, age). For example, estimation of vehicle weight information, which is collected at only limited numbered WIM stations (~20), on thousands of bridges in the network so that the variable of interest (i.e., overweight vehicle loads) can be explicitly incorporated into fee computation. Furthermore, after developing an accurate machine-learning model for predicting bridge service life, one still needs to come up with a way to leverage the developed model to compute the penalty for the vehicles that violate the weight limits (i.e., to develop OW fee).

The developed framework, "Detect and Charge", outlines the steps that address the aforementioned challenges for the fee development. This framework consists of three main steps: pre-processing, machine-learning model development and post-processing. The preprocessing step includes structuring raw data into an input set for the model development. The inputs can be grouped into two: vehicle weight frequencies and bridge characteristics. The vehicle weight frequencies (VWFs) on each bridge were estimated using the Gaussian Mixture Model (GMM) based interpolation. First, VWFs from limited number of WIM stations are computed. Then, these VWFs are interpolated to each bridge in the network based on their location (i.e., latitude and longitude). The bridge characteristics (including historical performance data) are extracted from the National Bridge Inventory (NBI). Later, a subset selection is performed to determine the most significant variables in NBI for performance prediction. The second step, model development, consists of training Support Vector Machine using selected inputs to predict bridge deck condition. In the third step, post-processing, the trained model is employed to calculate bridge service life under two scenarios: with and without damaging load (DL), which is defined as any load greater than the bridge load carrying capacity. The difference between the service lives from these two scenarios quantifies the reduction in bridge service life due to OW loads. Finally, a bridge life-cycle cost assessment was conducted to convert this service life difference into a fee. The flowchart of the developed framework is illustrated in Fig. 1.

This framework introduces three contributions. The first one is fusing two different data sources (WIM and NBI) to develop a fully data-driven framework for computing the overweight fee. One of the main advantages of using NBI is incorporating realistic field performance of the bridges into fee calculation rather than the outcomes of mechanistic simulations. The second contribution is exploiting GMM to get accurate load information on each bridge over the network based on WIM data. While Chowdhury et al. [4] considered a few vehicles with specific load and axle configuration for the structural analysis, Lou et al. [7] assumed the same traffic characteristics for bridges located on the same highway. The third contribution is represented in the direct consideration of bridge load carrying capacity into the data-driven models for permit fee calculation.

Many DOTs have already had an online permit issuing system that reports routes for OW vehicles based on origins and destinations