Impact assesment of permit vehicles on bridge lifetime

SYLWIA STAWSKA[1, *], JACEK CHMIELEWSKI [2], ANDZREJ S. NOWAK[1]
[1] Auburn University
[2] Cracow University of Technology

Abstract: Overloaded traffic significantly contributes to accelerated bridge damage. There is a noticeable growth of 7–10% annually in the number of issued permits in the US. Analysis of Weigh-in-Motion data shows that 10–15% of the recorded trucks are exceeding Federal Truck Weight and Size Law. Heavy permit traffic is becoming regular heavy traffic. Thus, it is necessary to better control the operation of an increasing number of permit vehicles. The permit fee structure varies from state to state, and for some, it has not been updated for decades. There is a need to update a new permit fee structure for heavy permit traffic. This paper presents a methodology to evaluate the damage caused by permit vehicles on bridges. Bridge life consumption is computed by the incremental consumption equation. The proposed method provides a simple approach that captures the relative amounts of the deterioration based on AASHTO bridge design life. The consumption equation converts fatigue damage to dollar damage by considering the bridge construction cost, traffic volume, and bridge parameters. A developed methodology can help state agencies to establish a rational and fair permit fee structure. It is transparent and can be used by any bridge owners utilizing the available databases.

Key words: bridge, damage, truck, overload, permit, WIM, consumption

1. Introduction

Highway infrastructure is a major part of the national investment. Good condition of bridges is crucial for efficient transportation. According to the American Association of Civil Engineers, ASCE Infrastructure Report Card from 2021, there are approximately 617,000 bridges in the United States, and over half of them are approaching the end of their design life. It was reported that 25% of bridges are not adequate for normal traffic, including 7.5% of them being structurally deficient (ASCE Cards, 2021). The trucking industry is important for economic growth; therefore, the operation of heavy vehicles has to be managed and controlled to prevent premature damage to bridges.

The bridge's poor condition can result in the need for repair, rehabilitation, and replacement. In addition to the deteriorating condition of bridges, there is a growing number of heavy trucks. Based on the Florida Weigh-in-Motion (WIM) data analysis, it was observed

*Autor do korespondencji: svs0011@auburn.edu

that annual truck traffic growth could be over 3%. The number of overloaded trucks recorded by WIM is at 10–12%.

Heavy trucks affect the service life of bridges and may contribute to accumulated damage. The traffic includes three groups of vehicles: (1) legal vehicles which do not exceed state and federal provisions; (2) illegal vehicles exceeding the weight, size, or weight and size limits; and (3) permit vehicles, which can legally exceed the legal limits after purchasing the permit. The number of issued permits is growing every year (7–10%), and their impact has not been quantified. In most states, the permit regulations are outdated.

In this study, bridge consumption is considered in terms of service life or the number of load cycles until the structure reaches the fatigue limit state. The goal is to provide a simple method that captures the relative consumption of the AASHTO bridge design life caused by overloaded permit vehicles. A main assumption of the proposed method is that life of the bridge is defined by 75 years of crossings by the AASHTO fatigue design truck. Each passage of a vehicle contributes to the accumulation of fatigue damage that eventually results in a lack of ability to carry the loads. The damage contribution depends on load distribution and axle configuration. However, fatigue life can be considered as corresponding to the cost of a bridge replacement. Therefore, each vehicle passage can be attributed a monetary value.

The objective of this study is to develop a methodology to assess bridge dollar damage caused by heavy permit vehicles. The approach is intended to help bridge owners to establish a rational and equitable permit fee structure. The presented approach is demonstrated on selected permit vehicles in Florida.

2. Permits

Permit regulations and monitoring procedures aim to provide safety to the road and bridge infrastructure. Nevertheless, the problem of controlling the drivers violating the law remains vague. In the United States, Federal Truck Weight and Size law requires permits for vehicles exceeding the legal limits on size and/or weight. State Departments of Transportation (DOT) issue permits daily for both oversize and overweight vehicles. The permit fee structure varies significantly by state. There are typically single and annual multi-trip permits. The annual multi-trip permits are valid for 12 months and an unlimited number of trips. Single trip permits are valid from one point of origin to one destination. In the US, there are five basic permit fee structures, including flat fees, distance-based fees, weight-based fees, weight-distance-based fees, and axle-based fees. Figure 1 shows the map with various permit fee structure adopted by different states (Chowdhury et al. 2013).

The impact of heavy vehicles on bridges has been studied to help assess the damage and behaviour of bridges under excessive loading. In Louisiana, the impact of overweight permit vehicles was checked to assess the economic impact on pavements and bridges. The analysis estimated permit fees and provided the recommendation for timber trucks in Louisiana [3]. InWisconsin, a special user guide was developed to calculate the effect of overloaded vehicles for single and dual trailer configuration [4, 5]. In Connecticut, an overloaded vehicle's impact was assessed by checking the effect of one passage of a large permit vehicle across a specific bridge. The measured stresses from superload vehicles were significantly lower than calculated by AASHTO Guide Specification [6]. Fatigue of older steel bridges in northern Indiana due to overweight and oversized loads were evaluated on the heavy-duty corridor. It was found that 15% of class 9 trucks and 26% of class 13 trucks travel heavier than their respective legal limits [7].

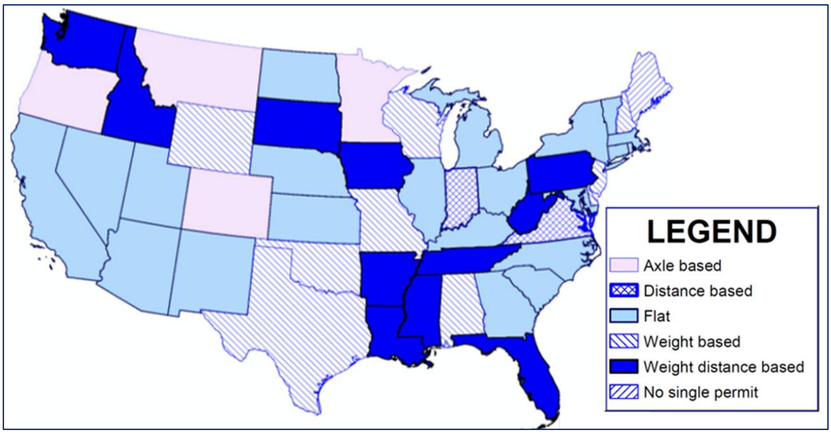

Fig. 1. Permit fee structures in the US.

There are several studies sponsored by state DOTs targeted to evaluate the impact of overloaded permit vehicles on bridges. Wisconsin presented a review of permitting fee structure for several states [8]. In many instances, overloaded trucks operate on highways, roads, and bridges that are not designed for such a weight or traffic volume. A new permit fee structure needs to be calculated based on the actual damage caused by heavy permit vehicles. Texas Department of Transportation (TxDOT) recommended a new permit fee schedule. Bridge consumption was developed for representative permit vehicle configurations and routes. The analysis presented the inadequacy of current permit fee schedules [9]. South Carolina DOT commissioned the study to develop a new permit policy recommendation. A bridge deterioration model was based on WIM data analysis. The fatigue damage was calculated based on stress cycle analysis and compared to an allowable number of stress cycles (Chowdhury et al., 2013). Illinois Department of Transportation examined the permit system by evaluating the impact of overweight vehicles. The bridge damage assessment was based on load-carrying capacity and vehicle weight frequency. National Bridge Inventory Database (NBI) and WIM were utilized to develop the prediction engine to calculate the bridge fees. The study assessed the damaging effects on pavements, bridges, and traffic safety [11]. Florida DOT sponsored a study to assess the damage caused by permit vehicles. An approach was developed to calculate the monetary consumption caused by overloaded permit vehicles on bridges and pavements in Florida. The incremental bridge consumption assessment utilized in the Florida study is partially utilized in this paper [12].

3. Traffic Data

The traffic data is essential to evaluate load effects on bridges. Assessment of the overloaded vehicles is possible by using the state-specific permit database. In Florida, the Permit Application System (PAS) include detailed information about every issued permit based on permit applications. The permit data contain the axle weights and spacings, which are essential to determine the load effects. The permit database has unmeasured values provided by the permit applicant. The trucking company declares axle spacings and the expected axle load distribution of a vehicle.

Moreover, Weigh-in-Motion (WIM) can be used to determine overloaded traffic-induced load effects, traffic volume, and lane load distribution. The WIM is an excellent source of information and is widely available all over the United States. It continuously collects massive traffic data about weight and configuration of passing vehicles. To define the impact of permit vehicles on bridge structures, it is required to filter heavy trucks from WIM traffic flow. A filtering procedure can be developed, but it will not guarantee that the vehicles captured by WIM operate based on the issued permit.

In this study, Florida permit and overloaded WIM databases are used to evaluate bridge damage under heavy trucks. Figures 2 and 3 present a summary of utilized traffic databases. There are three sources of data: raw WIM data from Florida DOT, years 2012–2017, Federal Highway Administration (FHWA) Florida WIM, years 2016–2019, and Florida permit database, years 2016–2019 (with no data for December 2019). After applying the filtering criteria to the WIM data, approximately 10–12% of trucks are classified as overloaded by Federal Truck Weight and Size Law.

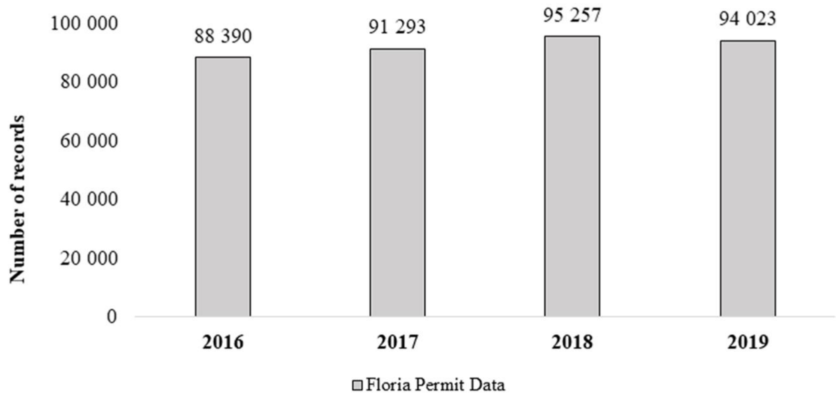

Fig 2. Florida permit database.

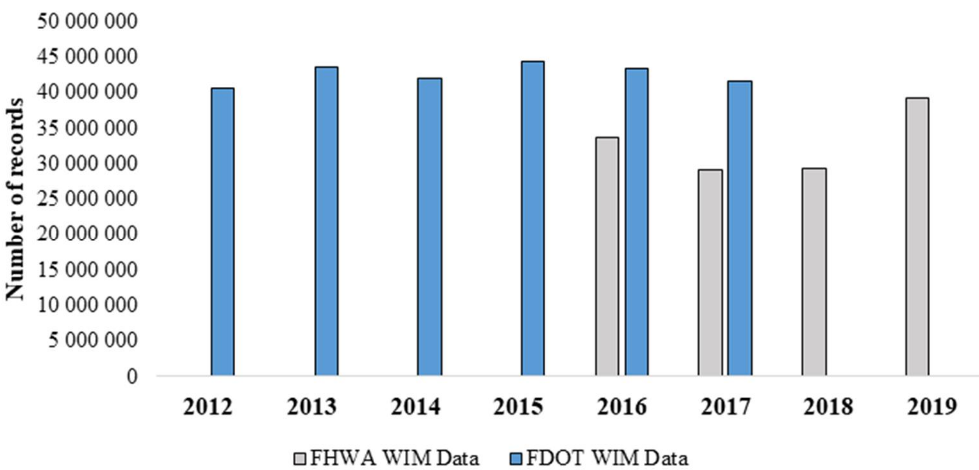

Fig 3. Florida WIM database.

The available permit and WIM data provide extensive information that can be used to determine the impact of overloaded trucks on bridges. Further, it allows estimating the dollar damage and provides a basis to develop a new permit fee schedule. The Gross Vehicle Weight for permit and overloaded WIM trucks is shown in Figure 4. It shows that about 5% of permit trucks are extremely heavy and need to be carefully analyzed.

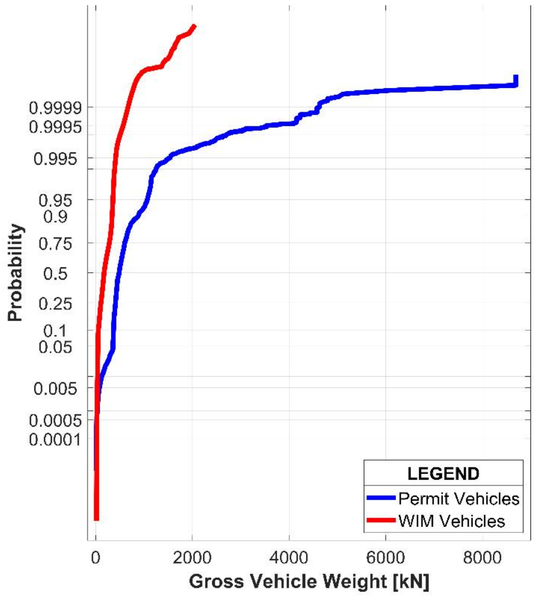

Fig. 4. FL: permit database.

4. Bridge Consumption Assessment

The service life of a bridge depends on many factors such as climate, natural hazards, defects in material production, extreme events, and surely traffic loads etc. Traffic-induced loads may cause damage to a bridge by fatigue and overload. Every truck's passage across a bridge creates stress cycles in the structural components, resulting in the accumulation of fatigue damage over time. A bridge may experience many fatigue cycles by heavily loaded trucks over its lifetime. If the stress cycles are of a particular number and magnitude, they will result in fatigue damage.

In the current bridge design code AASHTO LRFD 2020, the economic design life of a bridge is defined as 75 years. AASHTO specifies the fatigue design approach for traffic-induced load. The stress range is calculated for a code-specified fatigue design truck to prevent fatigue cracking caused by the accumulation of damage from cyclic truck loading.

Therefore, bridge consumption can be considered as a fatigue process in which each vehicle passing over a bridge utilize a part of its design life. The damage caused by a vehicle depends not only on weight, but its configuration.

Permit data is used to determine the load envelop. Each permit truck creates a bending moment that changes as the truck crosses the bridge. This change in bending moment may result in a single cycle or multiple cycles of different magnitudes depending on the truck bridge configuration. In this study, the bending moment at midspan due to a permit truck crossing bridge is determined using an influence line analysis. The rainflow counting method (ASTM E1049-85) is used to determine the number and magnitude of moment cycles resulting from each permit truck. Equation 1 is used to determine the equivalent single cycle bending moment that accounts for all of the cumulative fatigue damage due to multiple cycles caused by the passage of a permit truck.

$$M_{eq} = [\sum n_i M_i^m]^{1/m} \tag{1}$$

where:

n_i – number of cycles at the ith moment range, M_i,
M_i– ith moment range [kNm/kip-ft],
$m -$ fatigue exponent, material dependent.

In the AASHTO the number of fatigue load cycles defining the service life is represented by the relationship between the bridge design life and the single lane average daily truck traffic (ADTT). According to AASHTO, this number of cycles in the 75-year service life is the number of days multiplied by Average Daily Truck Traffic per lane.

The number of AASHTO fatigue design truck crossings will cause the same amount of fatigue damage as a considered permit truck. It can be found by setting the amount of damage equal for a single passage of permit vehicle to a number of fatigue truck crossings by AASHTO fatigue truck. The consumption ratio between considered permit vehicles and fatigue trucks captures the relative amounts of bridge design life reduction caused by a permit vehicle. This fundamental relationship was used to assess the fatigue damage caused by a permit truck in terms of the design fatigue truck in AASHTO. It is assumed that when a bridge reaches its economic lifetime of 75 years, it has to be replaced at a certain construction cost that depends on the structural type, material, etc. The bridge consumption is determined by a single cycle equivalent moment. The estimated fatigue truck effect and number of cycles within the economic lifetime of 75 years is assumed as equal to the bridge construction cost. Monetary consumption by a single passage of a permit vehicle can be expressed as:

$$Consumption_{permit} = \left(\frac{Construction\ Cost}{(365)(75)n\ (ADTT)_{SL}}\right) \cdot \left(\frac{M_{permit}}{M_{fatigue\ truck}}\right)^m \tag{2}$$

where:

$365 -$ days in a year,
$75 -$ design life of a bridge in years,
$(ADTT)_{SL} -$ single-lane average daily truck traffic,
$M_{permit} -$ equivalent single moment due to permit truck,
$M_{fatigue\ truck} -$ equivalent single moment due to fatigue truck.

This equation allows determining the cost of one passage of permit vehicles on the particular bridge. The consumption given by Equation 2 is the total dollar damage for a permitted vehicle, and it includes the consumption that would be allowed without a permit if the vehicle met the legal load limits. In fairness, it is necessary to calculate incremental consumption, which can be expressed as the permit consumption minus the legal consumption by using:

$$Incremental\ Consumption = Consumption_{permit} - Consumption_{legal} \tag{3}$$

The legal consumption can be assessed for every permit vehicle configuration and Federal Bridge Formula. The legal vehicle configuration can be assessed for all possible axle combinations.

Therefore, the incremental consumption can be calculated using the following steps:

1). Run permit vehicles over an influence line to obtain a bending moment history.
2). Use a rainflow counting to determine the number and magnitude of load cycles from the bending moment history and calculate the equivalent single cycle moment.
3). Determine the equivalent single moments for the AASHTO fatigue truck and the legal vehicle.
4). Calculate the incremental consumption for permit vehicle.
5). Determine a monetary bridge consumption.

The proposed incremental consumption approach is not intended to be an exact analysis of the consumption of the remaining life until structural failure. However, the goal is to provide a simple approach that captures the relative amounts of the consumption or deterioration of the AASHTO bridge design life caused by a wide range of overloaded permit vehicles. The fundamental assumption of the proposed method is that the life of the bridge is defined by 75 years of crossings by the AASHTO fatigue design truck.

5. Monetary Consumption

Using the incremental consumption approach, and a specific route with known bridge parameters, the monetary consumption calculations were performed. A random permit vehicle with GVW of 62 tonnes and six axles of 7.25, 10.4, 10.0, 12.25, 10.8, 11.3 tonnes, with the axle spacings of 5.0, 1.5, 5.5, 1.5, 1.5 m was used to determine a monetary bridge consumption.

Table 1 presents characteristics of eight bridges in Florida such as maximum span length to determine equivalent single moment values, Average Daily Truck Traffic (ADTT), deck area, and Florida specific cost in $/m^2 to determine the bridge construction cost.

Afterward, the moments' effects were computed for all bridges, for simply supported beam based on bridge maximum span length. This approach does not reflect the real bridge support conditions, but due to the lack of available data in the NBI database about consecutive span length, the maximum span length is used.

Table 1 Bridge characteristics for sample bridges in Florida.

No.	Bridge Type	Max Span Length [m]	ADTT per lane	Deck Area [m^2]	Cost [$/m^2]	Bridge Construction Cost
1	P/C Segmental Box	3.0	1714	25,169	$ 1,647	$ 41,449,536
2	Steel Girder	3.0	2786	16,151	$ 1,722	$ 27,816,000
3	P/C Cont. Girder	10.4	308	8,828	$ 1,647	$ 14,538,825
4	P/C Girder	3.0	795	559	$ 1,270	$ 710,006
5	P/C Girder	4.6	185	12,668	$ 1,270	$ 16,090,362
6	Steel Cont. Girder	9.1	2193	8,596	$ 1,970	$ 16,933,173
7	P/C Girder	81.2	2101	9,915	$ 1,270	$ 12,592,842
8	P/C Girder	81.2	2101	13,632	$ 1,270	$ 17,314,612

Table 2 Individual incremental bridge consumption.

No.	Moment fatigue truck [kNm]	Moment legal truck [kNm]	Moment permit truck [kNm]	Legal Consumption	Permit Consumption	Incremental Consumption
1	105.9	79.3	110.3	$ 0.32	$ 1.02	$ 0.70
2	109.6	83.0	115.8	$ 0.16	$ 0.43	$ 0.27
3	334.7	405.4	689.3	$ 3.37	$ 21.61	$ 18.24
4	105.9	79.3	110.3	$ 0.01	$ 0.04	$ 0.03
5	148.2	149.0	219.1	$ 3.24	$ 12.48	$ 9.24
6	330.9	371.4	593.0	$ 0.40	$ 1.62	$ 1.23
7	4611.8	6179.0	11278.5	$ 0.61	$ 5.01	$ 4.40
8	4611.8	6179.0	11278.5	$ 0.84	$ 6.88	$ 6.05

Table 2 presents bridge consumption costs for a random truck and various types of bridges. The approach uses the relative damage, which justifies the use of simply supported beams. It allows determining legal and permits monetary consumption, using bridge construction cost and a number of cycles during the service life of the bridge using bridge ADTT per lane. The permit fee for the selected truck and specific route with known parameters would be $40.16.

6. Conclusions

An incremental consumption method was developed to assess bridge life reduction under overloaded permit vehicles. The conclusions are summarized as follows:

The incremental consumption formula allows calculating the monetary consumption of bridges. It captures bridge design life reduction caused by a permit truck.

The developed equation provides a simple approach that captures the relative amounts of bridge design life reduction caused by permits.

The bridge life is defined by 75 years of crossings of the AASHTO fatigue design truck. Therefore, the monetary loss is represented by the cost of new bridge construction.

The consumption method is transparent, and may be used by any state, using state-specific available databases (WIM, permit, NBI, and bridge cost databases).

The use of massive permit and bridge databases provides reliable results and a rational basis for determining new bridge permit fees.

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