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Deterioration Analysis of Concrete Bridges Under Inadmissible Loads from the Fatigue Point of View

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Despite the importance of the effects of inadmissible loads in the reduction of the life cycle and operation time of bridges, there is no scientific and systematic procedure for the deterioration analysis of bridges under overloaded vehicles. The main objective of this article is to outline a methodology for determining the damage effects of inadmissible loads on concrete bridge decks, considering the fatigue effect. With recourse to the fatigue phenomenon, the relationships between the passing loads and the number of allowable load cycles were determined. These relationships were the bases for constructing models by which the deterioration ratios of concrete bridges could be assessed and, consequently, the amount of fines for vehicles can be calculated.

INTRODUCTION

The amount and frequency of loading are among the most important parameters to be considered in the design and the deterioration pattern of bridges [1]. Despite this fact, not enough attention is paid to the loading system, inadmissible loads and the effect of excess loads might have on the life cycle of bridges. Developed countries face this problem to a lesser extent because they have good access to aerial and rail transportation. About 90% of heavy freight is carried on trains, leaving only 10% to be carried on city roads and highways. In Iran, on the contrary, the transportation of heavy freight by train does not exceed 20% at most. The statistics in this regard indicate the following problems [2]:

1. Roads and highways in Iran are not developed sufficiently;
2. Sound distribution patterns for load transportation do not exist;
3. The excess loads on Iranian highways are tremendous being mostly in the form of rocks and iron being carried in heavy trucks and trailers whose axles are structurally low in number, according to international standards.

There are two solutions for the reduction of inadmissible loads. The first and the most crucial one is to improve the transportation system by developing more branches of transportation, increasing the bearing capacity of pavements and bridges, considering more traffic loads in the design process and by improving heavy vehicle structures by adding to the number of axles in order to distribute loads evenly. The second solution is to set ticketing regulations for overloaded vehicles, by which offenders would compensate for damages. Regarding the second solution, there is no systematic procedure, leaving the current one to be based on personal judgment and directives whose scientific and analytical background is doubtful. This research has been made towards this need, aiming at an investigation into the deterioration pattern of concrete bridges under excess loads from a fatigue point of view. In this article, first, bridges and vehicles are classified in some certain groups, second, fatigue criterion is discussed and third, bridge modeling procedures, software implementation and loading systems of bridges are explained. Then, analysis results are used to find bridge deterioration models, which are used to obtain scientific models for ticketing.

BRIDGE AND VEHICLE CLASSIFICATIONS

Inspections indicate that the condition of concrete bridges in Iran is not satisfactory, being due to many

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causes, including environmental conditions and inadmissible loads. Of course, the lack of documented directives for investigation and lack of due attention paid to the issue have intensified the problem [3]. To come up with an applicable ticketing model, it is necessary to consider the classification of bridges and vehicles. There are four groups of bridges in Iran [4]:

1. One-span concrete bridges under 4 m in length,
2. One-span concrete bridges between 4 to 8 m in length,
3. Two-joint span bridges over 10 m in length,
4. Three-joint span bridges over 10 m in length.

About 90% of the bridges fall into one of the above-mentioned categories.

On the other hand, excessively loaded trucks in Iran fall into the following three groups, which make up about 95% of the trucks traveling the roads [5]:

1. 2-axle trucks (19 tons),
2. 3-axle trucks (26 tons),
3. 5-axle trailers (40 tons).

Axle loading and geometrical arrangement of axles for the above trucks are presented in Figure 1.

DAMAGE CRITERIA

Generally, the damage occurring in concrete bridges under inadmissible loads falls into three categories [6]:

a) Cracks beneath the beams and slabs,
b) Extra settlement of bridge slabs,
c) Extra vibration of bridge under passing loads.

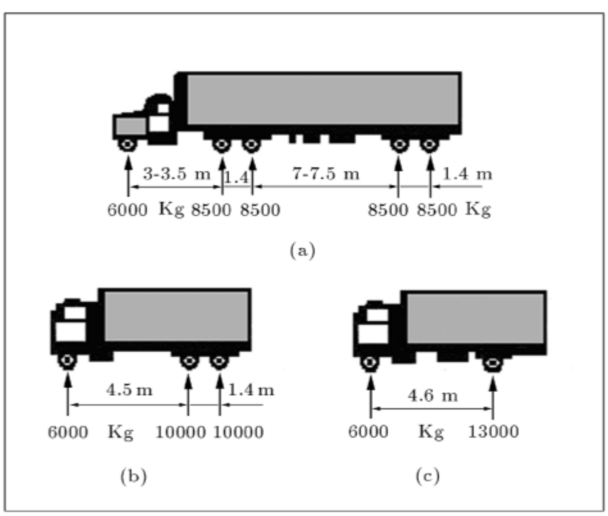

Figure 1. (a) 5-axle trailers; (b) 3-axle trucks and (c) 2-axle trucks.

With regard to the mentioned damage, the following criteria could be considered when studying the effects of overload in bridge deterioration [7,8]:

a) Increased proportion of stresses and strains caused by overload compared to those caused by acceptable loads,
b) Growth of crack widths caused by the passing of overloaded trucks,
c) The speed of bridge fatigue.

Due to the consideration of a large safety factor in the design of concrete bridges (for strength, durability and serviceability), as well as the limitation of existing excess loads (up to 50% of the total admissible loads), the third item (fatigue) is more effective when investigating concrete bridge deterioration [2]. Therefore, in this research, fatigue is chosen as the damage criterion.

FATIGUE CRITERION

Repeated loads lead to fatigue, which may cause cracking and, eventually, failure. Fatigue initiates at either a notch or because of an internal defect and the behavior involves changes within the crystal structure [9]. These eventually cause the initiation of a crack that spreads. The net section of the member is reduced and, finally, failure occurs, either by brittle fracture or in a ductile way [10]. Fatigue performance is commonly represented on graphs of stress ranges with the number of failure cycles [11]. To assess fatigue performance in this article, the Goodman diagram is used (Figure 2). This diagram has been mainly developed to investigate the fatigue performance of concrete materials [11].

In the Goodman diagram, the ratio of maximum stress, due to live and dead load, to the allowable stress

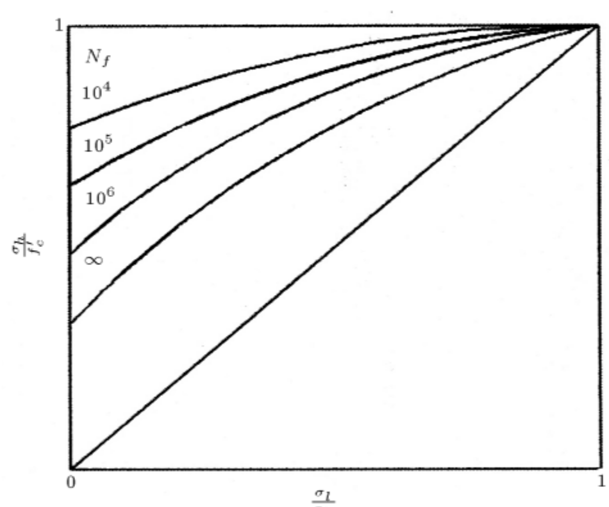

Figure 2. The Goodman diagram.

(σ_h/f'_c) is drawn against the ratio of the maximum stress, due to dead load, to the maximum stress, due to live and dead load (σ_l/σ_h). This diagram is sketched for a different number of load cycles (N_f).

Based on this figure, having the ratio of maximum stress, due to live and dead load, to the allowable compression stress (σ_h/f'_c), and the ratio of maximum stress, due to live and dead loads, to the maximum stress, due to dead load (σ_h/σ_l), one can obtain the number of allowable load cycles (N_f). In Figure 2, σ_l is the maximum stress caused by dead load, σ_h is the maximum stress caused by both live and dead loads, f'_c is the allowable compressive stress of concrete and N_f is the number of allowable load cycles. As shown, when the stress is increased, the allowable load cycles are decreased. It means that by the passing of more excess loads, the bridge life cycle is reduced.

FEM MODELS AND THE IMPLEMENTED SOFTWARE

According to the classification of bridges given above, three models are presented. They include a one-span concrete bridge with 4 m length (representative of the first group of bridges), a one-span concrete bridge with 8 m length (representative of the second group of bridges) and a two-span concrete bridge with 20 m length (representative of the third group of bridges). For modeling the bridges, the SAP2000 software was used, due to its fast processing and high accuracy. This software provides a finite-element-based structural program for both the analysis and design of civil structures. The first and second group of bridges were modeled using shell elements with a mesh size of 20 × 20 cm. The use of shell elements is due to the presence of the solid slabs of the bridges without girders. The third group was modeled as a frame element (detailed in [9]), because of the presence of longitudinal beams and diaphragms. The diaphragms are also modeled with a mesh size of 20 × 20 cm.

LOADING PATTERN

Using the Goodman diagram necessitates analyzing the bridge groups once under dead loads and once more under both dead and live loads. The dead load arises from bridge weight and the live load from both passing vehicles and the 139 Iran Loading Code [4]. According to this code, the most critical condition is met when the bridge is completely covered by the maximum allowable loads and the overloaded vehicle passes.

ANALYSIS

In this study, from among three common methods of analysis and design of concrete structures, the "Working Stress Method" was chosen. According to this method, which is based on linear solid mechanic theories, a structural member is designed and analyzed in such a way that the service load stress does not exceed the allowable stress. The mentioned service load includes both dead and live loads being effective during the operation time of the structure. The allowable stress is obtained by dividing the ultimate stress of the material to the safety factor. In this article, the elasticity module of 21 GPa and the Poisson ratio of 0.35 were selected. The concrete compressive stress was chosen to be 20 MPa, according to the AASHTO Code [12].

RESULTS

Modeling and analyzing data from the sample bridges led to the following results: The maximum stresses of dead loads for 4, 8 and 20 m bridges were 0.954, 2.203 and 4.083 MPa, respectively. The results of other analyses are presented in Tables 1 to 3. The maximum stresses in these tables refer to the maximum compression stresses that occur in the concrete and which are obtained from analyses of the bridge using the software (SAP 2000).

Table 1. The results of the analyses of the first bridge group (4 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$
10	68.84	10	65.2	20	65.8
15	74.45	20	73.38	30	70.21
19	79.5	26	78.29	40	74.63
20	80.61	30	82.54	50	79.81
26	86.59	40	93.14	60	84.9
30	92.47	50	103.81	70	90.16
35	98.38	60	114.45	80	95.64

Table 2. The results of the analyses of the second bridge group (8 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$
10	57.83	10	56.94	20	57.74
15	60.57	20	61.5	30	60.43
19	62.76	26	64.23	40	63.11
20	63.3	30	66.6	50	66.07
26	66.03	40	72.53	60	69
30	68.76	50	78.46	70	71.98
35	71.49	60	84.36	80	74.94

Table 3. The results of the analyses of the third bridge group (20 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$	Vehicle Weight (Ton)	Maximum Stress $\frac{kg}{cm^2}$
10	76.76	10	76.77	20	78.77
15	79.24	20	81.70	30	82.08
19	81.22	26	84.66	40	85.69
20	81.71	30	86.88	50	88.99
26	84.17	40	92.44	60	92.35
30	86.63	50	98.01	70	96.02
35	89.10	60	103.57	80	99.40

DETERIORATION MODELS

Using the Goodman diagram makes extracting the allowable load cycles possible. Separating the ratio of $\frac{\sigma_l}{\sigma_h}$ on the horizontal axis from the ratio of $\frac{\sigma_h}{f'_c}$ on the vertical axis gives rise to a point in the diagram that shows the number of allowable load cycles, N_f. Assuming that a vehicle has the allowable vehicle load of P_{all} and the allowable load cycle of $(N_f)_{\text{all}}$, it can be stated clearly that an increase in the vehicle load to $P + \Delta P$ will decrease the allowable load cycles from $(N_f)_{\text{all}}$ to N_f. Hence, the $\frac{N_f}{(N_f)_{\text{all}}}$ ratio will show a reduction in the allowable load cycles or, generally, the life cycle of the bridge. If the life cycle of the bridge under allowable loads is equal to 1, the new life cycle of the bridge under inadmissible loads is calculated using the following formula:

$$L_{\text{LN}} = 1 \quad \frac{N_f}{(N_f)_{\text{all}}}. \tag{1}$$

The above equation shows the ratio of the reduction of the life cycle of bridges when M number of trucks passes. Dividing the figure to the total number of passing trucks with excess loads (ΔP) gives rise to the rate of reduction of the life cycle of the bridge for every single truck. Thus, the life cycle reduction ratio (i.e., deterioration ratio) for overloaded vehicles can be calculated using the following formula:

$$F = \frac{1}{N_f} \quad \frac{1}{(N_f)_{\text{all}}}. \tag{2}$$

In the above equations, P is the truck load, ΔP is the truck excess load, L_{LN} is the new life cycle of the bridge under inadmissible loads (when the life cycle of the bridge under allowable loads is equal to 1), $(N_f)_{\text{all}}$ is the allowable load cycles related to P, N_f is the increased allowable load cycles related to $P+\Delta P$ and F is the life cycle reduction ratio (deterioration ratio) for overloaded vehicles. To present a mathematical model, at first, the allowable load cycles were determined using the maximum dead and live stresses of the analyzed bridges (Tables 4 to 6) and, then, the $P \quad N_f$ figures were drawn to make the horizontal and vertical axes represent the vehicle loads and the allowable load cycles, N_f, respectively. Finally the diagrams were processed using Excel software and mathematical equations were drawn, based on the least squared errors (Figures 3 to 5). If one substitutes $(N_f)_{\text{all}}$ and

Table 4. The allowable load cycles (N_f) of the first bridge group (4 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight	N_f	Vehicle Weight	N_f	Vehicle Weight	N_f
10	9.10E+05	20	5.43E+05	20	1.80E+06
15	4.35E+05	26	1.00E+05	30	7.82E+05
19	8.90E+04	30	6.00E+04	40	4.10E+05
20	8.00E+04	40	5.50E+03	50	8.95E+04
25	1.75E+04	50	4.10E+02	60	4.00E+04

Table 5. The allowable load cycles (N_f) of the second bridge group (8 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight	N_f	Vehicle Weight	N_f	Vehicle Weight	N_f
15	1.05E+08	20	9.28E+07	30	9.48E+07
19	8.88E+07	26	5.20E+07	40	7.58E+07
20	6.54E+07	30	2.05E+07	50	2.21E+07
25	4.55E+07	40	6.25E+06	60	9.00E+06
30	1.10E+07	50	8.78E+05	70	7.00E+06

Table 6. The allowable load cycles (N_f) of the third bridge group (20 m span).

Vehicle Type					
2-Axles (19 Tons)		3-Axles (26 Tons)		5-Axles (40 Tons)	
Vehicle Weight	N_f	Vehicle Weight	N_f	Vehicle Weight	N_f
15	8.82E+07	20	3.0E+07	30	1.0E+07
19	2.10E+07	26	6.67E+06	40	2.61E+06
20	3.25E+07	30	2.15E+06	50	7.69E+05
26	6.70E+06	40	2.31E+05	60	2.31E+05
30	2.00E+06	50	1.54E+04	70	7.45E+04

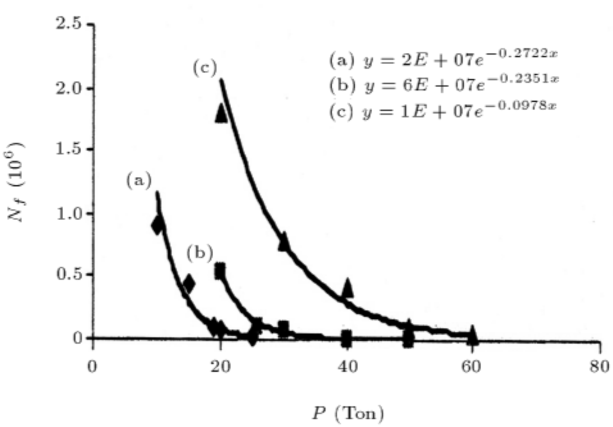

Figure 3. Load values vs. allowable load cycles of the first bridge group (4 m span); (a) 2-axle vehicle, (b) 3-axle vehicle and (c) 5-axle vehicle.

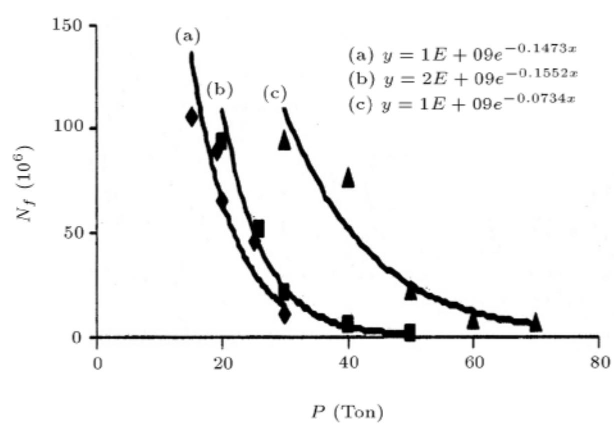

Figure 4. Load values vs. allowable load cycles of the second bridge group (8 m span); (a) 2-axle vehicle, (b) 3-axle vehicle and (c) 5-axle vehicle.

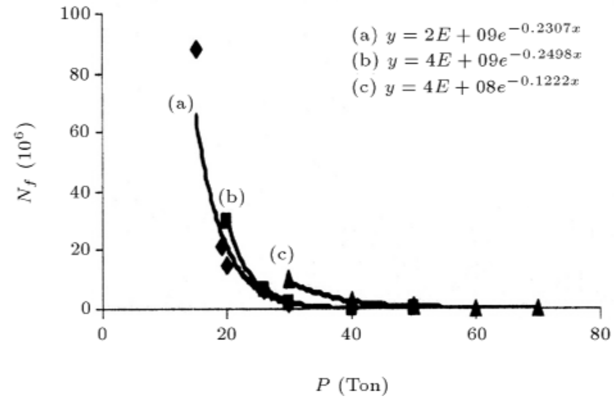

Figure 5. Load values vs. allowable load cycles of the third bridge group (20 m span); (a) 2-axle vehicle, (b) 3-axle vehicle and (c) 5-axle vehicle.

N_f in the above equations with the consideration of P N_f figures, new relations will be obtained between the allowable load cycles and the load values. Final models whose indexes show bridge and vehicle type, are presented in Table 7.

TICKETING MODELS OF OVERLOADED TRUCKS

By defining the bridge deterioration models under inadmissible loads and multiplying the obtained sum by the total cost of the bridge construction gives rise to the ticketing amount, i.e., $S = F \times L \times M$. Where, L is the bridge total length in m, M is the bridge construction value per meter, F is the bridge deterioration ratio and S is the ticketing sum. The final obtained models for classified bridges and vehicles are presented in Table 8. In this table, ΔP is the excess load, $\propto$ is the distribution coefficient of vehicle axles, β is the bridge importance coefficient, γ is the reconstruction difficulty coefficient ($\propto$, β and γ are defined by road and transportation offices) and Q is the offending ticketing amount that should be defined by the police force.

NUMERICAL EXAMPLE

To show the application of the models, a road between Bandar Abbas and Tehran was chosen and the payable ticket sum of classified vehicles for different bridge groups i.e., Bandar Abbas-Haji Abad bridge with 4 m span, Darab-Bandar Abbas bridge with 8 m span and Ramjerd-Salafchegan bridge with 20 m span were determined. They are presented in Figures 5 to 8. The $\propto$, β and γ coefficients were assumed to be equal to one and the bridge construction costs per meter for 4, 8 and 20 m span bridges were calculated to be 60, 90 and 150 million Rials, respectively. The relevant ticketing sum was determined to be 50 thousand Rials. The results obtained are much higher than the amount of fines, which is currently issued by the road authorities (detailed in [3]).

As shown, for the first bridge group, the 2 axle vehicles cause the maximum amount of damage. For the second and third bridge groups, the 3 axle vehicles are the most critical. This is because of the amount

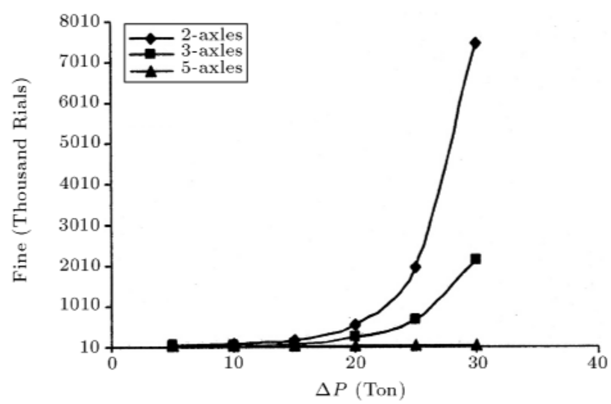

Figure 6. Ticketing sum of Bandar Abbas-Haji Abad bridge (4 m span).

Table 7. Deterioration models.

Bridge Group	Vehicle Type	Deterioration Percentage
1 (4 meter span)	2-axles (19 tons)	$F_{1T19} = 8.81 \times 10^{\ 6}(e^{0.2722\Delta P}\quad 1)$
	3-axles (26 tons)	$F_{1T26} = 7.53 \times 10^{\ 6}(e^{0.2351\Delta P}\quad 1)$
	5-axles (40 tons)	$F_{1T40} = 5 \times 10^{\ 6}(e^{0.0978\Delta P}\quad 1)$
2 (8 meter span)	2-axles (19 tons)	$F_{2T19} = 1 \times 10^{\ 8}(e^{0.1473\Delta P}\quad 1)$
	3-axles (26 tons)	$F_{2T26} = 2.82 \times 10^{\ 8}(e^{0.1552\Delta P}\quad 1)$
	5-axles (40 tons)	$F_{2T40} = 1.88 \times 10^{\ 8}(e^{0.0734\Delta P}\quad 1)$
3 (20 meter span)	2-axles (19 tons)	$F_{3T19} = 4 \times 10^{\ 8}(e^{0.2307\Delta P}\quad 1)$
	3-axles (26 tons)	$F_{3T26} = 1.66 \times 10^{\ 7}(e^{0.2498\Delta P}\quad 1)$
	5-axles (40 tons)	$F_{3T40} = 3.32 \times 10^{\ 7}(e^{0.1222\Delta P}\quad 1)$

Table 8. Ticketing models.

Bridge Group	Vehicle Type	Fine Models
1 (4 m span)	2-axles (19 tons)	$S_{1T19} = 8.81 \times 10 \ ^{6} \propto \times \beta \times \gamma (e^{0.2722 \Delta P} \quad 1) ML + Q$
	3-axles (26 tons)	$S_{1T26} = 7.53 \times 10 \ ^{6} \propto \times \beta \times \gamma (e^{0.2351 \Delta P} \quad 1) ML + Q$
	5-axles (40 tons)	$S_{1T40} = 5 \times 10 \ ^{6} \propto + \beta + \gamma (e^{0.0978 \Delta P} \quad 1) ML + Q$
2 (8 m span)	2-axles (19 tons)	$S_{2T19} = 1 \times 10 \ ^{8} \propto \times \beta \times \gamma (e^{0.1473 \Delta P} \quad 1) ML + Q$
	3-axles (26 tons)	$S_{2T26} = 2.82 \times 10 \ ^{8} \propto \times \beta \times \gamma (e^{0.1552 \Delta P} \quad 1) ML + Q$
	5-axles (40 tons)	$S_{2T40} = 1.88 \times 10 \ ^{8} \propto \times \beta \times \gamma (e^{0.0734 \Delta P} \quad 1) ML + Q$
3 (20 m span)	2-axles (19 tons)	$S_{3T19} = 4 \times 10 \ ^{8} \propto \times \beta \times \gamma (e^{0.2307 \Delta P} \quad 1) ML + Q$
	3-axles (26 tons)	$S_{3T26} = 1.66 \times 10 \ ^{7} \propto \times \beta \times \gamma (e^{0.2498 \Delta P} \quad 1) ML + Q$
	5-axles (40 tons)	$S_{3T40} = 3.32 \times 10 \ ^{7} \propto \times \beta \times \gamma (e^{0.1222 \Delta P} \quad 1) ML + Q$

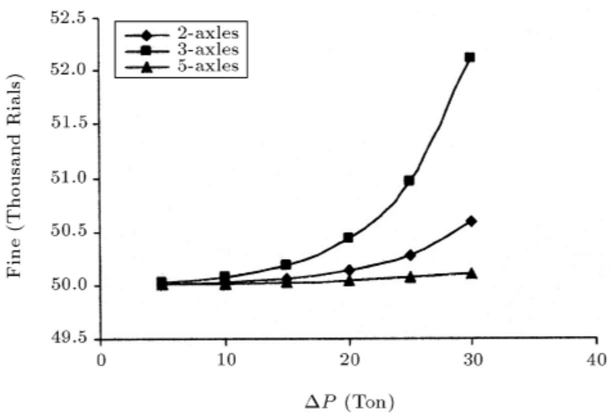

Figure 7. Ticketing sum of Darab-Bandar Abbas bridge (8 m span).

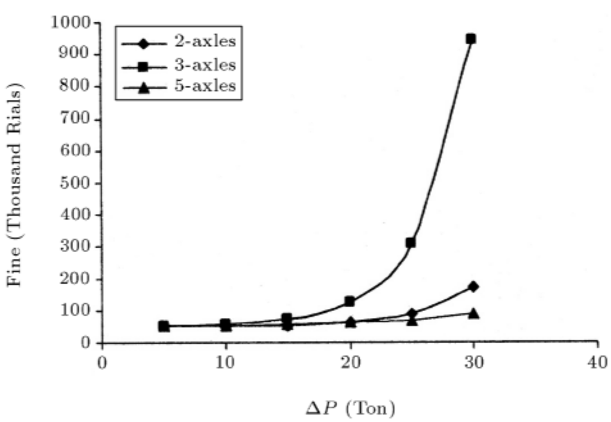

Figure 8. Ticketing sum of Ramjerd-Salafchegan bridge (20 m span).

and distribution of the vehicle loads on different span lengths.

CONCLUSION

This paper presents models for the deterioration ratios of concrete bridges under overloaded vehicles and the related ticketing sums. To calculate the bridge damage under overloaded vehicles, a fatigue criterion was chosen using the Goodman diagram by which the number of allowable load cycles against stress ranges can be obtained. To reach a relationship between excess loads and allowable load cycles, the numbers of allowable load cycles were defined using maximum stresses. Then, the life cycle reduction ratios (deterioration models) for overloaded vehicles were calculated and, consequently, the models for ticketing the offending trucks were presented. To show the applicability of the models, a numerical example is presented. The results indicate that the amount of fines issued by the road authorities is much less than that calculated here. Construction of the ticketing models is based on only damage to the bridges, while the main damage caused by overloaded vehicles is on the road pavements. To complete this study, one has to investigate the damage on asphalt pavements. Adding these two parts will provide the total excess load damage to roads and bridges, which will lead to a comprehensive ticketing model. Research in this field is in progress.

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