Safety Evaluation of Reinforced Concrete Highway Bridges Under Overloaded Truck Traffic: A Data-Driven Assessment Using Static Weighing Station Records

Yisihak Gebre Tarekegn [1,*], Biniam Wessenseged [2], Abrham Gebre [1], Getu Segni [1] and Asmerom Weldegerima[1]

[1] *School of Civil and Environmental Engineering, College of Technology and Built Environment, Addis Ababa University, Addis Ababa, Ethiopia*

[2]*Save the Children International, Addis Ababa, Ethiopia*

[*]*Corresponding Author's E-mail address: yisihak.gebre@aau.edu.et*

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ABSTRACT

Assessing performance assessment of reinforced concrete (RC) highway bridges subjected to overloaded truck is important in maintaining safety and sustainability of transport infrastructures. These trucks cause threat to bridges and lead to deterioration if not managed. The framework of assessment consists of structural analysis techniques, load rating methodologies, condition assessment procedures, and risk evaluation criteria. Studies showed that bridges in Ethiopia are overloaded and hence, in this study, a comprehensive safety assessment of selected RC highway bridges subjected to overloaded truck is presented. Nine RC girder bridges found along the selected routes have been considered for investigation. To investigate the effects of overloaded vehicles on Ethiopian bridges, 51,900 actual truck loading data from three static weighing stations (SWS) were collected over a period of five years. Rating factors for bridges were determined based on legal loads, actual truck load data, and extrapolated load data, taking into account the estimated remaining service life of the bridges and possible future reinforcement corrosion. The results revealed that, on average, 16.3 % and 33.85 % of the trucks violated the limit set on national regulation and bridge formulas, respectively. In addition, the rating factors for the bridges were reduced by 30.18 % and 56.29 % for the actual truck load data and extrapolated load data, respectively, compared to the legal loads. The result showed the bridges' performance is severely affected and hence enforcing the current law and developing appropriate mitigation strategies are recommended.

Keywords: Bridges, Overloaded trucks, RC, Rating factors, Safety, SWS.

1. INTRODUCTION

1.1 Overloaded Trucks

Overloaded trucks on bridge structures create difficulty due to the growing business activity and rising need for transportation infrastructure. Moreover, the susceptibilities of RC highway bridges to truck traffic are made worse by elements like aged infrastructure, poor maintenance methods, and changing regulatory standards. Engineers and researchers have created thorough methods and strategies for evaluating the performance of bridges under truck loads that are too heavy in response to these issues. These procedures include complex load rating techniques [1], sophisticated structural analysis tools, condition assessment techniques [2], risk evaluation criteria, and mitigation measures that are specifically designed to meet the requirements of highway bridges made of RC [3], [4].

The Ethiopian Roads Administration (ERA) has employed a rating legal truck model for the structural evaluation of highway bridges [5] which was adopted from [6]. This model can be used as a standard load for the safety evaluation of bridges in general but fails to represent the actual loading conditions of the country as there is a significant change in truck loads [7]. This has significant impacts on the safety, reliability, and maintenance of bridge structures and systems. Hence, a site-specific live load model which accounts the loading conditions of the country must be employed. The reliability of RC highway bridge is extremely important for uninterrupted and safe traffic flow. In Ethiopia, however, the increasing tendency to overloaded vehicles poses threats to these critical structures. These trucks not only put excess weight on bridges but also lead to potential failures.

Safety evaluation of RC girder bridges for the overloaded vehicles is paramount to ensure the structure's integrity and safety to the public. Using the methods of visual inspections, non-destructive tests (NDT), load testing and continuous monitoring, one can predict and prevent the risks associated with loading in structural systems. Applying design improvements, appropriate overload management techniques, and strict maintenance procedures can greatly enhance the durability and reliability of such structures [8]-[10]. Timely safety evaluation of bridges reduces rehabilitation costs and avoids unnecessary replacement of highway structures that are still in serviceable condition [11]. Several authors have paid much attention on research on the impact of overloaded trucks on performance of bridges. Increased stresses from overloads and accelerated material degradation caused by corrosion reduce the service life of bridges and pose a threat to safety and operational performance [12], [13].

Evaluation of existing bridges in Texas built in the 1950s and 1960s was conducted using the LRFR (Load and Resistance Factor Rating) method recommended by AASHTO (American Association of State Highway and Transportation Officials). The findings revealed that the calculated rating factors are lower than those required for the minimum design vehicle specified in the Manual for Condition Evaluation of Bridges (MCEB) [14]. In a similar study conducted in New York state, bridge load ratings were performed, revealing that the LRFR legal load rating factors were 53% higher than the inventory legal load factors determined using the LFR (Load Factor Rating) method [15].

1.2 Data Extrapolation

In some cases, heavy trucks may have bypassed the weighing stations and critical data may not be recorded. To account these missed data, extrapolation of the recorded extreme vehicle loadings is usually done, commonly, the maximum load effects which could occur within a 75-year return period [16]. There are basically several scenarios for selecting population size [17], [18]. Among them, the block maxima method grouped the data on a monthly basis and one extreme data is selected from each month [19]. Castillo's approach uses the top $2\sqrt{n}$ data [20], and Enright's fitting method selects the top 30% data [7], [21].

In extrapolating the traffic data, in this study, a Sivakumar extrapolation approach is selected over other extrapolation methods as the method was developed specifically for highway bridges to estimate maximum live load effects (like bending moment or shear force) for long return periods (e.g., 75 or 100 years) [22] and its practical suitability for estimating extreme bridge load effects using limited high-end traffic data [23]. Moreover, it provides a simplified empirical model based on observed traffic load effects, extrapolating rare extreme events through a fitted curve with reasonable accuracy, and has been successfully applied in the load rating of bridge structures [22]. Whereas generalized extreme value-based methods and block maxima techniques typically require extensive, continuous data and rely on specific distribution assumptions [23], [24]. Similarly, Enright [18] used data extrapolation by fitting a Weibull extreme value distribution to extrapolate bridge load effects which involve reliability-based formulations, making them data- and computation-intensive.

Hence, in the present study, extrapolated bending moment and shear force for a return period of 75 years were calculated using Eqn. (1) [25].

$$\mu_{max} = \mu + \sigma\sqrt{2\ln(N)} - b$$
$$b = \sigma\frac{\ln[\ln(N)] + \ln(4\pi)}{2\sqrt{2\ln(N)}} \quad (1)$$

Where N is the number of data in a specific return period, μ_{max} is the extrapolated mean value and σ is the standard deviation.

1.3 Reinforcement Corrosion

In addition to increasing load intensity, corrosion of reinforcing steel reduces cross-sectional area, which affects load-carrying capacity and structural integrity. Corrosion-induced expansion can also cause concrete to crack and spall, resulting in reduced serviceability [26]. In the case of RC bridges, corrosion significantly affects the rating factor and overall performance of the structure [13]. Furthermore, the study concludes that RC bridge decks experience increased longitudinal and transverse cracking due to overloads, which accelerates corrosion and structural deterioration [13]. A similar study on the service-life estimation of RC bridge structures exposed to chloride-induced reinforcement corrosion and variable traffic loads have been conducted. The findings indicate that the structural lifetime is significantly affected, with reductions ranging from 30% to 35%, and up to 70% in cases of high-frequency cyclic loading [27]. Hence, it is vital in analyzing how the bridge performs over time in relation to factors such as corrosion of reinforcing bars and variable load effects.

Since chloride-induced corrosion is primarily a concern in marine environments with high chlorine content in seawater [28], and Ethiopia is not exposed to such conditions, this study focuses on carbonation-induced corrosion as a dominant corrosion mechanism. Carbonation-induced corrosion with an exposure class of moderate humidity, i_{corr} of 0.10 to 0.20 μA/cm^2 [29] has been used. The attach penetration and the reduced diameter of reinforcement bars by corrosion are to be estimated from Eqs. (2) and (3), respectively [30].

$$P_x(t) = 0.0116\, I_{corr}\,(t - t_o)\,,\ t > t_o \quad (2)$$

$$\phi(t) = \phi_0 - \alpha P_x(t) \quad (3)$$

Where, $\phi\ (t)$ is residual diameter at time t (mm), ϕ_0 is the initial bar diameter (mm), a is equal to 2 (for carbonated concrete), $P_x(t)$ is the average decrease of bar radius at time t, in mm, t_o is the time of corrosion initiation (years), t is elapsed time (years) and I_{corr} is the corrosion rate (μA/cm^2).

Corrosion of reinforcing bars significantly affects their mechanical properties, leading to a reduction in yield strength and it is computed from Eq. (4) [31]:

$$f_y(t) = \left(1 - \alpha\frac{A_s - A_s(t)}{A_s}\right) f_y \quad (4)$$

Where $f_y(t)$ is the residual yield strength of steel reinforcement, $A_s(t)$ is the residual area of steel reinforcement, A_s is an initial area of steel reinforcement and f_y is an initial yield strength of steel reinforcement and α is a yielding strength uncertainty coefficient (with a mean value of 0.5 and coefficient of variation of 12 %) [31].

The objective of this research was to evaluate the safety of reinforced girder bridges under various loading conditions with the specific focus on overloaded vehicles. This research employs collected data from weighing stations to provide a systematic approach in evaluating the impact of heavy trucks on bridges. The conclusion made in this research revealed that overloaded vehicles have been identified to reduce the rating factors of RC bridges in Ethiopia by 23 %. The study also estimated that if the current trend of overloading and corrosion of reinforcing bars continues without the necessary monitoring and intervention, it would reduce the load carrying capacity of the bridges to 43 % as compared to their capacity under the legal loads. This significant reduction highlights the vulnerability of structural degradation over time. Thus, examining the effects of overloaded trucks on bridges and future possible corrosion of reinforcing bars aimed at raising awareness on the need for rigorous regulation and proper preventive measures towards enhancing the public safety.

2. METHODOLOGY

2.1 Data Collection

Traffic data, including truck loads, was acquired from three SWS sites; Modjo, Semera, and Sululta, over five-year period (Jan. 2018 to Dec. 2022) and more than 60,000 heavy trucks data were collected. Location of selected SWS sites is shown in Figure 1. The sites were chosen because there is a lot of heavy vehicle movement and those routes are where the majority of the country's economic transactions take place.

Figure 1 Location of weighing station sites.

2.2 Data Cleaning

The data were organized, filtered from erroneous records and the quality of the data was checked using the methodology and criteria provided in [32], [33]. Among the collected data, 51,900 were considered for analysis using the following criteria:

- trucks with a front axle weight of less than 3 tons were excluded as the minimum front axle weighs 3 ton to 4 ton [34], [35]
- vehicles with $GVW \geq 1.1\sum A_i$ or $GVW \leq 0.9\sum A_i$ were cleared [32]; where A_i is the i^{th} axle weight and GVW is the gross vehicle weight

An algorithm on Python software was developed to compute the impact of loads caused by moving vehicles. The program was prepared to produce all possible combinations taking into account varied bridge spans, axle arrangements, and axle weights and calculate the maximum load effects induced by vehicles. This tool enabled efficient simulation of critical load scenarios for different span lengths and the results were validated with hand calculations. To account future impacts, the live load was extrapolated for the remaining design period of the bridges. For the purpose of this research, the following methods were used; i) data collection and bridge inventory ii) traffic data analysis and iii) load rating analysis.

2.3 Bridge Selection

Bridge selection for evaluation is based on specific criteria to ensure a representative evaluation. In the present study, the Alemgena district has been selected as a critical area as it accounts for 74.3% of the collected truck load data, totaling 38,562 records. This substantial dataset provided a robust foundation for assessing the impact of traffic loads on bridges. Nine RC bridges from five road segments were selected with the following selection criteria:

- *Traffic exposure*: preference was given to bridges located along routes with high truck traffic intensity.
- *Age of structure*: bridges over 50 years old were prioritized to evaluate deterioration patterns and the impact of aging on structural load capacity. In addition, relatively newer bridges with an age of around 10 years were also included to enable performance comparison across different service life stages.
- *Span length*: bridges with a span length of 15 meters (each span) and above were selected, as this length accommodates the full front-to-rear axle spacing of a 7-axle truck, which measures approximately 15.0 m as indicated in Table 1.
- *Span type*: different span types were considered.
- *Structural type consistency*: only RC girder bridges were selected to ensure uniformity in load analysis and rating methodology.

The identified bridges and some of the pictures from ERA Bridge Management System (BMS) [36] are shown in Table 1 and Figure 2, respectively.

Table 1 Bridge data

Bridge Id.	Bridge name	Bridge length (m)	Span support type	Span composition	Construction year
A1-1-004	Gogecha	57.9	Multiple	3×19.3	2014
A1-2-008	Unnamed	42	Multiple	2×21	2013
A1-3-006	Mermersa	18	Single	18	1974
A3-1-024	Duber Guda	41	Multiple	2×20.5	1967
A4-2-025	Quribe	24	Single	1×24	1982
A7-1-001	Koka	55.55	Multiple	3×18.5	1953
A7-1-002	Awash	93.5	Multiple	5×18.7	1953
A7-1-003	Meki	20	Single	1×20	1961
A5-1-013	Awash	52	Continuous	9+34+9	1980

(a)

(b)

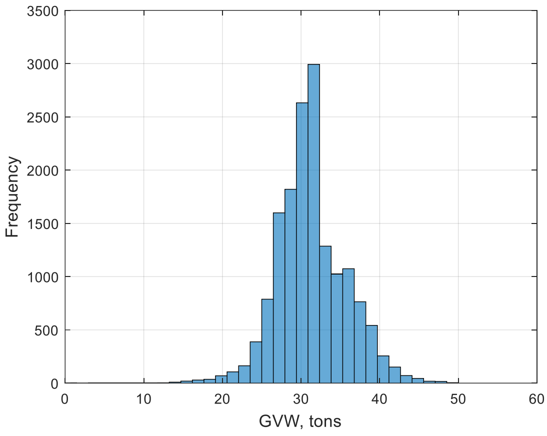
Figure 2 RC bridges a) Gogecha bridge and b) Koka bridge.

3. RESULTS AND DISCUSSION

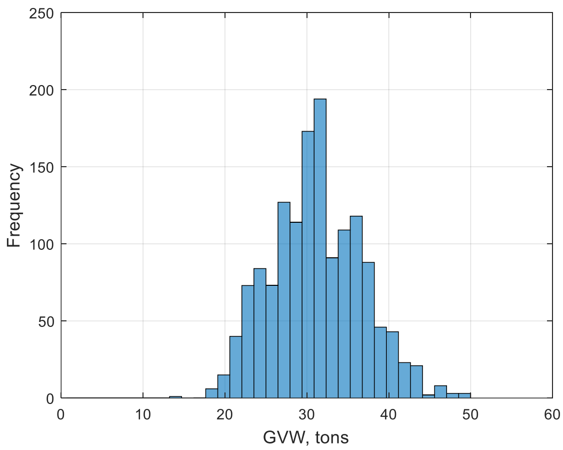
3.1 Statistical Properties of SWS Data

The Ethiopian Standards Agency (ESA) calibrated the weight measuring devices, and the quality control processes ensured the data was complete, axle load measurements were accurate, and the results were validated against manual inspection and calibration standards.

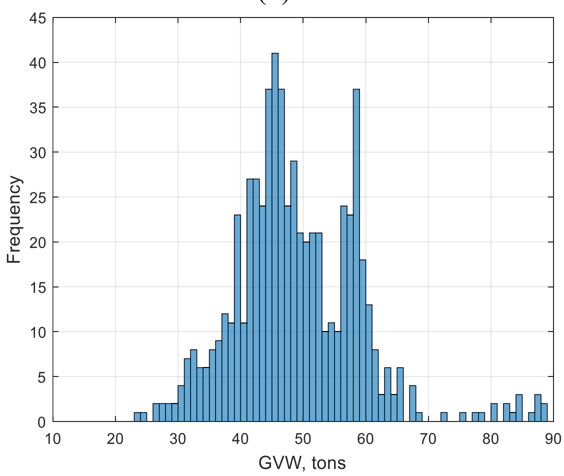
Hence, in this study, no additional checks on sensor stability and data integrity were made. The data were grouped and classified as per axle, and then a field survey was undertaken for the determination of axle configurations. The histogram plot of Gross Vehicle Weight (GVW) is shown in Figure 3.



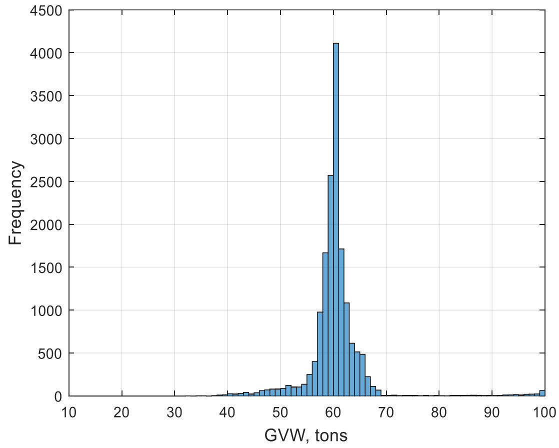
(a)



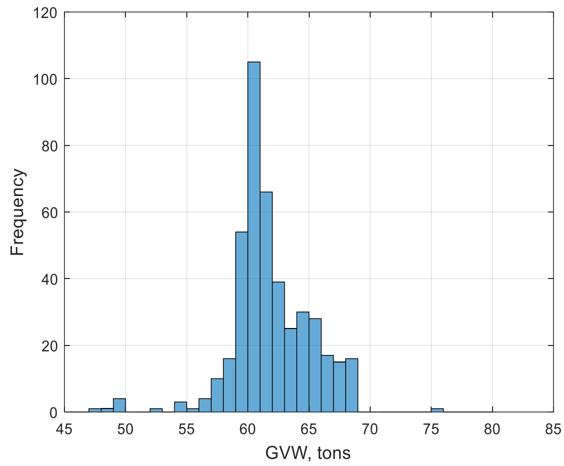
(b)



(c)



(d)



(e)

Figure 3: Histogram plot of GVW for (a) 3-axles (b) 4-axles (c) 5-axles (d) 6-axles and (e) 7-axles.

A diagram of a 7-axle vehicle configuration with a front axle designated as A1 is shown in Figure 4 and field measurements of axle spacings are shown in Table 2.

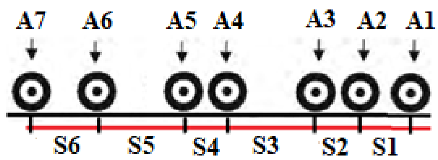


Figure 4: Schematic diagram of vehicle and axle load configurations.

3.2 Bridge Load Limit Requirements

3.2.1 National Law Requirement

Axle loads and GVW that violate load restrictions set forth in Ethiopian regulations and other standards are examined and the results are shown in Table 3. As shown in Table 3, for the case of 3-axle vehicles, among the 18,070 vehicles data, 9,938 vehicles (55%) exceed the axle load limit specified in the regulation of the country [37]. However, when it comes to GVW, it's worth noting that 44.9% of the 5-axles trucks exceed the national law's requirements [37]. The data shows a truck with 7-axles weighs a gross weight of 124-ton, which is a heavily loaded truck along the selected routes. A study on vehicle data collected from weigh stations across the East and Southern African regions (ESA) was conducted, and the results showed that the issue of vehicle overloading and the urgent need for effective control measures have long been recognized. However, due to various challenges, efforts to manage overloading have largely remained ineffective. According to the report, the incidence of overloaded trucks in the ESA region ranges from 10% to 50% [38], which aligns with the findings of the present study, where it ranged from 3.2% to 55%, as shown in Table 3.

Table 2 Axle spacing measurement

No. of axles	Values	Axle spacing (m)					
		S1	S2	S3	S4	S5	S6
3	Max.	4.3	1.3	–	–	–	–
	Min.	3.2	1.25	–	–	–	–
4	Max.	4.74	4.58	4.6	–	–	–
	Min.	1.7	2.3	1.4	–	–	–
5	Max.	3.35	4.4	6.9	1.6	–	–
	Min.	3.16	1.3	6.5	1.4	–	–
6	Max.	4.2	1.4	6.14	3.8	1.4	–
	Min.	3.36	1.34	4.8	1.34	1.35	–
7	Max.	4.2	1.36	5.42	1.4	1.35	1.32
	Min.	3.23	1.25	4.8	1.38	1.22	1.28

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Table 3 Number of illegal vehicles and bridge load limits violations.

No. of axles	No. of vehicles	Overloaded or illegal vehicles (National law, Negarit)					
		Axle load (ton)			GVW (ton)		
		Axle load limit	No.	%	GVW, limit	No.	%
3	18,070	8 - 10	9,938	55.0	28	5,819	32.2
4	1,915	8 - 10	411	21.5	38	120	6.3
5	3,540	8 - 10	893	25.2	48	1,589	44.9
6	27,720	8 - 10	7,762	28.0	58	892	3.2
7	655	8 - 10	165	25.2	68	42	6.4
	51,900		**19,169**	**36.9**		**8,462**	**16.3**

3.2.2 Regional and International Standard Requirements

In addition, the requirements for Federal Bridge Formula B (BFB) [39], [40] and the Tripartite Transport and Transit Facilitation Program (TTTFP) [41] to limit the permissible weight that a bridge can sustain were checked. For checking, Eqn. (5) [39], [40] and Eqn. (6) [41] have been used. The number of truck data exceeding the BFB and TTTFP limits are presented in Table 4.

$$W = 0.75\left(\frac{LN}{N-1} + 3.65N + 11\right) \quad (5)$$

Where W is maximum weight that can be carried on a group of two or more axles (ton), L is the distance between the outer axles of any two or more consecutive axles (m) and N is number of axles being considered.

$$W = 2100L + 18000 \quad (6)$$

Where W is the permissible mass (kg) and L is the distance between two axles (m).

From Table 4, it is observed that, among the total trucks considered, 40.2 % and 27.49 % of the BFB and TTTFP bridge formulas are violated, respectively. Hence, without controlling the movement of these types of trucks, the bridges will accumulate more damages and incur additional cost for maintenance intervention. Therefore, uncontrolled growth in loads and volumes of heavy trucks should be monitored, reassess bridges' strength accounting the current traffic conditions that actually exist in Ethiopia is found to be necessary.

In Tables 3 and 4, it is shown that more than 16% of the trucks were loaded beyond the weight limits set by the national regulations, and bridge formulas. This can compromise the efficiency and stability of the structure over time. Thus, addressing these issues on a regular basis and implementing regulatory enforcement are important to ensure safety of bridges.

Table 4 Trucks violating the bridge formulas

No. of axles	No. of vehicles	Trucks violating the bridge formulas					
		BFB			TTTFP		
		GVW, limit (ton)	No.	%	GVW, limit (ton)	No.	%
3	18,070	22.3	8,931	49.42	28.9	5,272	29.18
4	1,915	26.8	682	35.61	34.1	403	21.04
5	3,540	34.9	961	27.15	47.1	714	20.17
6	27,720	38.2	10,043	36.23	49.8	7,661	27.64
7	655	40.1	247	37.71	48.6	215	32.82
	51,900		**20,864**	**40.20**		**14,265**	**27.49**

3.3 Strength Evaluation

Utilizing load rating methodologies specified by ERA and AASHTO bridge evaluation manuals and the structural capacity of bridges under various loading conditions was found important. For bridge rating, Eq. (7) was used [1], [5].

$$RF = \frac{\varphi R_n - \gamma_{Di} D_i - \gamma_{DW} DW}{\gamma_{Li}(L_i + I)} \tag{7}$$

Where RF is the rating factor, φR_n is the nominal resistance $=A_s f_y(d\text{-}a/2)$, D_i is the effect of dead loads, L_i is the live-load effect for load i other than the rating vehicle, L_i is the nominal live-load effect of the rating vehicle, I is the impact factor for the live-load effect, γ_{Di} is the dead load factor, γ_{Li} is the live load factor.

Even though the principles of safety evaluation of bridges are generally the same, the requirements and norms governing the design and assessment of bridges may be different. These may include load factors, material specification, design codes, and safety margins which may be affected by the geographical area, historical practice, and improvement in engineering standards. Bridges constructed in different years have different remaining service lives; the extent of the deterioration of the material performance and the degradation of the overall structural performance are also different [1]. As a result, the corresponding material strengths and deterioration rates are considered as a criteria for the safety evaluation of bridges.

3.3.1 Bridge Data

The dimensions of the bridges used in this study were taken from ERA BMS and they were used to compute the effect of dead load of the bridge. Table 5 shows the bridge data used in the study [36].

Table 5 Bridge dimensions and damage

Bridge Id.	Span (m)	Slab thickness (cm)	No. of girders	Girder depth (m)	Girder spacing (m)	Girder width (m)	Damage %
A1-1-004	3×19.3	20	4	1.3	2.2	0.4	2.76
A1-2-008	2×21	25	5	1.35	3.1	0.4	1.88
A1-3-006	18	25	5	1.35	3.1	0.4	9.31
A3-1-024	2×20.5	20	4	1.35	2.1	0.4	11.69
A4-2-025	1×24	20	7	1.1	1.04	0.3	12.31
A7-1-001	3×18.5	20	4	1.0	1.75	0.4	14.2
A7-1-002	5×18.7	20	4	1.2	1.8	0.4	10.3
A7-1-003	1×20	20	4	1.3	2	0.45	10.67
A5-1-013	9+34+9	50	4	2.4	2.5	0.4	0.89

3.3.2 Loading Conditions

For strength evaluation of bridges, manuals specify the legal truck load in terms of number of axles, axle configuration, and axle load [1], [5]. For the computation of effect of live load, these truckloads were used. Furthermore, the live load data obtained from SWS were considered.

3.3.3 Effect ofL

The concept of influence lines was used to compute effects of loads. This approach enabled to evaluate corresponding maximum load effects in terms of shear force and bending moment. The analysis focused on bridges with single lanes loaded, and for longer spans, the impact of multiple vehicles with a specified headway distance between successive trucks was considered. Since the collected data were from SWS, headway distances were measured on-site, and various combinations of truck arrangement with headway distances were considered accordingly. The statistical distribution of headway distances showed a mean distance of 7.51 m and a standard deviation of 2.59 m, with values ranging from 3.28 m to 12.01 m.

For the analysis of the loading effects of the vehicles for a specific axle arrangement, a computer program was developed to consider all possible combinations (collected from the weighing stations). The effects of dead and live loads are shown in Table 6.

Table 6 Effects of dead and live loads

Bridge Id.	Dead load effects		Legal load effects			Effects of actual truck loads	
	Shear (kN)	Moment (kN-m)	Shear (kN)	Moment (kN-m)	Governing Load	Shear (kN)	Moment (kN-m)
A1-1-004	251.58	1,213.85	270.00	941.62	Legal load 1	609.31	2,499.19
A1-2-008	379.42	1,991.94	283.00	1,089.70	Legal load 2	642.31	2,867.77
A1-3-006	325.22	1,463.47	259.41	837.49	Legal load 2	583.94	2,232.98
A3-1-024	264.91	1,357.67	280.30	1,037.50	Legal load 2	632.62	2,756.96
A4-2-025	139.82	838.94	302.31	1,406.70	Legal load 3	700.14	3,574.82
A7-1-001	185.16	856.37	264.05	877.51	Legal load 1	597.33	2,333.77
A7-1-002	205.12	958.92	265.83	893.53	Legal load 2	597.60	2,374.65
A7-1-003	259.8	1,299.00	276.57	997.77	Legal load 3	622.91	2,648.15
A5-1-013	853.51	6,448.75	255.12	1,848.15	Legal load 3	740.87	4,964.26

3.3.4 Section Capacity of Bridges

In the absence of specific details on reinforcement and material grades for certain bridges, estimations of reinforcing bars (longitudinal and transversal) are made based on the assumption that the bridges were designed following standard manuals and they comply with the load requirement with appropriate material specifications defined in bridge design manuals [5], [6]. Furthermore, it was assumed that the construction was carried out according to the design specifications, using the specified materials, with proper detailing, and done by a qualified contractor [42].

In load rating calculations, variations in bridge age and the historical codes under which each bridge was originally designed presented a significant challenge. To address this, the study employed the following approaches:

- where original material specifications differed from current standards, material grades using conservative estimates were used as specified in [1], [5], [42].
- for bridges without plans, the area of reinforcing bars was estimated as a percentage of the gross area of the beams, provided there were no indications of significant distress [42]. Alternatively, assumption of original design were done by back-analysis or redesign [43].
- despite variations in original design procedures, the AASHTO LRFR method could be applied to uniformly rate all bridges [42].
- damage conditions of the bridge were to be used [44]. In the present study, damage rates obtained from the bridge data base [36] were considered.

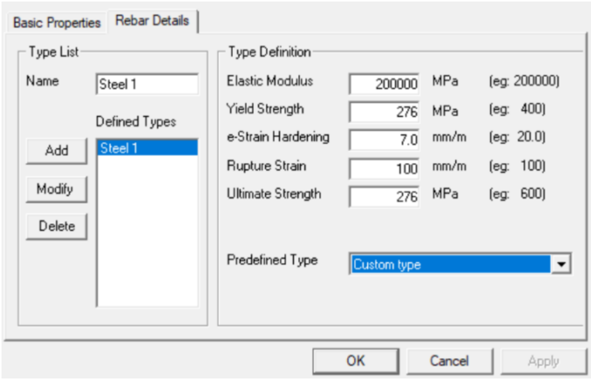
Regarding materials property, the compressive strength of concrete and steel yield stresses used for various types of reinforcing steel grades are given in Table 7. In most cases, the stress of the concrete was assumed to be 20.7 MPa and that of the steel as f_y=276 MPa. For newly constructed bridges, f_y of 314 MPa has been used. For deteriorated bridges, f_y=228 MPa, 248 MPa and for concrete a strength of 15 MPa were considered [1].

Using the above assumptions, the bridges were redesigned and their section capacities were evaluated using Response 2000 software, which uses the modified compression field theory [45]. The estimated reinforcing areas, material properties and section capacities of the bridges are presented in Table 7.

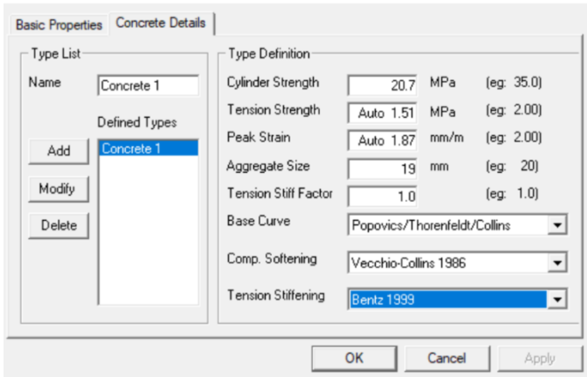
Table 7 Input data and section capacity of bridges

Bridge Id.	A_S (mm^2)	Stirrups (mm)	Yield stress, f_y (MPa)	f'_c (MPa)	Estimated section capacity	
					Shear (kN)	Bending (kN-m)
A1-1-004	8,844	ϕ 12 c/c 150	314	20.7	1,139.8	3,717
A1-2-008	12,060	ϕ 12 c/c 130	314	20.7	1,331.6	4,536
A1-3-006	12,060	ϕ 12 c/c 120	276	20.7	1,168.9	4,329
A3-1-024	10,452	ϕ 12 c/c 150	248	15.0	977.6	3,119
A4-2-025	19,296	ϕ12 c/c 170	276	20.7	830.96	3,137
A7-1-001	10,452	ϕ 12 c/c 230	228	20.7	626.2	2,034
A7-1-002	11,256	ϕ 12 c/c 210	228	20.7	740.24	2,817
A7-1-003	11,256	ϕ 12 c/c 210	248	20.7	791.98	3,310
A5-1-013	17,190	ϕ 12 c/c 110	276	20.7	1,954.6	10,950

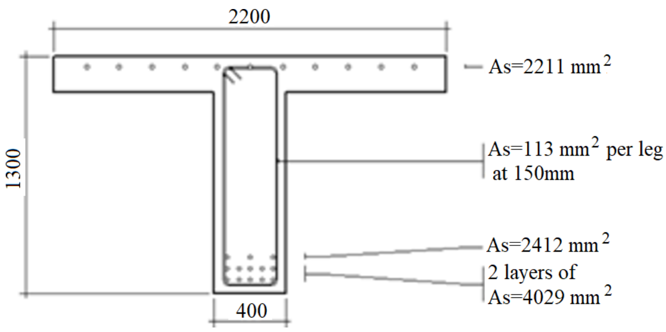
The reinforcement bars were assumed to have a diameter of 32 mm. However, no ground-penetrating radar or cover-meter measurements were conducted to validate this assumption, and the influence of bar diameter on section capacity was not included. Sample material properties and cross section details of Gogecha Bridge (A1-1-004) are shown in Figure 5.



(a)



(b)



(c)

Figure 5: (a) rebar properties (b) concrete properties (c) cross section details

3.3.5 Factors for strength evaluation

In the computation of rating factors for legal loads, the load factors were set at γ_D= 1.2 and γ_L = 1.65. However, for vehicles that exceed legal loading limits, these factors were reduced (in this study, γ_D and γ_L values of 1.05 were used), reflecting the need for flexibility in evaluating the structural capacity under more extreme conditions [46]. As per the recommendation of the manuals [1], [5], the resistance factors were set at 0.80 for deteriorated bridges and 0.95 for those in good condition. These values were vital in accounting for the current state of the bridge's materials and construction quality. Since all the bridges considered in this study were of two lanes, reduction factors for live load of 1.0 has been used. In addition, for all bridges, an impact factor of 0.1 (fair condition of wearing surface was reported [36]) and condition factor of 1.0 have been used [5]. Field test results showed that the dynamic amplification factor (DAF) for bridges depends on loaded length, vehicle speed and pavement condition [47]. However, in this study, a constant value of impact factor was used for all bridges. The live load distribution factors specified in the AASHTO LRFD (Load and Resistance Factor Design) specifications were used for strength evaluation [1], [14] and are generally conservative in most cases, especially for straight bridges [14]. The combination of load factors, resistance factors, impact factors, and distribution factors provided a comprehensive framework for evaluating bridge strength. This holistic approach was important for ensuring that all aspects of bridge performance were considered. The distribution factors (DF) are given in Table 8.

3.3.6 Bridge ratings

3.3.6.1 Current condition

The rating factors of bridges due to legal and actual truck load data were computed using Eqn. (7) and the results are summarized in Table 8.

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Table 8 Rating factors for shear and moment

Bridge Id.	DF		Rating factors for legal trucks			Rating factors for actual loads			
	SF	BM	SF	BM	RF_{Legal}	RF_{SF}	RF_{BM}	RF_{Actual}	RF hierarchy
A1-1-004	0.80	0.62	1.99	1.96	1.96	1.45	1.26	1.26	2
A1-2-008	0.80	0.79	1.97	1.23	1.23	1.46	0.85	0.85	6
A1-3-006	0.80	0.81	1.76	1.74	1.74	1.32	1.13	1.13	3
A3-1-024	0.77	0.64	1.43	0.98	0.98	1.07	0.68	0.68	8
A4-2-025	0.49	0.36	2.16	1.98	1.98	1.52	1.31	1.31	1
A7-1-001	0.68	0.54	1.05	0.93	0.93	0.79	0.64	0.64	9
A7-1-002	0.68	0.54	1.28	1.58	1.28	0.96	1.03	0.96	5
A7-1-003	0.75	0.70	1.07	1.13	1.07	0.82	0.76	0.76	7
A5-1-013	0.89	0.62	2.02	1.28	1.28	1.26	1.02	1.02	4

As shown in Table 8, under legal load conditions, the rating factors for two bridges (A3-1-024 and A7-1-001) are found to be less than 1.0, indicating there is a need to establish the LRFR posting load restriction [1], [5], [48]. However, these values do not indicate severe structural failure [49]. The deviations of these bridges from the standard are concerns for their structural capacity and the potential need for further investigation or reinforcement to ensure safety [1]. Table 8 presents the rating factor hierarchy, arranged from the highest RF to the lowest. This hierarchy serves as a systematic tool for identifying bridges with lower rating factors as priority cases, thereby supporting decisions on maintenance, rehabilitation, or replacement.

Actual truck data gathered from weighing stations, in all cases, reduces bridges' performance (rating factors) as compared to legal loads and shortens their service life. As a result of the overloaded trucks, the rating factors of seven bridges were now found to be less than 1.0. The identification of such reduced rating factors emphasizes the importance of continuous monitoring and assessment of bridge conditions to maintain infrastructure safety.

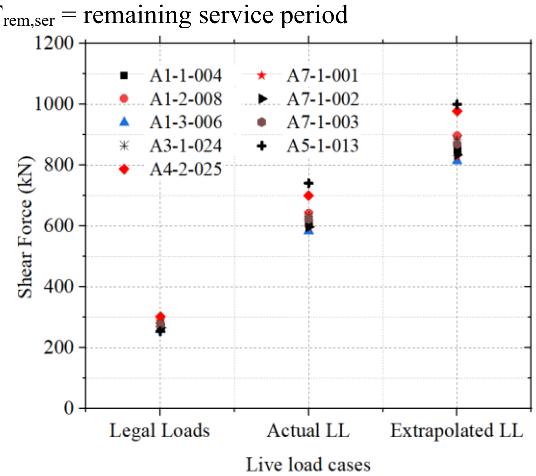
3.3.6.2 Future condition of bridges

To predict bridge's performance in the long-run, factors like deterioration rates and extrapolated loads which the bridges are likely to experience in the future need to be considered [7, 26]. For the calculation of extrapolated load data for a return period of 75 years, Eqn. (1) is used. In line with this, the extrapolated bending moment and shear force for the remaining service period are computed and shown in Table 9. Estimating the remaining service period of a bridge involves considering its original design life and the year it was constructed. This estimation is a fundamental step in bridge management and provides a basis for further assessments and informs maintenance interventions. Considering corrosion of reinforcing bars and reduced yield strength of rebars, the reduced section capacity of bridge was recalculated accordingly. Consequently, bridge rating factors for both shear and moment have been computed based on the updated values of extrapolated live loads and reduced section capacity as shown in Table 9. In this study, to account future deterioration, the resistance factors were reduced by 0.05. In Figure 6, comparison of live load effects is shown. The extrapolated live load effects demonstrated that a vehicle causes an increment of 40% on average for shear force and bending moment as compared to the current traffic with a load increment rate of 0.005 per year was obtained, showing that the live load intensity will increase by 40% over a 75-year period, which is in the same range with research carried by Wang and Li [50]. The analysis result of the current study also showed significant increments of live load effects, which were 56.9 % for shear force and 62.2 % for bending moment as compared to the effect of legal loads.

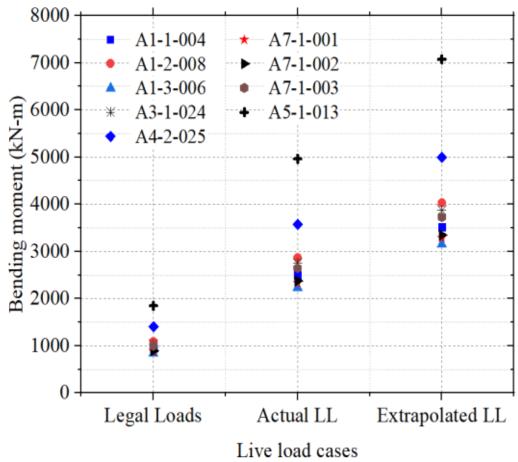
Table 9 Effects of corrosion rate on section capacity and extrapolated live loads

Bridge Id.	$T_{rem,ser}$*	Reduced rebar area (mm^2)	Reduced yield stress f_{yR} (MPa)	Reduced section capacity		Extrapolated live load effects		RF_{SF}	RF_{BM}	$RF_{Extrap.}$
				SF (kN)	BM (kN-m)	SF (kN)	BM (kN-m)			
A1-1-004	65	8,676.35	306.86	1,095.83	3,573.61	837.21	3,508.88	0.93	0.77	0.77
A1-2-008	64	11,834.85	306.97	1,280.61	4,362.29	880.62	4,015.26	0.93	0.50	0.50
A1-3-006	25	11,970.34	273.54	1,137.01	4,210.88	710.12	3,046.44	0.95	0.72	0.72
A3-1-024	18	10,395.44	246.39	952.86	3,040.08	742.00	3,737.60	0.81	0.42	0.42
A4-2-025	33	19,107.98	272.77	806.41	3,044.30	888.30	4,907.49	1.07	0.84	0.84
A7-1-001	4	10,437.80	227.63	612.84	1,990.61	776.53	3,119.83	0.54	0.41	0.41
A7-1-002	4	10,437.80	227.63	724.45	2,756.91	718.32	3,147.16	0.71	0.68	0.68
A7-1-003	12	11,214.63	246.91	773.29	3,232.08	747.49	3,543.79	0.60	0.49	0.49
A5-1-013	31	17,032.42	272.96	1,897.95	10,632.63	900.46	6,972.83	0.88	0.56	0.56

*$T_{rem,ser}$ = remaining service period



(a)



(b)

Figure 6 Comparison of live load effects (a) shear force and (b) bending moment

3.3.6.3 Summary of rating factors

In Table 10, summary of bridge ratings for legal loads, actual truck data and extrapolated live loads are shown. In the table, rating factors for legal loads considering deterioration of the bridge due to corrosion are indicated. It is also noted that most of the existing RC girder bridges do not meet the current standards for modern traffic loads. A consistent downward trend is observed from legal to actual to extrapolated rating factors across all bridge cases. The percentage reduction between RF_{Legal} and RF_{Actual} averages 30.18 %, indicating the impact of current loading conditions on structural performance.

On the other hand, the extrapolated live loads give rating factors ($RF_{Extrap.}$) below one for all bridges. The results indicate a significant reduction of 56.29 %, even in the absence of material deterioration of concrete and other environmental conditions which lead the bridges to fail. This result is relatively higher than that of a related study, which reported a 36.5 % reduction in reliability index under overloaded traffic conditions [51]. It was also observed that when steel bars are corroded in the future and legal load effects are considered, the rating factors ($RF_{Legal,corr}$) are, on average, 17.71 % greater than those based on current truck load data without corrosion (RF_{Actual}). This shows that overloading causes a more immediate reduction in section capacity while corrosion progressively deteriorates the steel reinforcement, resulting in a gradual reduction in section capacity and becoming a critical concern over time.

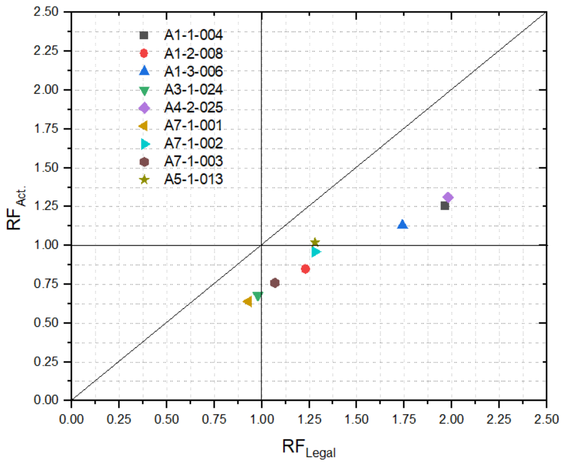
A comparison of rating factors under legal loads for both current and future condition is shown in Table 10. The result shows that, when considering the effect of corrosion alone, anticipated bridge conditions have an average reduction of 18.0 % in rating factors compared to their current performance. This falls within the findings of El Maaddawy et al. [52], where corrosion led to a reduction in section capacity ranging from 6.5 % to 29 % under sustained load.

Table 10 Summary of rating factors

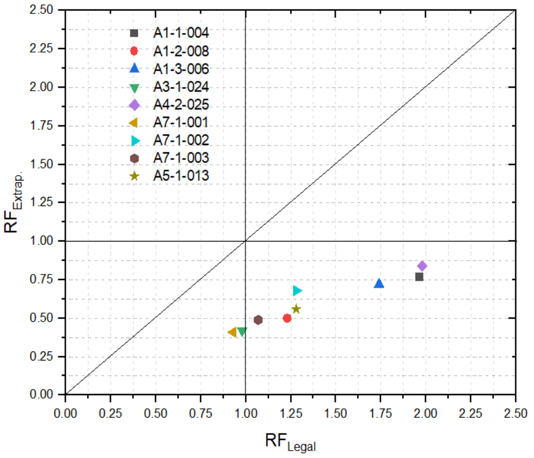
Bridge Id.	RF_{Legal} (1)	RF_{Actual} (2)	$RF_{Extrap.}$ (3)	$RF_{Legal,corr}$ (4)	% reduction (1) and (2)	% reduction (1) and (3)	% reduction (1) and (4)	% reduction (2) and (4)
A1-1-004	1.96	1.26	0.77	1.66	35.71	60.71	18.07	24.10
A1-2-008	1.23	0.85	0.50	0.98	30.89	59.35	25.51	13.27
A1-3-006	1.74	1.13	0.72	1.48	35.06	58.62	17.57	23.65
A3-1-024	0.98	0.68	0.42	0.79	30.61	57.14	24.05	13.92
A4-2-025	1.98	1.31	0.84	1.72	33.84	57.58	15.12	23.84
A7-1-001	0.93	0.64	0.41	0.77	31.18	55.91	20.78	16.88
A7-1-002	1.28	0.96	0.68	1.13	25.00	46.88	13.27	15.04
A7-1-003	1.07	0.76	0.49	0.92	28.97	54.21	16.30	17.39
A5-1-013	1.28	1.02	0.56	1.15	20.31	56.25	11.30	11.30
Average					**30.18**	**56.29**	**18.00**	**17.71**

The comparative plot of the rating factors for bridge is shown in Figure 7. Most data points lie below the reference line, indicating that the majority of bridges experience a reduction in rating factors when subjected to current and extrapolated traffic load effects. Results show a consistent decline from legal ratings to actual and extrapolated values, indicating progressive structural degradation over time, raising concerns about their structural safety. Similarly, Figure 8 presents a comparison of bridge ratings under various load cases.

The trends of rating factors of the present study show a significant decrease in load-carrying capacity over time, emphasizing the need for proactive maintenance, monitoring, and potential strengthening interventions. Variations in bridge characteristics and exposure conditions are required for bridge-specific assessments to ensure accurate management planning.



(a)



(b)

Figure 7: Comparison of rating factors a) RF_{Legal} vs. RF_{Actual} and b) RF_{Legal} vs. $RF_{Extrap.}$

In summary, the findings of this study highlighted the significance of controlling excessive truck loads to ensure the safety and capacity performance of highway bridges. In situations where the percentage of overloaded vehicle is significant, and to reflect their actual effect on bridge structures, researchers recommend calibration of live load models and load factors.

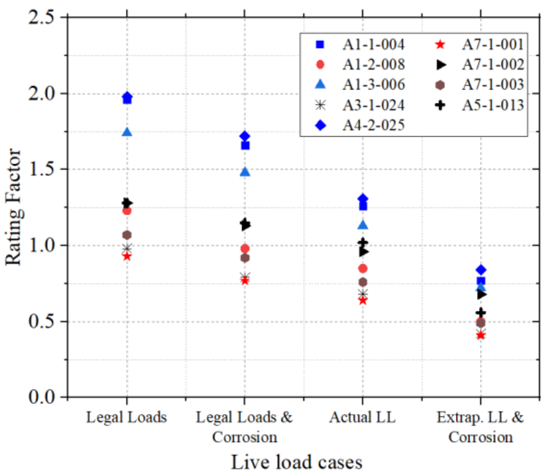


Figure 8 Bridge ratings for different cases.

Accordingly, efforts have been made toward developing design live load models [7], [17], [21], [32], [53] and calibrating load and resistance factors for bridge design and evaluation [7], [54], [55], [56]. This calibration aimed to reflect realistic loading scenarios more accurately, considering the variations and trends observed in current traffic patterns, particularly due to vehicle overloading and aging infrastructure.

4. CONCLUSIONS

A study on the effect of overloaded trucks on selected RC highway bridges in Ethiopia revealed that current traffic loading exceeds legal limits by 56.9% in shear force and 62.2% in bending moment, with vehicle overload percentages of 16.3%, 40.2%, and 27.49% compared to national, BFB, and TTTFP regulations, respectively. The absence of traffic monitoring has led to severe bridge damage, reducing rating factors by 30.18% and accelerating deterioration. The findings highlight the need for cost-benefit analysis to assess projected economic impacts, probabilistic assessments to account uncertainties of random variables (traffic growth, material degradation, climate change), and calibration of live load models, load and resistance factors. While extrapolated load analyses are valuable tools for bridge safety evaluations, their predictions should be supported by field monitoring, probabilistic load models, and sensitivity analyses.

Effective monitoring of overloaded truck is often lacking in the country. This issue can only be remedied through collaboration between regulatory bodies, law enforcement, and bridge owners. Therefore, it is important for transportation agencies to enforce regulatory standards and polices aimed at reducing impacts of trucks with excessive loads on bridge performance and safety.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with others.

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