On the Stabilizing Effect of Weigh Stations on Truck Equivalency Factors for Pavement Design

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Abstract: In Costa Rica, weigh stations for trucks and commercial vehicles were reinstated in 2008. Since then, a stabilizing trend in the percentage of heavy vehicles with excess loading was observed. For pavement design purposes, this resulted in reduced variability in truck equivalency factors. These were statistically validated by processing all the weight data collected at different stations located throughout the national road network between 2008 and 2011. Using linear regressions, it was verified that given a constant noncompliance percentage, the truck equivalency factor for C2, C3, and T3-S2 vehicles tended to stabilize at 0.20, 0.66, 1.19, respectively. These results were consistent with additional power regression performed on the data. Higher weight enforcement on the T3-S3 vehicles' tandem axle would result in a 0.17 decrease in the truck equivalency factor. The findings presented herein should aid countries that have yet to implement weigh stations, considering the benefits of exploring the evolution of truck factors if weigh stations were installed. This weigh station implementation case study exhibits the reality and development of pavement loading over time. Therefore, government authorities should be encouraged to control truck traffic with weigh stations to reduce pavement damage. **DOI: 10.1061/JPEODX.PVENG-1123.** *© 2023 American Society of Civil Engineers.*

Author keywords: Truck equivalency factors; Weigh stations; Regulation; Pavement design.

Introduction

The road network in Costa Rica is the primary means of transportation for people and goods. Therefore, it is fundamental to ensure its functional and structural condition. As in many countries, in Costa Rica, most of the cargo received at seaports and land is transported by heavy goods vehicles (HGVs) to different regions. As a result, HGVs occasionally exceed the maximum permitted weight established by Costa Rican legislation (Table 1).

Depending on the axle configuration, HGVs are generally the truck type with the highest impact on the deterioration of the road network as their loads are the most detrimental to the pavement structure. Consequently, inadequate weight controls will directly affect pavement life. Weight controls are one of the few means to prevent excessive damage to one of the country's most significant infrastructure assets.

The National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR) began a program to identify the actual loads associated with the axles of vehicles that regularly transport more than four tons (truck categories C2, C3, T3-S2, and T3-S3, as per local classification). Based on the collected data, these vehicle classes shown in Fig. 1 and Table 1 represent 98.5% of the truck vehicle fleet in Costa Rica. LanammeUCR's studies have prompted the national government to reimplement the use of permanent weigh stations along the main routes of the national road network (NRN) to ensure that the number of vehicles transporting excess weight is minimized. Unfortunately, no research studies have yet proven the stabilization of the percentage of vehicles that exceed the maximum permitted weight by Costa Rican legislation or its relationship with truck factors. In general, proper knowledge of vehicle weights could significantly advance local pavement design and improve modeling of loads passing through the national road network.

The feasibility of establishing overweight truck permit fees based on each truck's attributes, such as gross vehicle weight, axle loading, and axle spacing, has been proven to cover infrastructure damage caused by each overweight truck class (Agbelie et al. 2017).

Overweight trucks notably affect bridge damage (Dey et al. 2014). Critical damage to bridges due to overweight trucks has also been analyzed. In the case of steel bridges, this overweight traffic accelerates the cumulative damage associated to the steel superstructures and the concrete deck's cumulative damage (Cha et al. 2016). The amount of overweight trucks affects the expected service life of prestressed concrete girders (Lou et al. 2017). In Costa Rica, the bridges present inadequate maintenance, most of them have more than 30 years in operation, and the amount of bridges in critical condition is notable (Garita and Ortiz 2016). Therefore, a strict control of truck weights is crucial to reduce the risk of rapid

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Table 1. Types of vehicles according to national and international weight regulations

Vehicle type	Steering axle weight (t)	Second axle weight (t)	Third axle weight (t)	Legal gross vehicle weight (t)
C2	Single axle	Single axle	—	—
Mexico (2017)	6.5	11.0	—	17.5
US (2011)	5.5	9.0	—	14.5
Costa Rica (2004)	6.0	10.0	—	16.0
Guatemala (2010)	5.5	10.0	—	15.5
El Salvador (2013)	5.0	10.0	—	15.0
Nicaragua (2005)	5.0	10.0	—	15.0
C3	Single axle	Single axle	—	—
Mexico (2017)	6.5	19.0	—	25.5
US (2011)	5.5	15.5	—	21.0
Costa Rica (2004)	6.0	16.5	—	22.5
Guatemala (2010)	5.5	16.5	—	22.0
El Salvador (2013)	5.0	16.5	—	21.5
Nicaragua (2005)	5.0	16.5	—	21.5
T3-S2	Single axle	Tandem axle	Tandem axle	—
Mexico (2017)	6.5	19.0	19.0	44.5
US (2011)	5.5	15.5	15.5	36.5
Costa Rica (2004)	6.0	16.5	16.5	39.0
Guatemala (2010)	5.0	16.0	16.0	37.0
El Salvador (2013)	5.0	16.0	16.0	37.0
Nicaragua (2005)	5.0	16.0	16.0	37.0
T3-S3	Single axle	Tandem axle	Tridem axle	—
Mexico (2017)	6.5	19.0	26.5	52.0
US (2011)	5.5	15.5	19.0	40.0
Costa Rica (2004)	6.0	16.5	23.0	45.5
Guatemala (2010)	5.0	16.0	20.0	41.0
El Salvador (2013)	5.0	16.0	20.0	41.0
Nicaragua (2005)	5.0	16.0	20.0	41.0

Sources: Data from Allen and Badilla (2011); Ministerio de Comunicaciones de Infraestructura y Vivienda (2010); Diario Oficial del El Salvador (2013); Secretaría de Comunicaciones y Transportes (2017); Diario Oficial de Nicaragua (2005).

deterioration and safety of the bridges in order to pursue resiliency in the national road infrastructure.

Background

The provisions that govern official weight regulations in Costa Rica are defined in the national regulation 31363-MOPT (MOPT 2006) and its amendments. This document describes the axle configuration and legal weight limits for different vehicle types. Table 1 summarizes the weight regulations for each axle type and vehicle in the country and compares them with international regulations from Mexico, the US, and other countries in the region. Table 2 presents a comparison of vehicle types across Costa Rican legislation, Federal Highway Administration (FHWA 2014), and AASHTO (1993).

Truck Cargo Surveys

A load survey is a tool that determines the magnitude of typical and atypical loads applied to pavement structures under specific conditions. In Costa Rica, a study in 2007 was designed to collect the information required to calibrate local truck equivalency factors (Ulloa et al. 2008), as recommended by AASHTO (1993). These factors help describe the damage on the pavement structure produced by the vehicle's axles and vary according to the weight and type of each axle (single, tandem, or tridem), type of structure (rigid or flexible), and the structural number (SN). The used values are recommended by the Asphalt Institute for flexible pavements, with a serviceability index of 2.5 and a SN of 5. Truck equivalency factors are later used to determine average truck factors, determining equivalent single-axle loads (ESALs).

This initial local survey to study the truckloads on the national pavements was conducted by LanammeUCR (Ulloa et al. 2008). The study also intended to collect axle load spectra for the eventual implementation of the *Mechanistic-Empirical Pavement Design Guide* to characterize loading conditions for specific road sections (AASHTO 2002). The data generated in the study were used to calibrate typical truck equivalency factors by vehicle type, axle, and route (domestic routes) because there were no data available at the time. Table 3 summarizes the results.

The behavior of vehicle loads at different weigh stations, operated by the Administration, between November 2008 and October 2010 was analyzed. The authors identified a definite downward and stabilizing trend in the percentage of vehicles exceeding weight regulations based on the data. It was hypothesized that this was the result of increased driver awareness regarding the existence of a weight enforcement program.

Other weight studies include two thesis projects by the Civil Engineering Department at the University of Costa Rica. In 2017, one study focused on analyzing alternative domestic routes to the ones that have permanent weigh stations (Arrieta 2017). The study concluded that the vehicles with a higher weight exceedance are T3-S3, followed by T3-S2 and C3. In general, it was determined that trucks with more axles have higher noncompliance on roads without weight control (Arrieta 2017).

In 2018, another research study focused on the municipal road network (Rodríguez 2018). In the municipal road network, the single unit trucks dominated: C2 (67% of respondents' vehicles). In national routes, T3-S2 articulated trucks (42%) with multiple axles were most common (Arrieta 2017). Most weight exceedances related to the transport of material and construction goods (both scenarios). In national routes, twice as many heavy vehicles (18%) circulated compared with municipal roads (8%) (Rodríguez 2018). Additionally, a complementary study (Vargas-Sobrado et al. 2019) compiled and compared truck weights in routes where regulations were not enforced in Costa Rica. The analyzed routes can be observed in Fig. 2.

Infrastructure Damage Caused by Overweight Vehicles

A method to estimate bridge damage repair costs due to overweight vehicles using lifecycle expenditures on reconstruction, rehabilitation, and maintenance was suggested by Agbelie et al. (2017). An incremental cost approach was used to define the bridge damage cost based on the vehicle configuration and the average frequency of bridge use. This damage was defined as a function of gross vehicle weight, axle spacing, and the number of axles. Agbelie et al. (2017) showed that it is feasible to establish overweight truck permit fees based on their attributes. Based on these results, regulation policies related to infrastructure damage can be formulated, updated, or evaluated.

Another study (Cha et al. 2016) addressed the variability in the rate of deterioration caused by different loads. It gave particular focus to the effect of overweight trucks on steel bridge components through a detailed finite-element (FE) model of representative bridges in the state of Indiana to study the damage on the bridge over its lifetime. Hypothetical scenarios were conducted

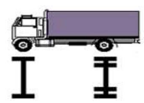
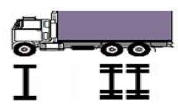
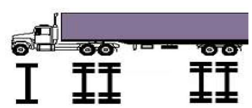
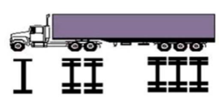
Vehicle axle type	Vehicle configuration	Vehicle classification
Lightweight vehicles		Passenger cars.
Bus		All buses with a dual wheel on the rear axle
Light-Duty Vehicles		Pick-up trucks.
C2+		Small trucks equipped for low loads (vehicles with light-duty license plates and a single rear axle).
C2		Trucks: axle configuration with a single dual axle at the rear of the vehicle.
C3		Tandem trucks: Axle configuration with tandem axles at the rear of the vehicle.
T3-S2		Five or six-axle articulated trucks: include tractor-trailers (articulated trucks), with two pairs of tandem axles (T3-S2), or tandem and a tridem rear axle (T3-S3).
T3-S3		

Fig. 1. Vehicle axle type and configuration for the most common vehicles in Costa Rica based on Allen and Badilla (2011).

Table 2. Vehicle type comparison between Costa Rican legislation, FHWA, and AASHTO

Vehicle type		
Costa Rica (MOPT)	FHWA	AASHTO
C2: trucks, axle configuration with a single axle at the front and dual axle at the rear of the vehicle	Class 5: two axles, six tires, single-unit	Single-unit (SU) truck
C3: trucks, axle configuration with tandem axles at the rear of the vehicle	Class 6: three axles, single-unit	SU truck
T3-S2: five or six-axle articulated trucks with two pairs of tandem axles	Class 9: five-axle tractor-semitrailer	WB-50: intermediate semitrailer
T3-S3: five or six-axle articulated trucks, with a tandem and a tridem rear axle	Class 10: six or more axles, single trailer	WB-100T: triple-semitrailer/trailers

Sources: Data from FHWA (2014); AASHTO (1993).
Note: MOPT = ministry of public works and transportation.

to determine damage progression due to overweight traffic, which increased the cumulative damage in the steel superstructure of bridges and its concrete deck. This study can determine how increases in truck weight limits could affect an infrastructure asset's life cycle, such as a bridge.

Using weigh-in-motion (WIM) equipment on Taiwan's freeway systems, the average truckload factor for combined heavy vehicles was determined to be 2.7 times higher than the original design value, which already took 30% of truck overloading into account (Chou 1996). It was also concluded that bridge design standard

Table 3. Average truck equivalency factors based on 2007 survey

Route	Vehicle type					
	Pick-up	C2 +	C2	Bus-C2	C3	T3-S2
Route 1: General Cañas Highway (toll road)	0.011	0.019	0.734	2.022	2.721	2.102
Route 1: Bernardo Soto Highway Naranjo (toll road)	0.011	0.016	0.902	3.680	1.971	3.701
Route 1: Bernardo Soto Highway Esparza (toll road)	0.011	0.233	0.723	2.911	2.834	4.153
Route 2: Florencio del Castillo Highway (toll road)	0.015	0.031	0.827	1.437	3.202	3.021
Route 2: Pérez Zeledón	0.012	0.014	0.446	1.858	3.330	2.080
Route 27: Próspero Fernandez Highway (toll road)	0.011	0.016	1.163	1.957	3.155	2.695
Route 32: Braulio Carrillo Highway (toll road)	0.011	0.022	0.695	3.692	2.271	4.229
Route 140: San Carlos, Ciudad Quesada	0.012	0.014	0.521	2.107	3.773	3.861
Average	0.012	0.046	0.751	2.458	2.907	3.230
Standard deviation	0.001	0.076	0.223	0.861	0.585	0.878

Source: Data from Ulloa et al. (2008).

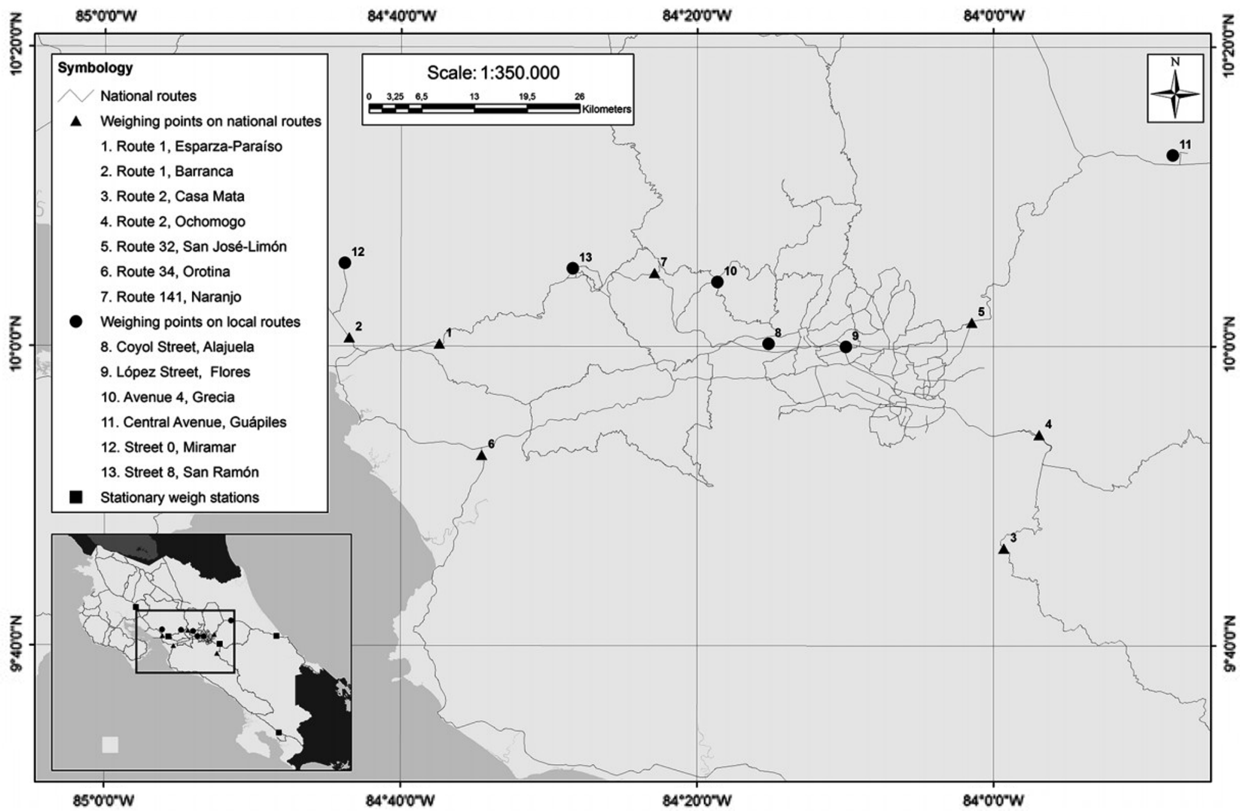


Fig. 2. Location of temporal weighing surveys based on Vargas et al. (2019).

specification would result in a 28% underestimation of steel volume in bridge deck design. The actual accumulative ESALs based on the WIM collection were 2.3 times larger than predicted, which indicates that the pavement structure could be underdesigned (Chou 1996).

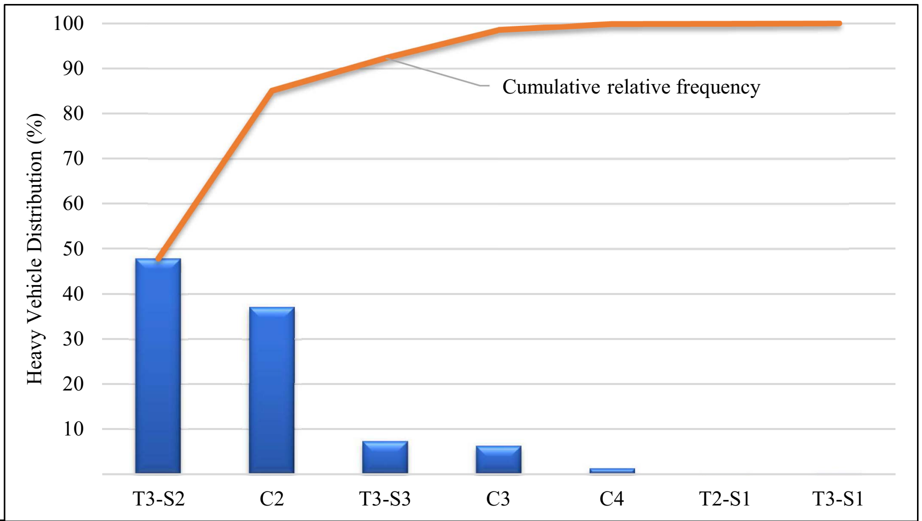
Weight Data Used in the Study

The data were collected on eight different weigh station sites: General Cañas Highway (Route 1), Bernardo Soto Highway (Route 1, Naranjo–Esparza), Florencio del Castillo Highway (Route 2), Pérez Zeledón (Route 2), Próspero Fernandez Highway (Route 27), Braulio Carrillo Highway (Route 32), and San Carlos (Route 140). The Administration collected the data as part of the weight verification performed continuously at each site. A descriptive summary of the vehicle distribution for all sites is shown in Fig. 3. C2, C3, T3-S2, and T3-S3 class vehicles represented 98.5% of the truck vehicle fleet. Consequently, this study does not include other vehicle types with different load axle configurations because they were not significant within the surveyed sample.

Research Results

Noncompliance Analysis of Weight Requirements

The percentage of heavy vehicles exceeding national weight regulations per month was analyzed using axle type and vehicle



Permissible Gross Vehicle Weight [Ton]	382.5 kN	156.9 kN	446.2 kN	220.6 kN	*	*	*

Fig. 3. Cumulative relative frequency and relative frequency distribution for all types of evaluated vehicles based on Allen and Badilla (2011). Vehicle type not relevant in the study.

class. Overweight traffic was defined as the type of vehicle class that exceeds its class weight regulations per axle as per Table 1. The data were summarized, and trends were modeled to simulate the change in noncompliance with time. Fig. 4 shows the monthly trend associated with the percentage of overweight vehicles exhibiting noncompliance with national regulations for C2, C3, T2-S3, and T3-S3, respectively. Except for the tandem axle on the T3-S3 vehicles, in all cases, a potential structural form adequately fits the data (Fig. 4). Therefore, the model that was estimated is as follows:

$$y = \alpha x^{\beta} \tag{1}$$

where y = percentage of the specific vehicle being overweight based on local regulations; x = month the measurement was made, starting with an initial value of $x = 1$ for November 2008; and α and β = model parameters.

Fig. 4 shows an evident decrease in the percentage of vehicle classes C2 [Fig. 4(a)] and C3 [Fig. 4(b)] with excess weight for single, dual, and tandem axles. It can also be noted that the trend stabilized toward the end of the period. However, from Fig. 4(c), the T3-S2 class vehicles differed for both axle types. In the case of the tandem axle, a decrease in the number of overweight axles was captured. However, no change was observed in the single axle (steering axle) during the analysis period (with approximately 0 % noncompliance to weight regulations). Therefore, as expected, no extra load can or should be applied to this axle.

Finally, the trends associated with the T3-S3 class vehicle are shown in Fig. 4(d). Different behaviors were observed for each of the three axles: single, tandem, and tridem. The tridem axle showed a slight decrease in the percentage of overweight vehicles during the initial 9 months of the analysis. After the initial period, no significant change was observed in the number of overweight axles. Regarding the tandem axle, considerable variability during the analysis period was noted. On average, a slight increase in the percentage of overweight axles was recorded. However, the trend is not statistically significant. Finally, as in the single steering axle for the T3-S2 truck, the T3-S3 steering axle trend remained constant with approximately 0% excess weight.

Estimation of Noncompliance Trend Models

To further characterize the change in the percentage of overweight vehicles and statistically infer if the implementation of the permanent weigh stations had a significant impact on the compliance of weight regulations, linear regression models were used to fit three different analysis periods (Tables 4 and 5). This type of model was selected because it can determine the relationship between two or more variables. The model results include the t- stats, which determine if the average value is stabilized. This can be achieved when the value is below 2.0, meaning that in approximately 95% of the cases, a slope value of zero is within the confidence range; the hypothesis that the percentage of vehicles that exceed weight regulations is not time-dependent cannot be rejected.

The analysis period's segmentation was performed based on the Administration's permanent weigh station's data availability. Consequently, yearly periods from November to October of the following year were consistent with the truck cargo survey. The data should include the seasonal load transportation variation based on demand from different productivity sectors throughout the year. This analysis was performed by modeling the percentage of overweight vehicles as a linear function of time (as measured in months). The results are given in Table 4.

A clear tendency toward convergence of the percentage of overweight C2 vehicles exceeding the maximum legal weight per month can be observed by analyzing the yearly trends. Furthermore, there was an evident decrease in the slope associated with the models with time: zero, suggesting that the percentage of overweight axles for the vehicle class becomes constant, with a value of 0.02%.

In the case of the T3-S2 single axles, no changes were evident in the models' slope, suggesting that, on average, the monthly number of overweight vehicles associated with the class remained constant. Regarding the tandem axles, a decrease in the percentage of

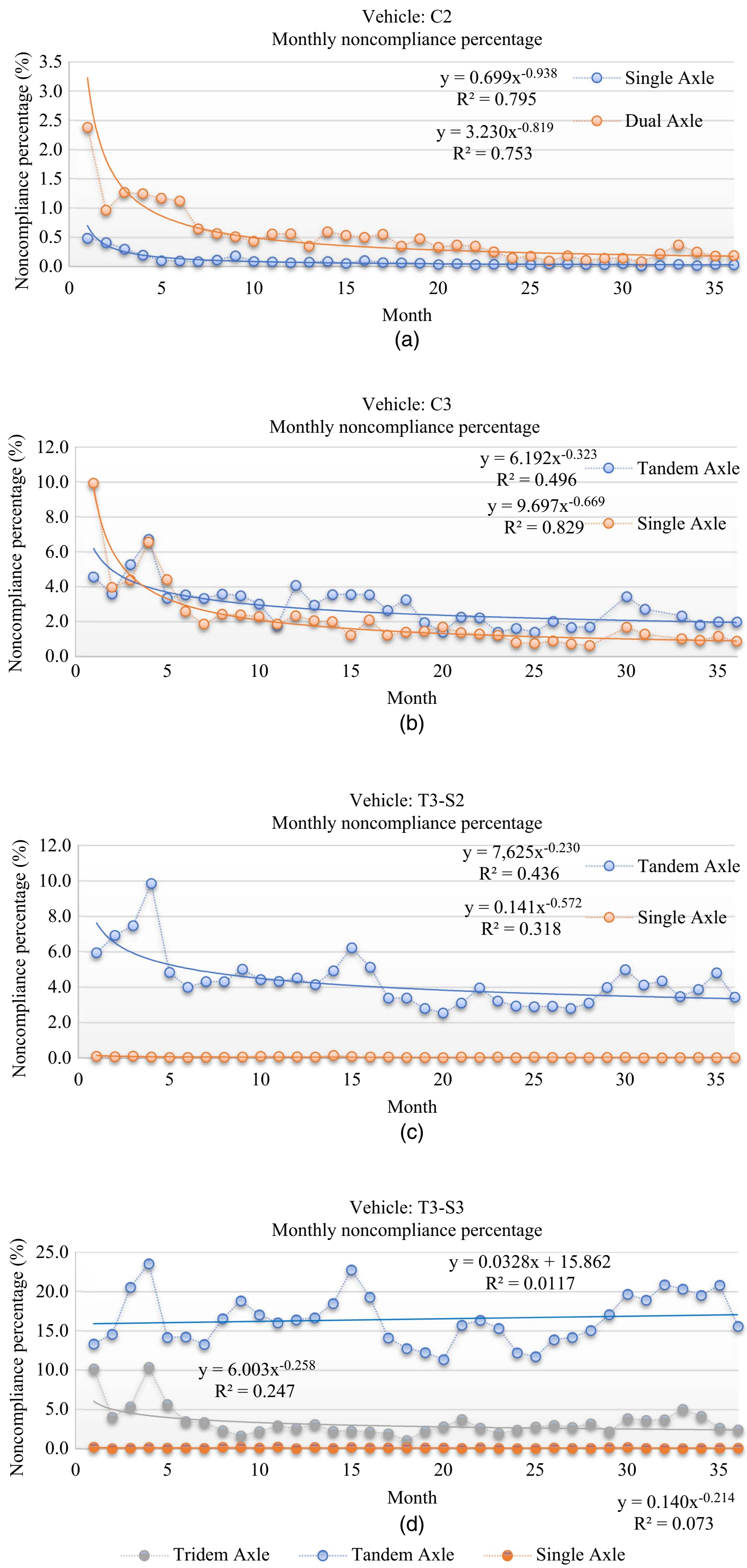


Fig. 4. Noncompliance in (a) C2; (b) C3; (c) T3-S2; and (d) T3-S3 class vehicles during the study period (from 2008 until 2011, in which x = months) for the analyzed weigh stations.

Table 4. Yearly noncompliance trends for each vehicle's class and axle: C2 and C3

Vehicle class	Period	Average (y = NC) (%)	Standard deviation (%)	Model (x = month)	SE (slope)	t-stat (slope)
C2 single axle	November 2008–October 2009	0.18	0.14	$y = 0.39 - 0.0320x$ and $R^2 = 0.66$	0.0073	4.38
	November 2009–October 2010	0.06	0.02	$y = 0.09–0.0054x$ and $R^2 = 0.68$	0.0012	4.50
	November 2010–October 2011	0.03	0.01	$y = 0.04–0.0014x$ and $R^2 = 0.16$	0.0010	1.40
C2 dual axle	November 2008–October 2009	0.95	0.55	$y = 1.76–0.1244x$ and $R^2 = 0.66$	0.0280	4.44
	November 2009–October 2010	0.40	0.13	$y = 0.57–0.0273x$ and $R^2 = 0.55$	0.0079	3.46
	November 2010–October 2011	0.17	0.08	$y = 0.11 + 0.0100x$ and $R^2 = 0.21$	0.0061	1.64
C3 single axle	November 2008–October 2009	3.74	2.40	$y = 7.03 - 0.5063x$ and $R^2 = 0.58$	0.1365	3.71
	November 2009–October 2010	1.47	0.40	$y = 1.99 - 0.079x$ and $R^2 = 0.51$	0.0244	3.24
	November 2010–October 2011	0.98	0.30	$y = 0.81 + 0.0256x$ and $R^2 = 0.10$	0.0256	1.00
C3 tandem axle	November 2008–October 2009	3.86	1.23	$y = 5.07–0.185x$ and $R^2 = 0.29$	0.0907	2.04
	November 2009–October 2010	2.53	0.84	$y = 3.78–0.1918x$ and $R^2 = 0.68$	0.0416	4.62
	November 2010–October 2011	2.10	0.56	$y = 1.89 + 0.0347x$ and $R^2 = 0.05$	0.0488	0.71

Note: NC = percentage of noncompliance; and SE = standard error.

Table 5. Yearly noncompliance trends for each vehicle's class and axle: T3-S2 and T3-S3

Vehicle class	Period	Average (y = NC) (%)	Standard deviation (%)	Model (x = month)	SE (slope)	t-stat (slope)
T3-S2 single axle	November 2008–October 2009	0.06	0.02	$y = 0.06–0.0006x$ and $R^2 = 0.01$	0.0021	0.29
	November 2009–October 2010	0.05	0.03	$y = 0.08–0.0058x$ and $R^2 = 0.37$	0.0024	2.42
	November 2010–October 2011	0.02	0.01	$y = 0.03–0.0016x$ and $R^2 = 0.18$	0.0011	1.45
T3-S2 tandem axle	November 2008–October 2009	5.48	1.77	$y = 7.44–0.3003x$ and $R^2 = 0.38$	0.1224	2.45
	November 2009–October 2010	3.80	1.11	$y = 5.11–0.2016x$ and $R^2 = 0.43$	0.0734	2.75
	November 2010–October 2011	3.72	0.75	$y = 2.98 + 0.1137x$ and $R^2 = 0.30$	0.0549	2.07
T3-S3 single axle	November 2008–October 2009	0.12	0.07	$y = 0.10–0.0023x$ and $R^2 = 0.01$	0.0061	0.38
	November 2009–October 2010	0.10	0.05	$y = 0.16–0.0081x$ and $R^2 = 0.36$	0.0034	2.38
	November 2010–October 2011	0.07	0.04	$y = 0.08–0.0017x$ and $R^2 = 0.02$	0.0039	0.44
T3-S3 tandem axle	November 2008–October 2009	16.53	3.11	$y = 16.40–0.0192x$ and $R^2 = 0.0005$	0.2731	0.07
	November 2009–October 2010	15.59	3.38	$y = 18.97–0.52x$ and $R^2 = 0.31$	0.2471	2.10
	November 2010–October 2011	17.29	3.13	$y = 13.22–0.6254x$ and $R^2 = 0.52$	0.1900	3.29
T3-S3 tridem axle	November 2008–October 2009	4.50	2.95	$y = 8.34–0.5904x$ and $R^2 = 0.52$	0.1787	3.30
	November 2009–October 2010	2.37	0.66	$y = 2.28–0.0138x$ and $R^2 = 0.01$	0.0577	0.24
	November 2010–October 2011	3.27	0.82	$y = 2.91–0.0548x$ and $R^2 = 0.06$	0.0699	0.78

Note: NC = percentage of noncompliance.

vehicles exceeding the regulation indicates convergence to a minimum value at the end of the observation period.

For the C3 vehicles, an apparent convergence on the percentage of overweight vehicles was observed. The slope of the annual regression on the last period tends toward zero. The yearly regression analysis for the tandem axle showed a decrease in vehicles exceeding the weight regulations. Even though a downward trend in the overweight vehicle proportion was observed, the authors believe cyclical behavior is still present.

By analyzing Fig. 4(d) for the T3-S3 vehicles, no outliers were evident, so it can be concluded that the number of overweight vehicles converged to a default value of 0.07% for the single axle. As observed in the figure, it tended to stabilize in the last analysis period. On the other hand, the tandem axle did not show a stabilizing trend; it exhibits a cyclic behavior. Concerning the tridem axle, a stabilization trend from 2010 was captured. However, the pattern changes toward an increase from 2011 onward. Table 6 summarizes the findings associated with convergence trends to a specific overweight noncompliance percentage during the 36-month analysis period.

Effect in Truck Equivalency Factors

The average truck equivalency factor (TEF) can be associated with the damage a given truck generates on the pavement structure. Eqs. (2) and (3) show the mathematical definitions for load equivalency and average truck equivalency factors (Ulloa et al. 2008)

$$\text{Load equivalency factor} = \left(\frac{\text{Weight of the main axle}}{\text{Weight of standard axle}}\right)^{\beta} \quad (2)$$

$$\text{Average truck equivalency factor} = \frac{\sum(\text{Amount of axles} \times \text{Load equivalency factor})}{\text{Amount of surveyed vehicles}} \quad (3)$$

$$\beta_x = 0.40 + \frac{0.81 \times (L_x + L_2)^{3.23}}{(\mathrm{SN}+1)^{5.19} \times L_2^{3.23}} \quad (4)$$

where the weight of the central axle is the weight of an ESAL of 80.07 kN (18.000 lb); β is determined through Eq. (4), in which L_x = load on a single wheel or one tandem-axle set (kips); L_2 = axle code (1 for single axle, and 2 for tandem axle); and SN = structural number (AASHTO 1993). Thus, the average truck equivalency factor depends on the axle combination for each vehicle class. The data were grouped for all permanent weigh stations, and the average truck factor with time was analyzed as per Fig. 5.

Table 7 summarizes the observed trends associated with the change in truck equivalency factors with time for the pooled weigh station data associated with C2, C3, T3-S2, and S3-T3 class vehicles.

Truck Equivalency Factor Behavior

There was a direct relationship between the percentage of vehicles exceeding the weight regulations and the average truck factor associated with these vehicles. The truck factor was used to determine the damage generated to a pavement structure due to the application of standard axles' weights (Amorim et al. 2013). Therefore, this section aims to establish the relationship between these variables to decide how the truck equivalency factor can be related to the percent of noncompliance regarding weight regulations.

The analysis was performed based on a simple linear regression between the overweight axles per vehicle class (i.e., percentage of noncompliance) and the truck equivalency factor as the dependent variable. This analysis estimated the correlation between noncompliance rates for the different axles and each vehicle type.

Table 6. Average noncompliance percentages afterconvergence

Vehicle	Axis	Convergence?	Default value after convergence (%)
C2	Single	Yes	0.02
	Dual	Yes	0.17
C3	Single	Yes	0.97
	Tandem	Yes	2.10
T3-S2	Single	Yes	0.02
	Tandem	Yes	3.72
T3-S3	Single	Yes	0.07
	Tandem	No	—
	Tridem	Yes	3.27

The variations in truck equivalency factors were also adequately modeled through a power (i.e., potential) regression for the data collected between October 2008 to November 2011 [Eq. (2)]. As a result, the truck equivalency factor for each vehicle type showed a reduction with time. Fig. 6 shows the change in truck equivalency factor for T3-S3, T3-S2, C3, and C2 vehicles, and their respective regression results.

For C2 vehicles, a significant relationship between the percentage of noncompliance in the dual axle and the truck equivalency factor was observed. Furthermore, there was a positive correlation between the noncompliance in the single and dual axles. Consequently, the estimation of a regression model, including the two factors, should be avoided because of the predictors' collinearity.

The C3 vehicles showed a higher correlation between the truck equivalency factor and the noncompliance percentage for the single axle than for the tandem axle. Because there is a correlation between the variables, no multiple regression analysis was pursued. Instead, the single axle noncompliance was selected because it showed the highest correlation with the truck equivalency factor.

For the T3-S2 models, a high correlation between the truck equivalency factor and the tandem axle's noncompliance (as a percentage) was found. Therefore, a multiple linear regression model was developed because the noncompliance between the single and tandem axles showed no significant correlation. However, no improvements in the relationship were obtained.

For the T3-S3 vehicle type, there was a low correlation between the truck equivalency factor and noncompliance for each axle type. The truck equivalency factor exhibiting the highest correlation coefficient corresponds to the tridem axle noncompliance with a correlation of approximately 39%. Furthermore, a multiple linear regression model was performed because of the absence of a

Table 7. Summary of TEF change with time: 2008 to 2011

Vehicle type	Model (t = month)	R^2	TEF (projected at month 36)	Convergence?
C2	$\text{TEF} = 0.44t^{-0.24}$	0.90	0.19	Yes
C3	$\text{TEF} = 1.13t^{-0.16}$	0.75	0.64	Yes
T3-S2	$\text{TEF} = 1.60t^{-0.10}$	0.79	1.12	Yes
T3-S3	$\text{TEF} = 2.00t^{-0.09}$	0.58	1.46	Yes

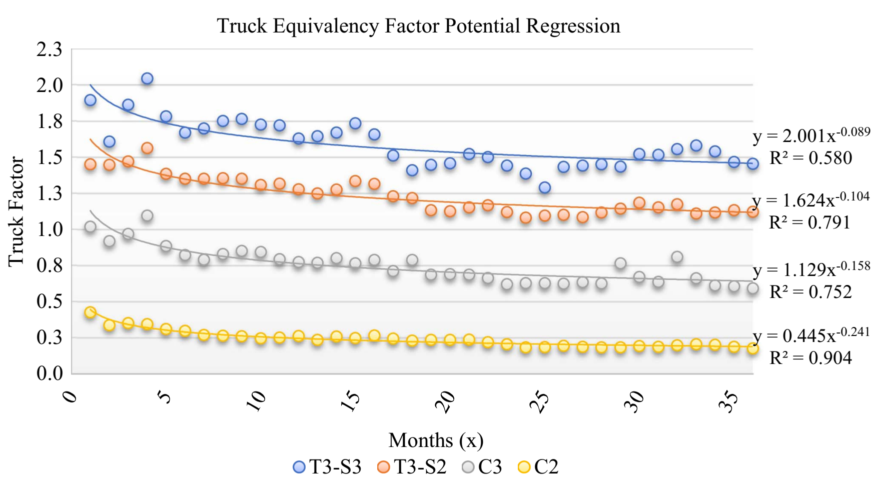
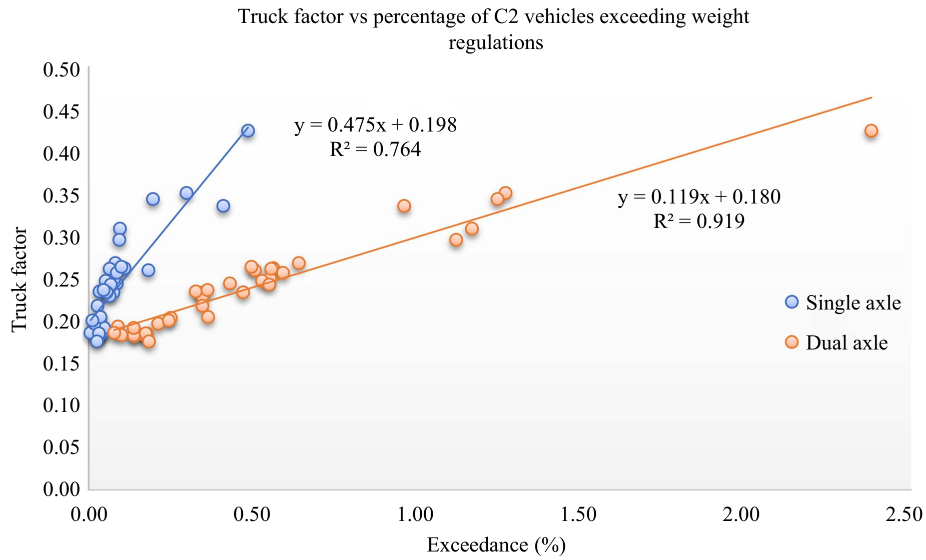
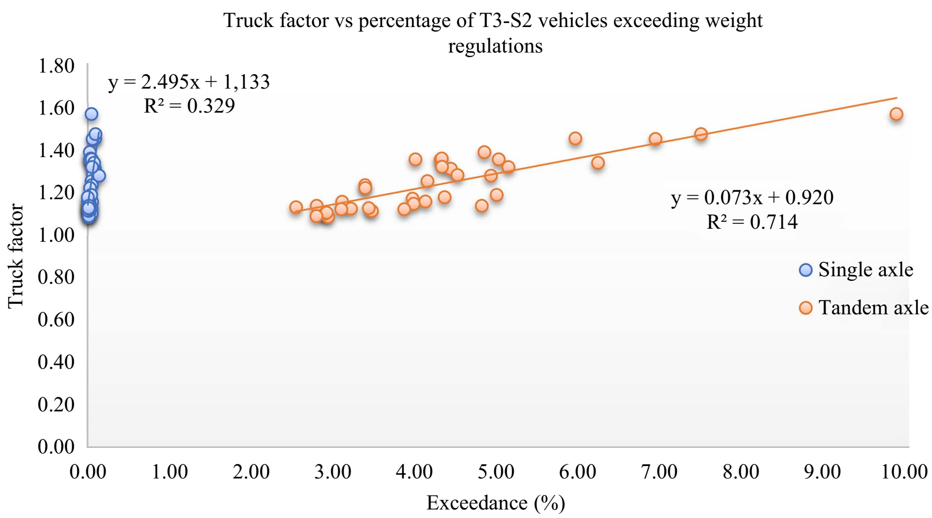


Fig. 5. Truck equivalency factor potential regressions for T3-S3, T3-S2, C3, and C2 class vehicles during the study period.



(a)



(b)

Fig. 6. Regressions between truck factor and noncompliance in (a) C2 class vehicles axles; and (b) T3-S2 class vehicles axles.

relationship between each axle type's noncompliance and the truck equivalency factor. The regression model with additional factors improved the correlation value to 62%, which is significantly better than those obtained with simple regression models. Eq. (5) shows the obtained model

$$\begin{aligned} \mathrm{TEF} = 1.10 &+ 0.998 \times \mathrm{Noncompliance}_{\mathrm{Single}} \\ &+ 0.0149 \times \mathrm{Noncompliance}_{\mathrm{Tandem}} \\ &+ 0.0434 \times \mathrm{Noncompliance}_{\mathrm{Tridem}} \end{aligned} \tag{5}$$

Discussion

Based on the results of the previous section, Tables 7 and 8 summarize the most statistically significant models for determining truck equivalency factors. The parameters included in the tables can be described as follows:

- Potential truck equivalency factor (i.e., power regression). The time-series analysis estimates the truck factor after 36 months: the equivalency factor after implementing the permanent weigh stations and the convergence process, a reduced value associated with the reduction in noncompliance to weight regulations.
- Truck equivalency factor default value. This is the convergence value calculated using the model that presented the best fit for each truck type after 36 months.
- Truck equivalency factor with 0% noncompliance (linear regression). This is calculated by the intercept of the linear regressions between the truck equivalency factor and noncompliance associated with one or more axles, corresponding to each vehicle class. This case represents the lowest theoretical truck equivalency factor that could be achieved (i.e., 0% noncompliance).
- Truck equivalency factor considering 5%, 10%, and 15% noncompliance. This is the value of the truck equivalency factors with the proposed equations in Table 9 under the assumption that the percentage of vehicles that exceed the allowed weight corresponds to 5%, 10%, or 15% (in the case of T3-S3, the excess was only considered for the tandem and tridem axles). It serves as a reference for possible noncompliance scenarios.

Another analysis was performed on the T3-S3 class vehicle category because there was no convergence for the tandem axle

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Table 8. Relationship between truck factor and weight compliance by vehicle class

Vehicle class	Dependent variable, y	Independent variable, x	Model
C2	Truck equivalency factor	Noncompliance in single axle	$Y = 0.542x + 0.194$ and $R^2 = 0.787$
	Truck equivalency factor	Noncompliance in dual axle	$Y = 0.117x + 0.180$ and $R^2 = 0.929$
	Noncompliance in single axle	Noncompliance in dual axle	$Y = 0.179x - 0.008$ and $R^2 = 0.814$
C3	Truck equivalency factor	Noncompliance in single axle	$Y = 0.086x + 0.578$ and $R^2 = 0.894$
	Truck equivalency factor	Noncompliance in tandem axle	$Y = 0.089x + 0.489$ and $R^2 = 0.764$
	Noncompliance in single axle	Noncompliance in tandem axle	$Y = 0.924x - 0.715$ and $R^2 = 0.709$
T3-S2	Truck equivalency factor	Noncompliance in single axle	$Y = 2.495x + 1.133$ and $R^2 = 0.329$
	Truck equivalency factor	Noncompliance in tandem axle	$Y = 0.073x + 0.920$ and $R^2 = 0.714$
	Noncompliance in single axle	Noncompliance in tandem axle	$Y = 0.009x + 0.001$ and $R^2 = 0.222$

Table 9. Comparison of the estimated truck equivalent factors

Vehicle type	Axle	Noncompliance (%)	TEF versus noncompliance models	R^2	TEF 0% noncompliance (linear)
C2	Dual	0.17	TEF = 0.1165 NC + 0.1802	0.93	0.18
C3	Single	0.97	TEF = 0.0857 NC + 0.5781	0.85	0.58
T3-S2	Tandem	3.72	TEF = 0.073 NC + 0.92	0.71	0.92
T3-S3	Single Tandem Tridem	0.07 17.29 3.26	TEF = 0.998 NC_single + 0.0149 NC_tandem + 0.0434 NC_tridem + 1.10	0.62	1.10
T3-S3[a]	Single Tandem Tridem	0.07 3.72 3.27			

Note: TEF = truck equivalent factor; and NC = percentage of weight noncompliance for respective axle.
[a]T3-S3 vehicle class analysis is determined using T3-S2 tandem axle regression.

Table 10. Comparison of the estimated truck equivalent factors includes potential TEF

Vehicle type	Axle	TEF constant noncompliance value	Potential TEF	TEF 5% noncompliance	TEF 10% noncompliance	TEF 15% noncompliance
C2	Dual	0.20	0.19	0.76	1.35	1.93
C3	Single	0.66	0.64	1.01	1.44	1.86
T3-S2	Tandem	1.19	1.12	1.29	1.65	2.02
T3-S3	Single Tandem Tridem	1.54	1.46	1.39	1.75	2.04
T3-S3[a]	Single Tandem Tridem	1.37				

Note: TEF = truck equivalent factor.
[a]T3-S3 vehicle class analysis is determined using T3-S2 tandem axle regression.

group, as demonstrated in previous sections. Therefore, the value associated with the T3-S2 tandem axle vehicles is used to show the hypothetical impact of noncompliance by this axle type.

After convergence based on the linear regression models, the truck equivalency factor's different values significantly correlated with the truck equivalency factor calculated by the power models. The truck equivalency factor increased as the number of articulated vehicle axles load also increased. Up to 25% of differences between the truck equivalency factors for the default condition and the zero-noncompliance scenario can be observed.

For the T3-S3 vehicles, two analyses were performed for stabilized truck factors: the first one used stabilization values for single and tridem axles and the minimum annual average obtained for the tandem axle; the second analysis was performed in a similar way but using the stabilization value of the tandem axle for the T3-S2 vehicles. The results show that a decrease in the truck factor values of up to 0.17 by demanding more strict and efficient control of the overload in the tandem axle for T3-S3 vehicles could be expected (TEF constant noncompliance values in Tables 9 and 10).

Transportation agencies could benefit from applying the suggested models to review the current legislation regarding overweight vehicles, infrastructure maintenance, and the design standard specifications for pavement structures and bridges. At the same time, countries that do not have current legislation or strong enforcement for overweight vehicles can observe the benefits of reducing truck factors in roads and bridges regarding this asset's lifetime.

The timely review of these factors when transportation agencies consider increasing or decreasing the limits for overweight vehicles may support the economy because it quantifies the damage costs these vehicles could generate on the infrastructure.

Conclusions

In general, the implementation of weight controls on national routes stabilized the truck equivalency factors and noncompliance percentages. The T3-S3 tandem axle type was the only load-carrying vehicle axle type that did not show convergence to a specific weight limit. For the same truck type, single and tridem axles stabilized at specific values.

The truck equivalent factors computed using a potential-power regression for C2, C3, T3-S2, and T3-S3 vehicles converged to 0.19, 0.64, 1.12, and, 1.46, respectively. The truck factors computed based on linear regressions on the percentage of vehicles with weights exceeding compliance limits on their axles converged to 0.20, 0.66, 1.19, and 1.54 for the same vehicle classes.

Regression models related to truck equivalency and noncompliance percentages captured considerable differences between the different vehicle axle types. There is a significant weight of some axle types on the truck equivalency factor. For example, in the C3 class, the correlation between the truck equivalency factor and noncompliance in the single axle type showed R^2 of 0.85 versus the tandem axle group's R^2 of 0.76. The previous difference can be explained by the fact that a single axle is more sensitive to overloading. Therefore, a policy recommendation is that weight control must be strict on the single axle associated with C3 vehicles.

In the future, analysis of the seasonal variation of truck traffic on the road network is recommended. For pavement design, it is essential to consider the evolution of the truck equivalency factors over time. An overestimation/underestimation of the design parameter can result in significant consequences to pavement performance and should be calibrated for local specific conditions. The results presented herein may help justify the benefit of an adequate weight control program to reduce the damage in pavement structures associated with truck traffic.

Future Work

The data set will be used to estimate local axle load spectra at a national level for Costa Rica and each site, to be used in mechanistic-empirical pavement design methodologies currently being implemented. Finally, future work with this data set involves a cost-benefit analysis regarding the implementation and maintenance of the weigh stations during the pavement's service life.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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