Transport and Communications Science Journal, Vol. 75, Issue 4 (05/2024), 1555-1566

Transport and Communications Science Journal

A CASE STUDY ON SCENARIO-BASED OPTIMIZATION FOR AXLE LOAD SURVEY DATA SELECTION FOR FLEXIBLE PAVEMENT DESIGN IN VIETNAM

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ARTICLE INFO

TYPE: Research Article
Received: 04/04/2024
Revised: 07/05/2024
Accepted: 09/05/2024
Published online: 15/05/2024
https://doi.org/10.47869/tcsj.75.4.7

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Abstract. The unique traffic patterns in Vietnam, characterized by a mix of vehicle types, axle configurations, and overloading, pose challenges to current flexible pavement design methods. This study investigates how selecting different vehicle axle load survey data scenarios impacts the accuracy of pavement design and rehabilitation for roads in Vietnam. Evaluation of various data selection methods and their influence on pavement response using the current flexible pavement calculation procedure in Vietnam. By comparing the pavement design criteria calculated under each scenario, this research aims to provide clear guidelines for engineers choosing appropriate axle load data for pavement design. This, in turn, will lead to the design and maintenance of more durable and sustainable pavements, ultimately promoting a more efficient and resilient transportation infrastructure in Vietnam. The research approach involves analyzing various axle load survey data scenarios, including those representing typical traffic conditions, overloaded vehicles, and specific vehicle types. The calculated pavement responses under each scenario are then compared to assess the impact of data selection on design outcomes. This study's findings are expected to provide valuable insights for pavement engineers in Vietnam, enabling them to select appropriate axle load data for accurate pavement design and rehabilitation. This will contribute to building more durable and sustainable road infrastructure, resulting in a more efficient and resilient transportation network.

Keywords: pavement structure, scenario-based, optimization, axle load, pavement design.

1. INTRODUCTION

Pavement design plays a crucial role in Vietnam's infrastructure development, impacting transportation efficiency and economic growth. Accurately accounting for traffic loads, particularly axle weight distribution, is essential for designing pavements that are both durable and cost-effective [1–5]. Axle load surveys provide valuable data on these loads, but collecting comprehensive data can be time-consuming and expensive [6–8]. This paper proposes a novel approach: scenario-based optimization for axle load survey data selection. This approach leverages the power of scenario planning to prioritize data collection efforts. By considering various traffic scenarios – for example, anticipated changes in vehicle types or freight volumes – the method strategically selects data that best represents the expected future pavement usage. This targeted data collection ensures pavement designs are optimized for the specific demands they will face, maximizing their lifespan and minimizing life-cycle costs.

1.1. Axle load for pavement design

In Vietnam, the current standard for flexible pavement design is TCCS38:2022/TCDBVN [9]. This standard specifies a single-axle, double-wheel configuration as the reference axle load (P) for design purposes. Typically, flexible pavement design utilizes a standard single-axle load (P) of 100 kN. However, for specialized roads encountering heavy axle loads exceeding 120 kN and constituting more than 5% of the total traffic volume, a single-axle, double-wheel load of 120 kN is employed as the design standard.

To account for tire-pavement interaction, the contact area of a single axle's two wheel tracks is converted into an equivalent circular area. This equivalent area has a diameter (D) of 33 cm for the standard single-axle load (P) of 100 kN and 36 cm for the heavier single-axle load (P) of 120 kN. The design process assumes a calculated wheel pressure (p) of 0.6 MPa on the road surface (see Table 1).

Table 1. Characteristics of standard axle loads [9].

Standard axle loads P (kN)	Wheel pressure p (MPa)	Equivalent wheel track diameter D (cm)
100	0.6	33
120	0.6	36

Equivalent Single Axle Load Conversion:

Vehicles operating on the road whose axle configurations differ from the design standard require load conversion to a standard equivalent single axle load (ESAL) using a specified formula. This conversion is performed for each front and rear axle group of the vehicle, considering individual axle loads, the number of axles, and the number of wheels per axle. Axle clusters are defined based on axle spacing: axles less than 3.0 meters apart are considered part of the same cluster, while axles exceeding 3.0 meters are considered separate. The following equation details the conversion from various axles to the standard ESAL:

$$N = \sum_{j=1}^{k} C_1 C_2 n_i \left(\frac{P_i}{P_{tt}}\right)^{4.4} \tag{1}$$

Where:

N: is the total number of axles converted from k different types of axles to standard axle across a road cross-section in a day (ESAL);

n_i: is the number of axle load i with load P_i converted to the standard axle load P. Normally, n_i is taken as the number of each vehicle i will pass the cross-section of the design road in a day for both directions;

C_1: is a coefficient considering the number of axes in an axis group determined by the equation:

$$C_1 = 1 + 1.2(m - 1) \tag{2}$$

With m is the number of axle in the axle cluster i;

C_2: is a coefficient that takes into account the effect of the number of wheels in a wheel cluster: for a single wheel $C_2 = 6.4$; double wheels $C_2 = 1.0$; and 4 wheels $C_2 = 0.38$.

In the following data processing section, eq. (1) will be employed to convert the surveyed axle loads to standard axle loads.

1.2. Effect of axle load on pavement life

The influence of axle load on pavement structural durability and lifespan is well established. It is understood that a higher number of load repetitions, particularly those exceeding a certain weight threshold, significantly impacts pavement lifespan. This effect is often quantified by the E_{yc} value (in Vietnam) or other pavement quality indicators. However, despite this established knowledge, theoretical and experimental research conducted in Vietnam has rarely addressed or adequately elucidated this crucial aspect.

Wang and Machemehl [10] used mechanical - emprirical methods to study the effects of wheel pressure on asphalt pavement. Research results have shown the relationship between axle load and pavement fatigue cracking (Fig. 1a) and rutting (Fig. 1b). These figures show that, as the axle load increases, the fatigue crack index and rut depth increase.

Salama et al. [11] studied the effect of heavy multi-axle trucks on flexible pavement damage. In this study, in-situ traffic and pavement performance data for flexible pavements in the state of Michigan (USA) are examined. Truck traffic data for different vehicle types were used to determine their relative destructive effects on flexible pavements in terms of cracking and rutting. The results indicate that trucks with multiple axles (tridem or more axles) appear to produce more rutting damage than single-axle and tandem-axle vehicles. On the other hand, trucks with single and tandem axles tend to cause more cracks.

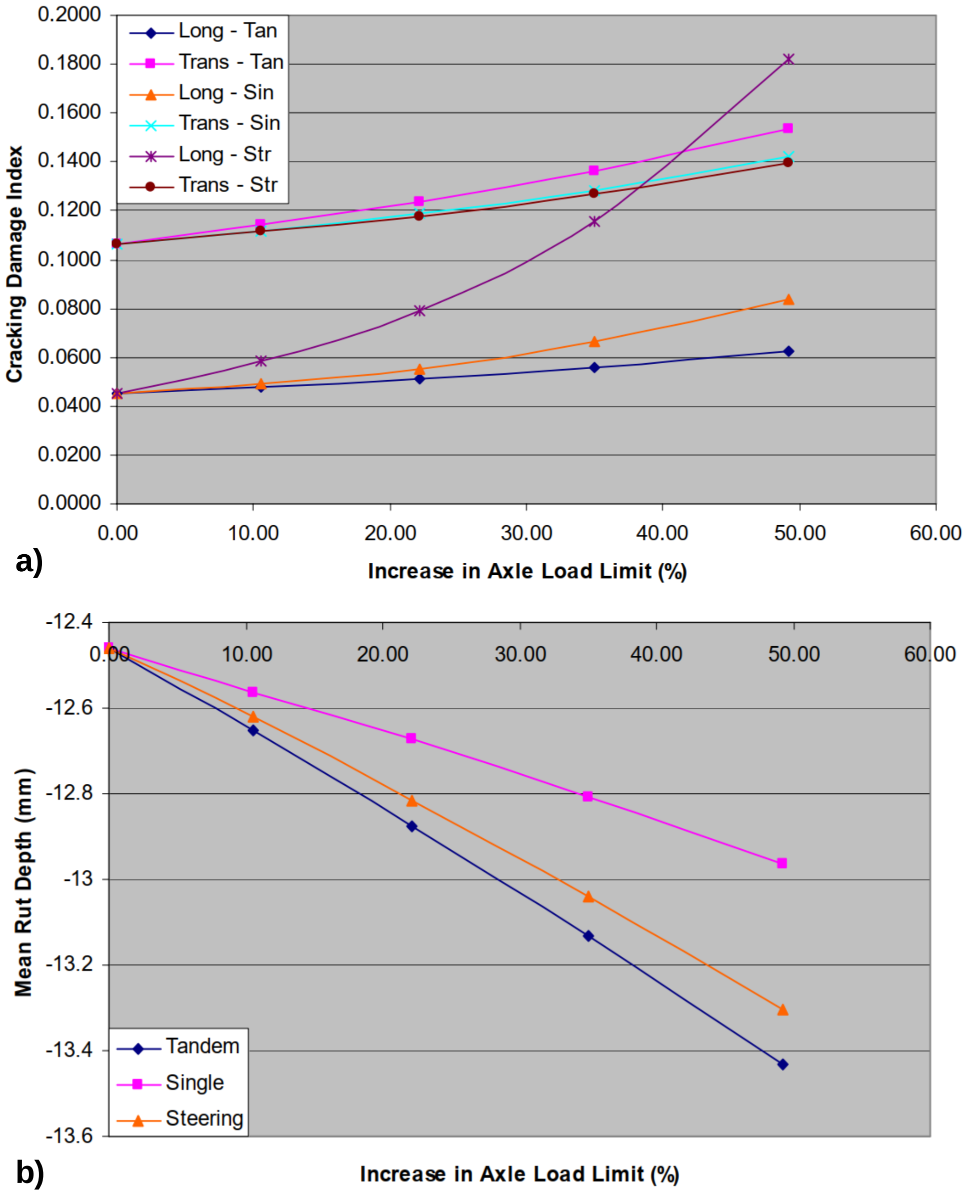

Figure 1. Correlation between axle load vs a) pavement fatigue cracking b) pavement rutting [10].

1.3. Flexible pavement design method with axle load in Vietnam

The TCCS 38:2022 standard [9] outlines a process for designing flexible pavement structures. Following the selection of a preliminary pavement structure, the standard mandates subsequent calculations to verify its load-bearing capacity. These calculations may necessitate adjustments to the thickness of individual pavement layers. The evaluation process considers three primary criteria:

Assessment of allowable elastic deflection: This step involves comparing the pavement structure's overall elastic modulus (E_{ch}) with the required elastic modulus (E_{yc}). This comparison ensures that traffic loading induces limited fatigue development within the pavement materials. Consequently, the pavement maintains its serviceability throughout the design life.

$$E_{ch} \geq K_{cd}^{dv} \times E_{yc} \tag{3}$$

where: E_{ch}: Pavement structure's overall elastic modulus, MPa; E_{yc}: Required elastic modulus, MPa; K_{cd}^{dv}: Safety factor of strength according to elastic deflection criteria.

Assessment of shear resistance in subgrade and unbound material layers: This assessment compares the calculated shear stress values with the allowable limits to ensure that plastic deformation is minimized or prevented within these layers.

$$T_{ax} + T_{av} \leq \frac{C_{tt}}{K_{cd}^{tr}} \tag{4}$$

where: T_{ax}: The maximum active shear stress is caused by wheel load in the subgrade or in unbound material layers; T_{av}: Active shear stress is caused by the self-weight of the material layers above it; K_{cd}^{tr}: Safety factor of strength according to shear resistance criteria; C_{tt}: Calculated cohesion of the subgrade or unbound material layers at the calculated moisture and density.

Assessment of tensile bending stresses in adhesive material layers: This step involves evaluating the tensile bending stresses arising at the bottom of bound material layers. The objective is to limit the development of cracks that could compromise the integrity of these layers.

$$\sigma_{ku} \leq \frac{R_{tt}^{ku}}{K_{cd}^{ku}} \tag{5}$$

where: σ_{ku}: The maximum tensile bending stress arises at the bottom of the bound material layer under the effect of wheel load; R_{tt}^{ku}: Calculated tensile bending strength of the bound material layer; K_{cd}^{ku}: Safety factor of strength according to tensile bending stress criteria.

Calculation of this assessment is solely required for pavement structures of grades A1 and A2 that incorporate asphalt concrete layers and unbound granular materials (soil, sand, and stone) stabilized with inorganic binders.

This study aims to provide recommendations for selecting axle loads for pavement calculations within the framework of TCC38:2022/TCDDBVN . This research is motivated by the recent change in the standard axle load specified in TCC38:2022/TCDDBVN compared to its previous version, 22 TCN 211-06 [12] (previously used for flexible pavement calculations in Vietnam before 2022). Prior to 2022, the standard axle load for North-South Expressway construction projects in eastern Vietnam was 120 kN according to 22 TCN 211-06. However, TCC38:2022/TCDDBVN implemented from 2022 lowered the standard axle load to 100 kN for these projects. This change in standard axle load selection has the potential to result in unsuitable flexible pavement structures, leading to premature pavement damage. Therefore, this study identifies this critical issue and proposes recommendations for selecting appropriate standard axle loads for Vietnamese conditions within pavement calculations.

2. SURVEY DATA OF AXLE LOAD

2.1. Presentation of survey locations

Axle load survey was carried out on National Highway 1 in August 2020 to serve the design of the Quang Ngai-Hoai Nhon expressway section, part of the North-South Expressway construction project in the Easten part of Vietnam. Five road sections were chose to perform axle load survey: Section 1: Quang Ngai – Provincial Road 624B; Section 2: Provincial Road

624B – National Highway 24; Section 3: National Highway 24 – Duc Pho; Section 4: Duc Pho – Sa Huynh; Section 5: Sa Huynh – Hoai Nhon.

The vehicles surveyed include 11 types, each vehicle type is weighed to determine the load of each axle: (T1) Small buses, (T2) Large buses, (T3) Light trucks, (T4) 2-4T medium trucks, (T5) 4-10T medium trucks, (T6) 10-18T medium trucks, (T7) 3-axle heavy trucks - Type I, (T8) 3-axle heavy trucks - Type II, (T9) 4-axle heavy trucks, (T10) 5-axle heavy trucks, (T11) 6-axle trucks. For buses, to facilitate the calculation steps, two types of 12-24 seats and 25-30 seats are classified in the same group of small buses, buses > 30 seats are classified in the group of large buses. Axle load conversion coefficients, C_1 and C_2, were established for the vehicle types surveyed and presented in Table 2.

Table 2. Statistics of vehicle types surveyed and corresponding coefficients C_1 and C_2.

Code	**Vehicle types**	**Number of axles**	**Axle position**	**Axle type**	C_1	C_2
T1	Small buses	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, single wheel	1	6.4
T2	Large buses	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, dual wheels	1	1
T3	Light trucks	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, single wheel	1	6.4
T4	2-4T medium trucks	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, dual wheels	1	1
T5	4-10T medium trucks	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, dual wheels	1	1
T6	10-18T medium trucks	2	Front axle	Single axle, single wheel	1	6.4
			Rear axle	Single axle, dual wheels	1	1
T7	3-axle heavy trucks - Type I	3	Front axle	Single axle, single wheel	1	6.4
			Rear axle 1	Single axle, single wheel	1	6.4
			Rear axle 2	Single axle, dual wheels	1	1
T8	3-axle heavy trucks - Type II	3	Front axle	Single axle, single wheel	1	6.4
			Rear axle 1	Tandem, dual wheels	2.2	1
T9	4-axle heavy trucks	4	Front axle	Single axle, single wheel	1	6.4
			Rear axle 1	Single axle, dual wheels	1	1
			Rear axle 2	Tandem, dual wheels	2.2	1
T10	5-axle heavy trucks	5	Front axle	Single axle, single wheel	1	6.4
			Rear axle 1	Single axle, dual wheels	1	1
			Rear axle 2	Tridem, dual wheels	3.4	1
T11	6-axle trucks	6	Front axle	Single axle, single wheel	1	6.4
			Rear axle 1	Tandem, dual wheels	2.2	1
			Rear axle 2	Tridem, dual wheels	3.4	1

The expressway sections are expected to complete construction and be put into operation in 2025. The proposed design life is 15 years. Therefore, the traffic of the component vehicles forecasted at the end of the design period (2040) is used for calculation. The figures are taken from transport demand results [13], shown in Tables 3.

Table 3. Forecasting transportation demand on expressways in 2040 (vehicles/day) [13].

Vehicle types	**Section**				
	Section 1	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Small buses	1358	1349	1231	1088	1119
Large buses	222	221	201	178	183
Light trucks	2001	1899	1381	1190	1199
2-4T medium trucks	4539	4308	3133	2700	2719
4-10T medium trucks	974	924	672	579	583
10-18T medium trucks	291	276	201	173	175
3-axle heavy trucks - Type I	35	33	24	21	21
3-axle heavy trucks - Type II	251	238	173	149	150
4-axle heavy trucks	512	486	354	305	307
5-axle heavy trucks	342	324	236	203	205
6-axle trucks	897	851	619	533	537

2.2. Results of axle load survey

Table 4 summarizes the vehicle axle load data surveyed on the route sections (mean value). The survey vehicle load is compared to the manufacturer's registration, the overload rate of vehicles is therefore shown in Fig. 2. The data indicate a high overload rate (29.9-62.5%) among the surveyed vehicles. This finding highlights the importance of stricter control on heavy vehicle loads during road management and operation. Additionally, it underscores the need to investigate and potentially implement the use of heavier design axle loads for pavement design.

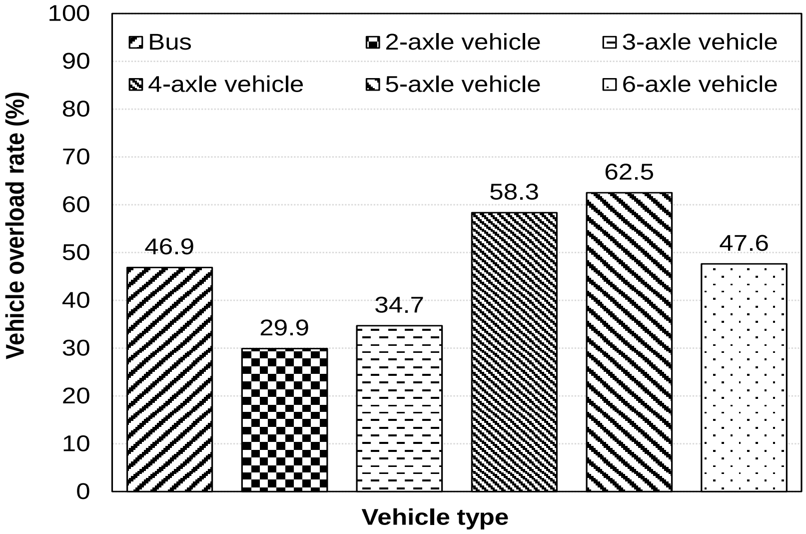

Figure 2. Rate of overloaded vehicles according to axle load survey results.

Table 4. Summary of axle loads for surveyed vehicles on studied sections (mean values - Kg).

Vehicle types	Number of axles	Number of vehicles	Axle load (Kg)						Total vehicle weight (Kg)
			Wt1	**Wt2**	**Wt3**	**Wt4**	**Wt5**	**Wt6**	
T1	2	6	1750	1980	-	-	-	-	3730
T2	2	26	5813	11120	-	-	-	-	16933
T3	2	1	530	350	-	-	-	-	880
T4	2	14	1331	1781	-	-	-	-	3112
T5	2	52	2039	2956	-	-	-	-	4995
T6	2	50	4337	7662	-	-	-	-	11999
T7	3	6	3528	3637	6830	-	-	-	13995
T8	3	43	5425	7333	7873	-	-	-	20631
T9	4	12	5462	5518	8200	8103	-	-	27283
T10	5	8	5763	6421	3949	7238	7263	-	30634
T11	6	21	5774	7136	7029	5830	6372	6043	38184

3. APPROACH FOR SELECTION OF AXLE LOAD DATA INTO PAVEMENT CALCULATION

3.1. Scenarios for selection of axle load data

Based on the vehicle load survey results presented in Section 2.2, the analysis revealed a significant presence of overloaded vehicles across all vehicle types. To account for this real situation, the study proposes employing four distinct scenarios to determine the elastic modulus (E_{yc}) for each survey location. These scenarios will include:

- *Scenario 1*: Calculated vehicle number Including Overloaded Vehicle (IOV) with a standard axle load of 100 kN.
- *Scenario 2*: Calculated vehicle number Including Overloaded Vehicle (IOV) with a standard axle load of 120 kN.
- *Scenario 3*: Calculated vehicle number Excluding Overloaded Vehicle (EOV) with a standard axle load of 100 kN.
- *Scenario 4*: Calculated vehicle number Excluding Overloaded Vehicle (EOV) with a standard axle load of 120 kN.

3.2. Calculation of required modulus for pavement calculation

The total number of standard axles (N) is calculated using eq. (1) and eq. (2), incorporating a lane coefficient of $f_l = 0.35$ for a four-lane road with a median strip. This lane coefficient is in accordance with TCCS 38:2022 [9]. Subsequently, the required pavement elastic modulus (E_{yc}) is determined using Table 9 in TCCS 38:2022 [9]. The calculated values of E_{yc} for analysed sections is presented in Fig.3.

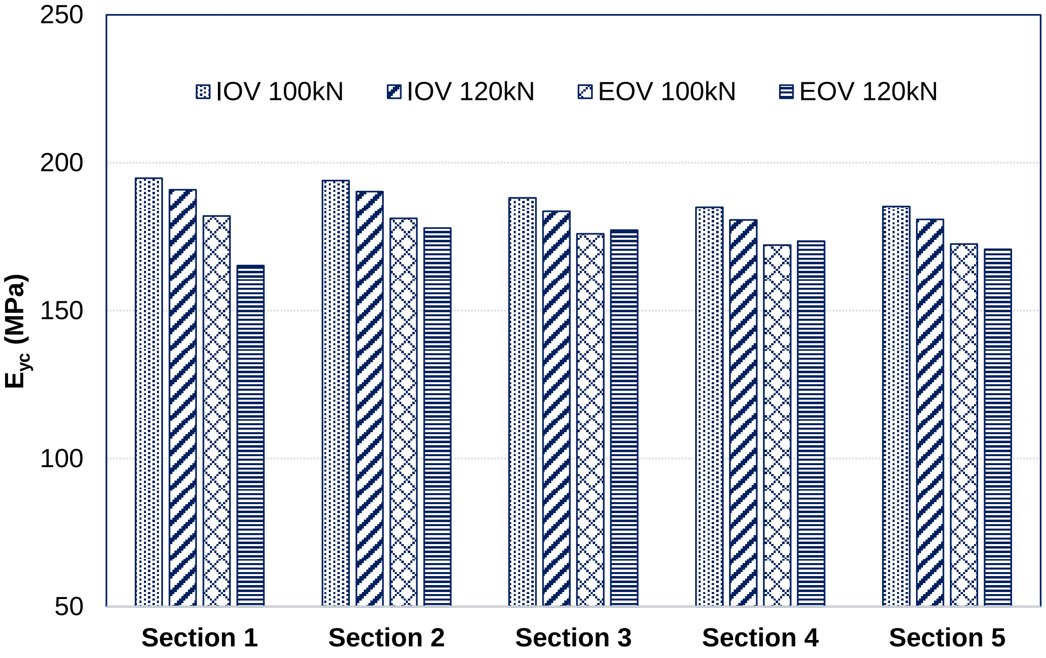

Figure 3. Comparison of calculated elastic modulus (Eyc) for pavement sections in Quang Ngai - Hoai Nhon area.

The E_{yc} calculations across the four scenarios reveal several key findings. Scenarios that excluded overloaded vehicles (EOV) yielded lower required elastic modulus values compared to scenarios that incorporated them (IOV). This highlights the significant impact of overload prevalence on pavement design requirements. Additionally, most of scenarios employing a 100 kN standard axle load resulted in higher calculated elastic modulus values than those using a 120 kN load possibly due to the existence of a relationship directly between the denominator of eq. (1) and the value of N. As the denominator increases, N exhibits an exponential decrease. This emphasizes the influence of the standard axle load on the design process.

3.3. Assessment of different axle load scenarios

TCCS 38:2022 [9] specifies two standard axle loads for flexible pavement design:

- **Single Axle Load 100 kN**: This load applies to conventional flexible pavement design. It features double wheels with a calculated pressure of 0.6 MPa on the road surface and an equivalent wheel track diameter of 33 cm.
- **Single Axle Load 120 kN**: This load is used for specialized roads with an axle load exceeding 120 kN representing more than 5% of the total traffic. It also features double wheels with a calculated pressure of 0.6 MPa on the road surface and an equivalent wheel track diameter of 36 cm.

However, this study will present two pavement structure design examples using axle loads of 100 kN and 120 kN. These examples will evaluate the applicability of TCCS 38:2022 with actual axle load survey data collected on the Quang Ngai-Hoai Nhon area. Input design data consists of flexible pavement structure, high grade A1; Design period: 15 years; Design reliability: 0.95; Calculated axle load: Single axle with double wheel, standard axle load of 100 kN and 120 kN; Calculated number of vehicle axles N in the last year of the design term: 1181 axles/day/lane for calculated axle load of 100 kN and 529 axles/day/lane for calculated axle load of 120 kN (all includes overloaded vehicles). The other data is presented in Table 5.

Table 5. Proposed pavement structure and calculation characteristics of pavement layers.

Pavement layer (from the bottom)	**Thickness (cm)**	**E (Mpa)**			**R_{ku} (Mpa)**	**C (Mpa)**	**φ (°)**
		Calculation of delection	**Calculation of shear resistance**	**Calculation of tensile bending stress**			
Clayey soil		42	42	42		0.032	24
Crushed stone aggregate - class 2	30	230	230	230			
Crushed stone aggregate - class 1	25	280	280	280			
Crushed stone aggregate stabilized with 4% cement	13	600	600	600	0.8		
Asphalt concrete C19	7	420	300	1800	2.8		
Polymer asphalt concrete C12.5	6	439	264	1113	5.3		

The test results to assess allowable elastic deflection and shear resistance in subgrade and unbound material layers, and tensile bending stresses in adhesive material layers are illustrated in Table 6 and Table 7, respectively.

Table 6. Assessment of allowable elastic deflection and shear resistance in subgrade and unbound material layers.

Standard axle load (P-kN)	**Elastic deflection**			**Shear resistance in subgrade and unbound material layers**		
	E_{ch} (MPa)	**$K_{cd}^{dv} \times E_{yc}$ (MPa)**	**Test result**	**$T_{ax} + T_{av}$ (MPa)**	**$\frac{C_{tt}}{K_{cd}^{tr}}$ (MPa)**	**Test result**
100	230.7	227.8	Passed	0.0031	0.019	Passed
120	219.3	223.2	**Failed**	0.0037	0.023	Passed

Table 7. Assessment of tensile bending stresses in adhesive material layers.

Standard axle load (P-kN)	**Layer**	**Tensile bending stresses in adhesive material layers**		
		σ_{ku} (MPa)	**$\frac{R_{tt}^{ku}}{K_{cd}^{ku}}$ (MPa)**	**Test result**
100	Polymer asphalt concrete C12.5	0.81	2.43	Passed
	Asphalt concrete C19	0.62	1.08	Passed
	Crushed stone aggregate stabilizied with 4% cement	0.17	0.43	Passed
120	Polymer asphalt concrete C12.5	0.78	2.04	Passed
	Asphalt concrete C19	0.64	1.28	Passed
	Crushed stone aggregate stabilized with 4% cement	0.20	0.46	Passed

The evaluation of two pavement structure designs using the standard axle loads of 100 kN and 120 kN revealed contrasting results. Under the 100 kN load scenario, the proposed pavement structure adequately satisfied all criteria. However, when subjected to the 120 kN axle load, the design does not meet the elastic deflection criteria, despite a lower required elastic modulus (E_{yc}). This highlights the importance of considering the impact of axle load beyond just the E_{yc} value in pavement design.

4. CONCLUSION

This study underscores the importance of incorporating realistic axle load data, including overloaded vehicles, into the pavement design process for Vietnamese expressways. Analyzing four scenarios revealed that designs excluding overloaded vehicles resulted in lower required elastic modulus (E_{yc}) values. However, counterintuitively, these lower E_{yc} designs (e.g., 120 kN standard axle load) might not translate to a stronger pavement. The proposed evaluation using design examples demonstrated that pavements designed for lower E_{yc} scenarios failed to meet elastic deflection criteria despite having a lower required E_{yc}. This finding highlights a critical limitation: relying solely on E_{yc}, without considering the actual traffic load distribution, can lead to pavements susceptible to excessive deflection under real-world conditions. This emphasizes the need for pavement design procedures in Vietnam to integrate realistic traffic load data, encompassing the prevalence of overloaded vehicles. By doing so, engineers can design more durable and sustainable pavements for Vietnam's unique traffic patterns.

ACKNOWLEDGMENT

This research is funded by University of Transport and Communications (UTC) under grant number T2024-CT-005TĐ.

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