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Assessment of Concrete Pavement Performance on Istanbul's BRT Lines

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Abstract

The performance of concrete pavements is directly related to stresses and vertical displacements generated by vehicle loads. Selecting appropriate pavement and base thickness is crucial for extending service life in heavy vehicle areas like Istanbul's bus rapid transit lines. This study aims to calculate the maximum stress and vertical displacements caused by Istanbul's bus rapid transit vehicles on concrete pavements. There are currently four types of buses actively operating on Istanbul's bus rapid transit line, each with different axle configurations and load capacities. Stresses and vertical displacements were calculated for the heaviest axle configuration of these buses under edge and center loading conditions using the Finite Element Method (FEM). These analyses were repeated across three different overlay conditions: concrete overlay of asphalt, concrete overlay of concrete, and concrete overlay on granular base. A total of 24 analyses, covering various loading conditions and pavement configurations, were conducted using the EverFE software. This research reveals maximum stress and vertical displacement values under various loading conditions, base properties, and slab thicknesses, offering critical insights for determining pavement thickness and guiding maintenance strategies. This study also fills the gap in the literature regarding the determination of concrete pavement thickness for BRT lines.

Keywords: Bus rapid transit (BRT), concrete pavement, structural design, FEM, foundation materials.

1. Introduction

Concrete pavements offer significant advantages in carrying traffic loads on roads exposed to heavy vehicle traffic, with their low-cost and environmentally friendly characteristics [1-3]. Thanks to their high bearing capacity and rigidity, concrete pavements can effectively distribute traffic loads over broader and more uniform areas to the base and subbase layers, making them an effective alternative to asphalt concrete pavements in numerous road applications [4-6].

At first, concrete slab thickness was determined exclusively by experimental research and observation. However, with the advancement of numerical and FE methods, it has become possible to examine the structural responses of slabs [7]. Westergard, who is considered a pioneer of these studies, developed closed-form formulas using FEM to calculate maximum strains and maximum displacements [8]. After these studies, the structural response of concrete pavements under vehicle loads became the main method for thickness design. In the thickness design of concrete pavements, two criteria "erosion" and "fatigue" began to be taken into consideration [8-11]. The PCA 1984 method is one of the primary mechanical methods developed by considering stresses and vertical displacements. The two damage conditions identified by this procedure are erosion and fatigue. The fatigue damage of the concrete pavement is determined by maximum strain, and the erosion damage of the base layer is determined by vertical displacements [12].

There are three primary types of concrete pavements used in road projects: continuously reinforced concrete pavement (CRCP), jointed reinforced concrete pavement (JRCP), and jointed plain concrete pavement (JPCP). Although concrete slabs are designed in different types, two main properties are expected from all of them. The first of these is to exhibit good performance against axle loads on the pavement structure by utilizing the flexural strength of concrete, ensuring that the bending stresses remain below this flexural strength. The second is to resist shrinkage tendencies of the concrete due to the release of hydration energy during the setting process, along with expansion tendencies induced by environmental factors [3,13].

Today, in addition to traditional concrete pavements, roller compacted concrete pavements (RCCP) and concrete pavements constructed with a slipform paver, which are produced using specially prepared gradations, have also become widely used in road construction. These type of pavement can be swiftly placed and compacted, and in a matter of days, it can be made accessible to traffic. These characteristics make them ideal for roads that need to be opened to traffic urgently. Additionally, they offer long-lasting performance with their durable structure and require minimal maintenance especially under heavy traffic conditions [14,15].

In the literature, there are some studies that examine the mechanical effects caused by vehicle loads on asphalt and concrete pavements using FEM. In their study, Singh and Ghosh analyzed the mechanical stresses occurring in concrete pavements under vehicle axle loads and environmental loads using the SAP2000 FEM software [16]. The performance of BRT lines in Nevada, USA, under high bus loads was investigated by Hajj et al. The Nevada BRT line used asphalt pavements, so their study included rutting and fatigue analyses [17]. In his study, Vargas analyzed the transitions between Portland Cement Concrete Pavements (PCCP) and Asphalt Concrete Pavements (ACP) constructed for Bogotá's BRT lines, TransMilenio, using the Abaqus FEM software. He examined the dynamic loading effects caused by vehicles at the concrete-asphalt pavement transitions [18].

There are numerous studies focused on enhancing the mechanical and strength properties of concrete and soils by adding fibers [19-22]. Concrete is transformed into a composite material by adding fibers. The primary purpose of these fibers is to improve crack control by increasing the concrete's flexural and tensile strength. Adding fibers to concrete used as road pavement will increase its resistance to tensile stresses on the top and bottom surfaces of the concrete due to repeated axle loads and environmental conditions. In addition to improving the pavement's fatigue and erosion performance, this will increase its resistance to cracking [23-25]. Although fibers additives to concrete improve flexural strength and crack resistance, they do not have a significant effect on compressive strength or static modulus of elasticity [26, 27]. Its effect on Poisson's ratio is also quite limited. Therefore, the stresses occurring in concrete pavements under vehicle loads are not highly related to whether the concrete contains fibers or not.

Concrete pavements can be constructed directly on natural or granular subgrades. Nonetheless, they may be constructed on top of pre-existing pavements. In this regard, concrete pavements can be constructed in a composite structure as concrete overlay of asphalt and concrete overlay of concrete [28]. In the Istanbul BRT network, known as the 'Metrobus' system, concrete pavement applications have started to involve both concrete overlays of asphalt and concrete overlays of concrete [29]. In this context, a total of 35.9 km (71.8 km for the round trip) of roads were covered with concrete pavement, commonly referred to as 'white road' by Istanbul Municipality, in three stages, starting from 2022 [30].

In this paper, stress and vertical displacements were calculated caused by Istanbul's BRT transit vehicles through FEM analysis. The four types of buses currently operating on the Istanbul BRT line are the Mercedes Conecto, Mercedes Capacity, Otokar Kent XL, and AKIA Ultra

LF25. The heaviest axle loads of these four vehicles have been selected as critical axle loads and used in the analyses. The analyses were repeated for three different overlay conditions: concrete overlay of asphalt, concrete overlay of concrete, and concrete overlay on granular base, with the first two already in use at the Istanbul BRT line. Using the EverFE FEM software, a total of 24 evaluations covering different pavement layouts and loading situations were carried out. There are limited studies in the literature that investigate the stress and vertical displacements caused by BRT lines and the vehicles operating on these lines. This study has unique value in filling this gap in literature. Additionally, the study examines stress and deformations under three different pavement conditions on the same BRT line represents another distinctive aspect of the work.

2. Material and Method

Istanbul's BRT service, which began with an 18.3 km line in September 2007, has expanded to become the city's most important transit system, with a 52 km one-way total length and 44 stations [30]. The primary public transit system in the city, Istanbul BRT connects to numerous other forms of transportation. From the beginning, the Istanbul BRT line has been run on an asphalt surface. However, under the intense repetitive traffic of heavy vehicles on the BRT line, it has suffered from various deteriorations, primarily including ruttings (Fig. 1.). Because of the BRT lane's narrowness, the tires of the vehicles travel on a single track, accelerating the development of rutting. After experiences with the low serviceability and high maintenance costs of the asphalt on the BRT line, the Istanbul Municipality adopted a concrete road application through a three-phase program.

Fig. 1. Asphalt deterioration in Istanbul BRT line [31]

BRT buses' sizes and high axle loads are the main factors behind the Istanbul municipality's wish to convert to concrete roads. The vehicles currently in use, including the Mercedes Conecto, Mercedes Capacity, Otokar Kent XL, and AKIA Ultra LF25, are high-capacity buses specifically designed for these roads. The number of BRT vehicles in the inventory of the Istanbul Municipality and their associated characteristics are as shown in Table 1.

In this study, the stresses and vertical displacements occurring on concrete pavements are examined based on the heaviest axle weight of each bus. As a result, the vehicles' axle construction and size have also been taken into account. The sizes of these vehicles range from 18 to 25 meters. The number of axles ranges from 3 to 5 and the axle configurations and spacing of the axles of these vehicles are presented in Fig. 2.

Table 1. Istanbul BRT vehicle details

	Mercedes Conecto G [32]	Mercedes Capacity [33]	Otokar Kent XL [34]	Akia Ultra LF 12 [35]
Vehicle length (mm)	18124	19725	20995	25000
Vehicle width (mm)	2550	2550	2540	2550
Axle spacings (mm)	1st-2nd 5900 2nd-3rd 5990	1st-2nd 5900 2nd-3rd 5990 3rd-4th 1600	1st-2nd 5900 2nd-3rd 7385 3rd-4th 1600	1st-2nd 5868 2nd-3rd 6652 3rd-4th 6680 4th-5th 2790
Maximum axle load (kg)	13200	13000	11500	12000
Gross weight (kg)	30500	32000	34000	45000
Seats	40	44	39	29
Standing capacity	110	137	182	252
Total capacity	150	181	221	281

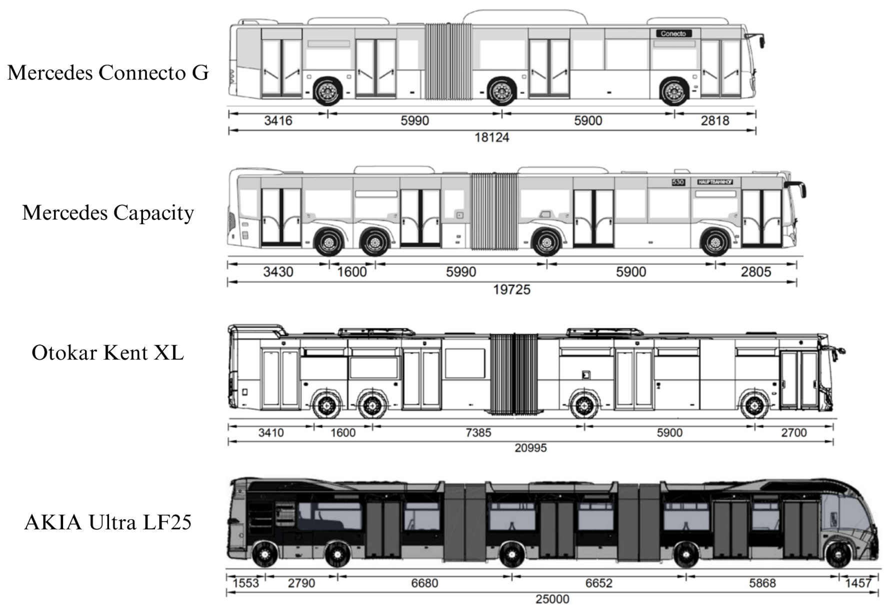

Fig. 2. Vehicle on the Istanbul BRT Line [32-35]

Considering the heavy usage and critical importance of the Istanbul BRT line, the Istanbul Municipality has chosen concrete road technology that can be laid with a slip-form paver to accelerate construction processes. The existing concrete and asphalt pavements were also chosen to serve as a base layer throughout the building phase. According to the technical specifications from the tender documents, two different layer structures were applied: concrete overlay of asphalt and concrete overlay of concrete [29]. It is thought that the concrete pavement was constructed directly on top of the granular subgrade in some sections. Consequently, it is noted that different BRT line segments utilize various layer structures. The pavement thicknesses of the three different layer structures are shown in Fig. 3. In Table 1, the selected material properties used in the pavement layer analysis are presented. The table includes the modulus of elasticity and Poisson's ratios for the newly placed fiber-reinforced C40 concrete, C25 existing concrete, existing asphalt pavement, and granular base layer. These parameters were chosen to represent each material’s specific mechanical characteristics in the analysis.

The pavement width of 330 cm was selected as part of the three-phase concrete pavement transition project for the Istanbul BRT line. Joint applications were positioned every 110 cm throughout this width, which was split horizontally into three equal sections. Longitudinally, joints were also placed at intervals of 110 cm, creating 110x110 cm square sections. In the construction method, a slipform concrete paver was used, and high-quality (C40) concrete with polypropylene/polyamide fiber reinforcement was utilized. In Table 2, the estimated material and layer properties are presented.

Table 2. Material Properties for Layers

Material	Modulus of elasticity (GPa)	Poisson's ratio	Density (kg/m^3)
Fiber-Reinforced Polypropylene Concrete Pavement (C40)	34.0	0.15	2300
Existing Concrete (C25)	30.0	0.15	2300
Existing Asphalt Pavement	1.0	0.30	2300
Granular Base Layer	0.3	0.25	2200

The axle weights of four vehicles actively serving on the Istanbul BRT line were examined. Analyses have been conducted based on the axles that, in terms of stresses and vertical displacements, put the most impact on the pavement. The following four axle configurations were selected for analysis: the third axle (rear) weighing 13.2 tons for the Mercedes Conecto G model, the third axle with a weight of 13 tons for the Mercedes Capacity model, the third axle weighing 11.5 tons for the Otokar Kent XL, and both the second and third axles, each weighing 12 tons, for the Akia Ultra LF25.

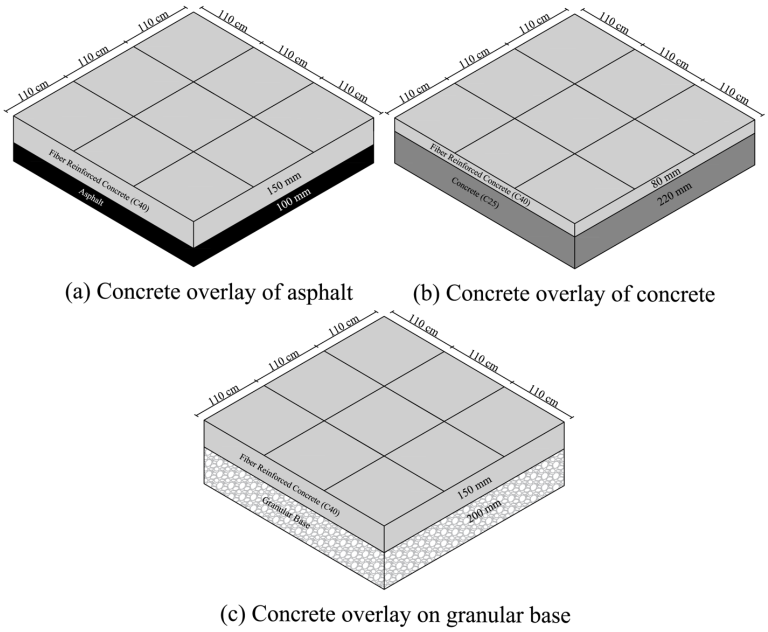

Fig. 3. Layers of the analyzed pavements

A detailed analysis of the selected axles revealed dual wheel configuration at both ends, with a wheel size of 275/70 R 22.5 used in the study. The axle structure corresponding to the applied loadings is illustrated in Fig. 4.

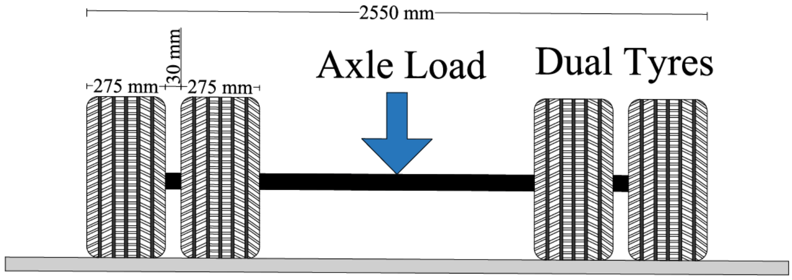

Fig. 4. Critical axle configuration of buses

Given that Istanbul BRT lanes are only 3300 mm wide and vehicle widths are 2550 mm, it can be concluded that most vehicles follow the same route. Therefore, for each selected axle load, it is assumed that the axels are centered within their lane, and two different loading positions, at the center and edge of the slab, have been specified. Six different combinations have been identified based on two loading positions (L1 - mid-slab, L2 - edge) and three types of pavement base and thickness (BT1 - concrete overlay of asphalt, BT2 - concrete overlay of concrete, and BT3 - concrete overlay on granular base) (Fig. 5). For these six selected combinations, repeated analyses were conducted using axle weights from four different buses, resulting in a total of 24 analyses.

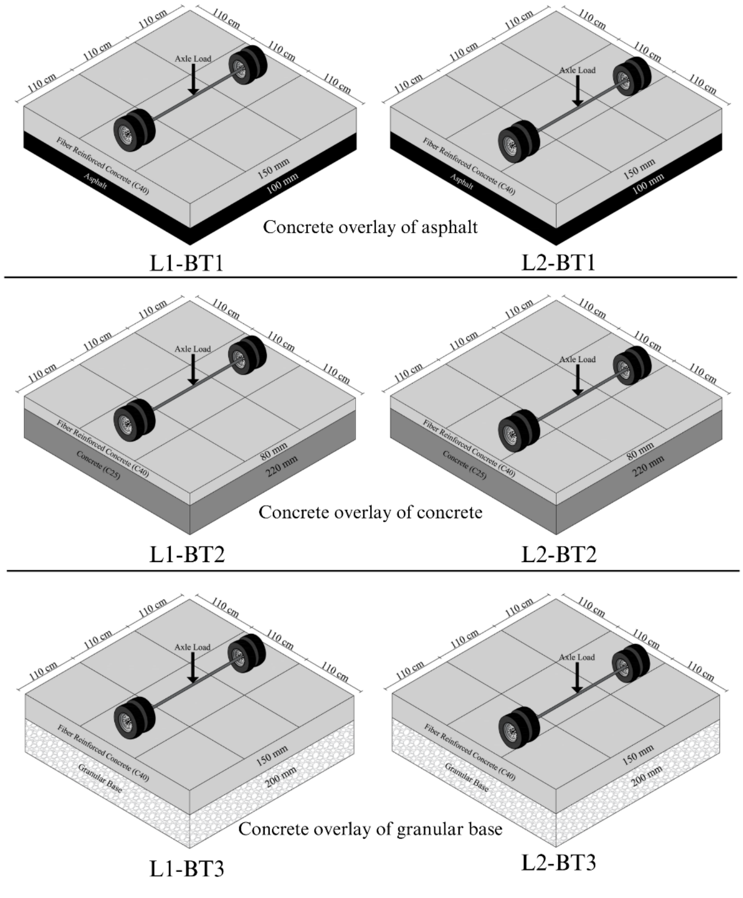

Fig. 5. Loading position and pavement structure combinations

In this study, 24 different finite element analyses are classified with codes assigned to each loading scenario. For the loading combinations, four different axle loads (A1, A2, A3, A4), two different loading conditions (L1, L2), and three different pavement types (BT1, BT2, BT3) were used. Table 3. provides a systematic overview of each code combination, along with the associated loading condition and pavement type, to support the organized tracking of all scenarios utilized in the analyses. This coding system was developed to simplify the examination of the effects of different loading and pavement parameters on the results.

Table 3. Loading and pavement codes of scenarios

Critical axle loads	
A1	Mercedes Conecto G - Rear Axle - 13.2 tons
A2	Mercedes Capacity - 3th Axle - 13.0 tons
A3	Otokar Kent XL - 3th Axle - 11.5 tons
A4	AKIA Ultra LF25 - 3th 4th Axle - 12.0 tones
Loading positions	
L1	Mid-slab loading
L2	Edge loading
Base and Thickness	
BT1	Concrete overlay (150 mm) of asphalt (100 mm)
BT2	Concrete overlay (80 mm) of concrete (200 mm)
BT3	Concrete overlay (150 mm) on granular base (200 mm)

The FEM has been developed as a powerful tool for the numerical solution of many problems, especially in engineering, and its applications are increasingly widespread. It has been used in numerous studies on concrete pavements to address vehicle loads and environmental factors. Today, the FEM can be applied using various software. For concrete pavement analysis, there are general-purpose finite element software options such as Ansys and Abaqus, as well as programs specifically designed for concrete roads, including EverFE, ISLAB, and KENSLABS. The EverFE [36-41] software, which is frequently used by researchers, was employed in this study. This methodology provides a significant advantage by enabling detailed modeling of the stress and deformation behavior of concrete pavements under axle and environmental loadings, thereby offering a reliable approach to optimizing pavement design and maintenance strategies.

3. Results and Discussions

Numerical analyses were completed using the EverFe software under various loading and layer conditions, and the stresses and vertical displacements were calculated. For this, the thicknesses and material properties of the layers were initially defined in the software. Then, the thicknesses and material characteristics of the pavement layers were specified, and the interface condition between the base and pavement was set as bonded. The axle loads and configurations of the vehicles were determined. Finally, the meshing process was completed before performing the analysis. Images of some selected analyses for performed in the EverFe program, showing the stress distribution underneath the pavement, are presented in Fig. 6.

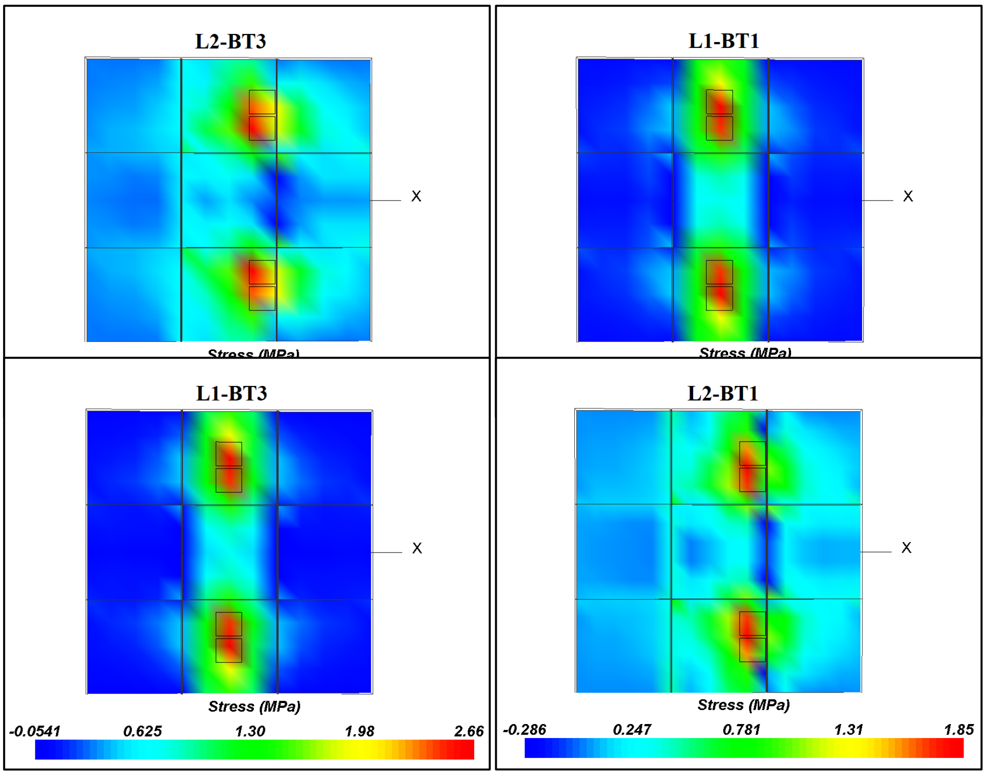

Fig. 6. Stress distribution of A1 axle loading in selected analyses

The analysis in this study shows that the Istanbul BRT vehicles generate significant stress and vertical displacement in concrete pavements. The effect of different base layers and concrete pavement thicknesses on stress and vertical displacement is investigated in this study. The maximum principal stress, maximum flexural stress, and maximum displacement values for the 24 scenarios examined in the study are presented in Table 4. In line with findings from previous studies [42, 43], the most critical stress region for concrete pavements is the stress that occurs at the interface between the pavement and the underlying base, that is, at the bottom surface of the pavement. Therefore, when determining the stresses, the section of the bottom surface of the pavement was considered, and the stress values in that area were presented.

As a result of the analyses, the highest stress among the examined conditions was observed under the 13.2-ton axle load of the Mercedes Conecto G model, with mid-slab pavement loading, in the case where granular base was used (A1-L1-BT3), with a maximum stress of 2.66 MPa. The largest vertical displacement, 1.63 mm, was observed under the same load and layered structure condition, with edge loading (A1-L2-BT3).

Other axle loads were also examined, and the highest stresses occurred during mid-slab loadings, while the maximum vertical displacements were observed during edge loadings. For all loading conditions, the highest stress and vertical displacements occurred with the concrete overlay on granular base (BT3) base and thickness condition. Conversely, the lowest stresses and vertical displacements were observed in the case of the concrete overlay of concrete (BT2) base and thickness condition. These results indicate that the base layer has a significant impact on stresses and vertical displacements.

Table 4. Summary of stress and displacement results

Scenarios	Max displacement (mm)	Max principal stress (Mpa)	Max flexural stress(Mpa)	Scenarios	Max displacement (mm)	Max principal stress (Mpa)	Max flexural stress(Mpa)
A1-L1-BT1	1.10	2.54	2.54	A3-L1-BT1	0.98	2.21	2.21
A1-L1-BT2	0.71	0.26	0.14	A3-L1-BT2	0.65	0.23	0.13
A1-L1-BT3	1.17	2.66	2.66	A3-L1-BT3	1.05	2.32	2.32
A1-L2-BT1	1.60	1.85	1.76	A3-L2-BT1	1.42	1.61	1.54
A1-L2-BT2	0.83	0.36	0.16	A3-L2-BT2	0.75	0.31	0.14
A1-L2-BT3	1.63	1.66	1.41	A3-L2-BT3	1.45	1.45	1.23
A2-L1-BT1	1.09	2.23	2.22	A4-L1-BT1	1.02	2.31	2.31
A2-L1-BT2	0.71	0.26	0.15	A4-L1-BT2	0.67	0.24	0.13
A2-L1-BT3	1.16	2.62	2.62	A4-L1-BT3	1.09	2.42	2.42
A2-L2-BT1	1.58	1.82	1.74	A4-L2-BT1	1.47	1.68	1.60
A2-L2-BT2	0.82	0.35	0.16	A4-L2-BT2	0.78	0.32	0.14
A2-L2-BT3	1.61	1.45	1.23	A4-L2-BT3	1.50	1.51	1.29

Despite the thinness of the concrete pavement, loadings with a concrete base were observed to result in the lowest stresses and vertical displacements. The main reason for this is the high rigidity of the concrete used as the base. Among the examined conditions, the lowest pavement stress, 0.23 MPa, was observed under the 11.5-ton axle load of the Otokar Kent XL vehicle, with edge loading on the pavement, in the case where concrete was used as the base (A3-L1-BT2). The lowest displacement, 0.65 mm, was calculated in the A3-L1-BT2 scenario, where concrete was used as the base.

4. Conclusions

This study thoroughly examined the maximum loads and displacements caused by Istanbul BRT vehicles' axles on concrete pavements in relation to pavement thickness and layer composition. The analyses utilized the actual axle loads of vehicles currently operating on the Istanbul BRT line, along with the pavement thicknesses and layer structures used in practice. Finite Element Method (FEM) analyses were conducted using the EverFe software to determine the maximum principal stress, flexural stress, and vertical displacements within the pavement. Some main conclusions may be drawn from the results, which are as follows:

- Among the examined conditions, the highest stress, 2.66 MPa, was observed under the 13.2-ton axle load of the Mercedes Conecto G model with mid-slab pavement loading and granular base (A1-L1-BT3), corresponding to approximately 33.3% of the estimated concrete flexural strength of 8 MPa.

- The largest vertical displacement, 1.63 mm, was noted under the same load and layered structure condition with edge loading (A1-L2-BT3).

- These findings contribute to the development of design and maintenance strategies tailored for heavy and high-traffic roadways. This study focused solely on stress and displacement assessments.

- Future studies may extend this work by examining the flexural stress-to-flexural strength ratio, along with fatigue and erosion analyses, using models such as PCA 1984.

- The insights from this research provide crucial information for determining appropriate pavement thickness by revealing maximum stress and vertical displacement values across various loading conditions, base properties, and slab thicknesses, thus supporting the advancement of effective maintenance strategies.

For future studies, assessing environmental impacts and evaluating the long-term performance of concrete pavements can improve the processes through field studies. The long-term performance of concrete pavements, combined with cost-benefit analyses, can form the basis of future research directions.

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