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An Exploratory Review of Pavement Structure Performance in Urban Public Transport Stop Areas

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***Abstract* - Urban public transport stop areas are exposed to repetitive heavy axle loads, braking actions, and prolonged static loading, conditions that significantly accelerate pavement deterioration compared to standard roadway sections. One of the most frequent forms of distress observed in these areas is rutting in asphalt mixtures, which directly affects pavement serviceability and user safety. This paper presents an exploratory investigation into the performance of pavement structures in urban public transport stop areas, based on representative situations identified in urban environments, including public transport stations located along major traffic corridors. The study reviews the primary causes of rut formation in asphalt pavements, considering material properties, traffic loading characteristics, and environmental influences specific to urban conditions.**

In order to complement conventional asphalt solutions, the paper further examines the use of cement concrete pavement as an alternative structural solution for heavily loaded stopping areas. A road concrete mixture was designed and laboratory-tested for application on short pavement sections with lengths of approximately 100 m. Mechanical strength, impermeability, and abrasion resistance were evaluated, as these properties are essential for ensuring long-term durability under intense urban traffic conditions. The results confirm the ability of road concrete pavements to withstand high load levels, demonstrating superior performance with respect to permanent deformation resistance, water action, and surface wear when compared to traditional asphalt solutions. The findings highlight the potential of rigid pavement alternatives for improving the structural performance and durability of public transport stop areas and provide a basis for future optimization-oriented research and field implementation.

Keywords - Pavement structures; Public transport stop areas; Urban transportation infrastructure; Pavement performance; Structural deterioration; Exploratory review component;

I. INTRODUCTION

The continuous increase in urban traffic intensity and the diversification of mobility requirements place growing demands on the performance of road infrastructure, particularly in areas operating under severe service conditions. In this context, urban public transport plays a central role in modern mobility systems, contributing to traffic efficiency, emission reduction, and improved resource utilization within urban environments. The effectiveness and reliability of public transport systems are, however, strongly dependent on the structural behavior of road infrastructure elements subjected to specific operational loads.

Public transport stop and standing areas represent structurally critical zones, as they are exposed to loading conditions that differ significantly from those acting on adjacent roadway sections. These areas are subjected to concentrated and repetitive loads generated by braking, standing, and acceleration cycles of heavy vehicles, combined with environmental and temperature-related effects. Consequently, pavement materials in such zones are prone to complex deterioration mechanisms, often leading to accelerated damage, reduced load-bearing capacity, and diminished functional performance.

The objective of this study is to explore the performance of pavement structures in urban public transport stop areas by identifying dominant degradation mechanisms and assessing suitable structural solutions for severe service conditions. Furthermore, the paper aims to provide a basis for selecting optimized pavement materials and configurations capable of improving durability and long-term performance in these critical urban zones.

II. MATERIALS AND METHODS

A. Degradation Mechanisms in Public Transport Stop Areas

Building on the general considerations regarding the structural behavior of urban public transport stop areas, this section focuses on the specific degradation mechanisms that govern pavement performance under severe service conditions. The analysis is based on representative urban case studies and documented field observations, which provide the framework for selecting appropriate materials and structural solutions.

Urban public transport stop areas are subjected to a complex loading regime characterized by concentrated loads applied over extended durations, resulting from repeated braking, standing, and acceleration of heavy vehicles. Unlike continuously trafficked roadway sections, these areas experience localized stress concentrations that promote the progressive accumulation of deformations within the pavement structure, particularly within asphalt layers.

One of the dominant deterioration mechanisms under such conditions is permanent deformation in the form of rutting, which arises from the visco-plastic response of asphalt mixtures. Repeated static and dynamic loading induces internal rearrangements of the asphalt material, leading to a gradual loss of structural stability. This phenomenon is further intensified by elevated pavement temperatures during warm seasons. Typical manifestations of rutting can be observed on heavily loaded urban pavement sections, as illustrated in Figure 1.

Figure 1. Typical rutting development in asphalt pavement subjected to repeated stopping and standing loads of public transport vehicles

Rutting significantly affects the functional performance of pavements by reducing ride comfort, impairing vehicle stability, and increasing safety risks. Additionally, rut formation facilitates water accumulation on the pavement surface, accelerating degradation processes through the combined effects of traffic loading and environmental exposure. Localized permanent deformation is commonly concentrated within the wheel paths of public transport lanes, as shown in Figure 2.

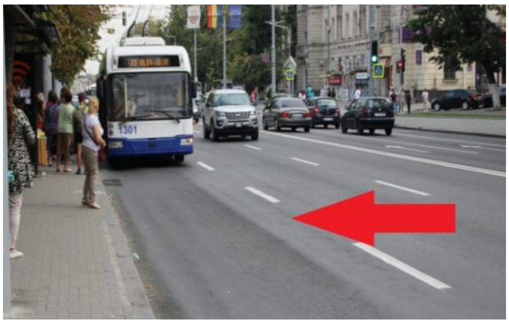

Figure 2. Localized rutting in the wheel path of an urban public transport lane.

Field experience indicates that conventional asphalt mixtures often fail to provide adequate performance in areas subjected to intensive standing loads. Consequently, alternative and optimized structural solutions must be considered. In this context, polymer-modified asphalt mixtures and cement concrete pavements are examined in the present study as potential solutions capable of improving resistance to permanent deformation and enhancing long-term durability.

B. Traffic Characteristics in Urban Public Transport Stop Areas

Traffic conditions in urban public transport stop areas exhibit characteristics that differ significantly from those of general traffic operating on standard roadway sections. Public transport vehicles, such as buses and trolleybuses, are characterized by high gross vehicle weights and axle loads, which generate concentrated stresses on pavement structures, particularly during stopping, braking, and repeated acceleration from rest.

In these zones, vertical loads are accompanied by substantial horizontal forces resulting from braking and acceleration processes. These combined loading effects lead to increased stress levels in the upper pavement layers, promoting the development of plastic deformations and premature structural deterioration. Furthermore, traffic in public transport stop areas is typically characterized by stationary or low-speed conditions, which result in prolonged load application durations and increased susceptibility of pavement materials to time-dependent deformation mechanisms.

Another critical factor influencing pavement performance in public transport stop areas is the high repetition of loading at nearly identical locations on the carriageway. Vehicle trajectories in these areas remain relatively constant, leading to the progressive accumulation of deformations in the same structural zones. This loading pattern accelerates damage mechanisms, particularly permanent deformation and material fatigue, thereby reducing pavement service life and functional performance.

Additionally, the combined effects of traffic loading and environmental factors, such as temperature variations and moisture exposure, further intensify pavement distress in these areas. Elevated pavement temperatures during warm seasons reduce the stiffness of asphalt layers, increasing their vulnerability to rutting under repeated loading. As a result, urban public transport stop areas require specialized structural design approaches and material solutions capable of accommodating severe service conditions and ensuring long-term durability.

C. Typical Pavement Distress Types in Urban Public Transport Stop Areas

Under the combined effects of concentrated loading, low-speed traffic conditions, and environmental influences, urban public transport stop areas are particularly susceptible to a range of pavement distress types. The most commonly observed forms of degradation include:

Permanent deformation (rutting) [1]:

Progressive accumulation of irreversible deformations in asphalt layers due to repeated static and dynamic loading, intensified by elevated pavement temperatures and visco-plastic material behavior. Typical pavement distress mechanisms observed in urban public transport stop areas, as reported in previous studies, are illustrated in Figure 3.

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In addition, the combination of frequent stopping, acceleration, and prolonged load application at designated stopping zones further exacerbates stress concentrations within the pavement structure, accelerating the onset and progression of rutting-related damage

Figure 3. Typical rutting and shear-related surface deformation observed in asphalt pavements subjected to repeated stopping and braking loads in urban public transport stop areas [1]

Shear-related surface deformations:

Localized surface distortions caused by horizontal forces generated during braking and acceleration, often leading to material displacement and surface irregularities.

Fatigue cracking:

Initiation and propagation of cracks resulting from repeated load applications, particularly in zones with high stress concentrations and reduced structural stiffness.

Thermal cracking:

Cracking induced by temperature variations, especially in asphalt pavements subjected to cyclic thermal stresses and restrained movements.

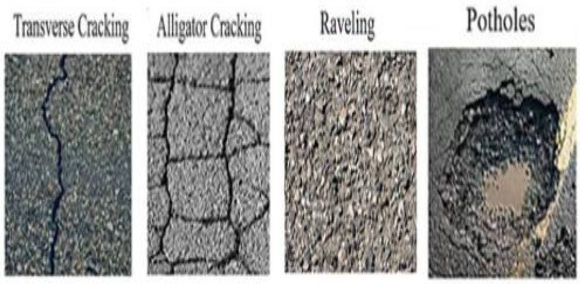

Figure 4. Classification of typical pavement distress mechanisms observed in asphalt pavements subjected to severe service conditions in urban public transport stop areas (concept based on [2], [3]).

Surface wear and polishing:

Progressive loss of surface texture due to repeated wheel passes, reducing skid resistance and negatively affecting traffic safety.

Moisture-related damage:

Degradation mechanisms such as stripping and loss of adhesion between asphalt binder and aggregates, promoted by water accumulation in rutted areas.

Overall, the coexistence and interaction of these distress mechanisms significantly reduce the structural and functional performance of pavements in urban public transport stop areas, highlighting the need for targeted design, material selection, and maintenance strategies adapted to these demanding service

conditions.

Figure 5. Fatigue cracking and moisture-related damage mechanisms in asphalt pavements under repeated loading and environmental effects (adapted from Ahmad and Khawaja [1]).

Joint and edge deterioration (for rigid pavements):

Localized damage in concrete pavements, including joint spalling and edge cracking, caused by load transfer deficiencies and repeated heavy vehicle loading.

These observed damage patterns confirm the cumulative effects of mechanical loading and environmental exposure, providing the basis for the performance evaluation and mitigation approaches discussed in the following sections.

III. DISCUSSIONS

Urban public transport stop areas represent a critical segment of the road infrastructure, where pavement structures are exposed to loading conditions that differ significantly from those encountered on conventional roadway sections. The literature reviewed in this study consistently highlights the combined influence of heavy axle loads, prolonged load application due to vehicle stopping, and frequent acceleration and braking, which together accelerate pavement deterioration processes.

An illustrative example of localized surface wear in a public transport stop area is shown in Figure 6, emphasizing the non-uniform distribution of pavement distress caused by repeated stopping and braking of heavy vehicles.

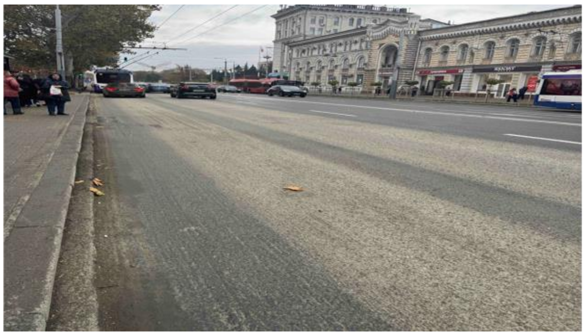

Figure 6. Typical surface wear patterns and localized permanent deformation observed in an urban public transport

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stop area, illustrating the effects of concentrated loading, repeated braking, and prolonged stationary traffic.

One of the primary factors contributing to premature pavement distress in these areas is the use of materials and structural solutions originally designed for general traffic conditions. Conventional asphalt mixtures often lack sufficient resistance to permanent deformation when subjected to repeated static and low-speed dynamic loading, particularly under elevated temperature conditions. As pavement temperatures increase, the viscoelastic behavior [2], [6], [7], [11] of the asphalt binder leads to reduced stiffness, promoting plastic deformation and rutting within the surface and binder layers.

Environmental conditions further intensify these mechanisms, especially in urban climates characterized by higher surface temperatures during warm seasons. In such conditions, the susceptibility of asphalt pavements to deformation increases, particularly in zones where traffic loading is concentrated within narrow wheel paths. Additionally, construction-related factors, including inadequate compaction and execution deficiencies, can significantly reduce the in-service performance of pavement structures, leading to accelerated distress development even when high-quality materials are employed.

In addition to permanent deformation, fatigue-related cracking represents a common distress mechanism in asphalt pavements subjected to repeated heavy vehicle loading. Such cracking is often associated with traffic-induced tensile stresses and reduced structural stiffness, particularly in areas where loading is concentrated and traffic operates at low speeds. A representative example of longitudinal cracking reported in the literature is illustrated in Figure 7.

Figure 6. Typical surface wear patterns and localized permanent deformation observed in an urban public transport stop area, illustrating the effects of concentrated loading, repeated braking, and prolonged stationary traffic.

The reviewed studies also indicate that traditional maintenance approaches, focused primarily on surface layer replacement, are often insufficient to address the root causes of pavement deterioration in public transport stop areas. Instead, an integrated approach that considers both material performance and overall structural capacity is required. Within this context, alternative pavement solutions, such as polymer-modified asphalt mixtures and rigid pavement systems, have been increasingly discussed in the literature as viable options for improving durability under severe service conditions.

D. *Influence of Traffic Characteristics on Pavement Performance*

Traffic conditions in urban public transport stop areas [5], [6], [13], [14] differ fundamentally from those on general roadway sections, primarily due to the repetitive nature of stopping, dwelling, and acceleration of heavy vehicles. Unlike free-flow traffic, these areas are subjected to prolonged load application at low speeds, resulting in increased stress concentrations within the pavement structure [14], [15]. The cumulative effect of these loading patterns significantly accelerates deterioration processes, particularly in the upper asphalt layers [11], [16].

Repeated braking and acceleration generate substantial horizontal forces, which, when combined with high vertical axle loads, contribute to shear-related surface deformations and permanent displacement of asphalt materials. These effects are further intensified by the localization of wheel paths, leading to non-uniform stress distribution and rapid degradation confined to relatively small pavement areas. As a result, damage in public transport stop zones often develops faster and exhibits greater severity compared to adjacent roadway segments.

E. *Limitations of Conventional Pavement Design Approaches*

Conventional pavement design methodologies typically assume traffic conditions characterized by continuous movement and relatively uniform load distribution. However, such assumptions are often invalid in urban public transport stop areas, where loading conditions are dominated by stationary and slow-moving heavy vehicles. As a consequence, pavement structures designed according to standard roadway criteria frequently lack sufficient structural capacity to withstand these demanding service conditions.

In many cases, rehabilitation interventions focus primarily on the replacement of the surface wearing course, without addressing underlying structural deficiencies. While such measures may provide short-term improvements, they often fail to prevent the recurrence of distress mechanisms such as rutting and fatigue cracking. This highlights the need for design approaches that consider both material performance and overall structural behavior, particularly in zones subjected to concentrated and repetitive loading.

Within this context, the literature increasingly emphasizes the importance of tailored pavement solutions for public transport stop areas. Enhanced asphalt mixtures with improved deformation resistance, as well as rigid pavement systems, are frequently cited as viable alternatives capable of providing improved long-term performance. However, the selection of appropriate solutions must be based on a comprehensive understanding of local traffic conditions, environmental influences, and expected service life requirements.

F. *Implications for Sustainable Urban Pavement Design*

Beyond structural performance considerations, pavement design in urban public transport stop areas must also address broader sustainability objectives [12], [17]. Frequent rehabilitation interventions caused by premature pavement deterioration result in increased material consumption, higher maintenance costs, and elevated greenhouse gas emissions over the pavement life cycle. Consequently, improving durability in these critical zones represents not only a technical challenge but also an important environmental and economic concern.

The literature increasingly highlights the role of performance-oriented design strategies in enhancing pavement sustainability. By reducing the frequency of maintenance and extending service life, pavement solutions tailored to public transport stop areas can significantly decrease resource consumption and traffic-related disruptions in dense urban environments. In this context, both enhanced asphalt mixtures and rigid pavement alternatives are often discussed as viable options for mitigating long-term environmental impacts associated with recurrent pavement rehabilitation.

From a sustainable urban infrastructure perspective, the selection of pavement solutions should therefore consider not only initial construction requirements but also long-term performance, maintenance needs, and life-cycle efficiency. Integrating durability-based design criteria into pavement planning for public transport stop areas can contribute to more resilient, cost-effective, and environmentally responsible urban mobility systems.

IV. CONCLUSIONS

This exploratory review highlights the distinctive loading and environmental conditions affecting pavement performance in urban public transport stop areas. The findings confirm that these zones are particularly vulnerable to premature deterioration due to concentrated heavy loads, prolonged stationary traffic, and elevated pavement temperatures. Permanent deformation, fatigue cracking, surface wear, and moisture-related damage emerge as the most prevalent distress mechanisms reported in the literature.

Conventional pavement structures designed for general traffic are frequently inadequate for such demanding conditions, emphasizing the need for dedicated design approaches and material solutions. The reviewed studies suggest that enhanced asphalt mixtures and rigid pavement alternatives offer improved resistance to deformation and long-term performance, particularly in areas subjected to intense and repetitive loading.

V. FUTURE RESEARCH

Despite the insights provided by existing studies, several aspects require further investigation. Future research should focus on experimental validation of advanced pavement materials under loading conditions representative of public transport stop areas. Long-term field monitoring is also necessary to assess in-service performance and durability over the pavement life cycle.

Additionally, further studies should explore optimized structural configurations, including transition zones between flexible and rigid pavements, as well as comprehensive performance-based design frameworks. Such efforts would contribute to the development of more resilient and sustainable pavement solutions tailored to the specific operational demands of urban public transport infrastructure.

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