



**Proceedings of the
10th S.I.I.V. Arena**

Napoli, Italy
21st November 2025

10th INTERNATIONAL S.I.I.V. ARENA

“RENATO LAMBERTI”

Edited by:

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10TH INTERNATIONAL S.I.I.V. ARENA
"RENATO LAMBERTI"
Università degli studi di Napoli Federico II
Complesso Universitario di San Giovanni a Teduccio
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Preface:

The Italian Society for Road Infrastructures (S.I.I.V.), founded in 1990, represents the academic community of the scientific-disciplinary sector "Roads, Railways, and Airports" with the statutory purpose of promoting and facilitating the dissemination of culture and scientific knowledge in the field of transport infrastructures, both within universities and towards public bodies and organizations operating in the mobility sector.

The contents of the disciplinary sector "Roads, Railways, and Airports" concern the theories, models, techniques, and processes for the conception, design, construction, upgrading, maintenance, and management of road, railway, airport, and intermodal assets. The main topics include functionality, performance, safety, sustainability, risk, resilience, environmental and territorial impact, the social and economic effectiveness of life-cycle investments, digitalization, and new technologies. Further in-depth studies are devoted to modeling and technological aspects of traditional, innovative, and eco-sustainable materials, of works and roadbeds, of superstructures and systems, as well as construction methods, quality, organization, and worksite safety. Issues related to safety devices, traffic safety, human factors, and the interaction between infrastructure and different users and vehicles, including connected and automated driving, are also addressed.

S.I.I.V. includes researchers, scholars, and professionals involved in the design, construction, maintenance, and management of roads, railways, and airports.

S.I.I.V. President
Prof. Gianluca Dell'Acqua



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Summary:

The S.I.I.V. Arena is a forum for discussion where Ph.D. students and young scholars from various universities present their research on topics of particular interest to the Scientific Disciplinary Sector CEAR-03/A "Roads, Railways and Airports."

The 10th S.I.I.V. Arena will take place in Naples on 21 November 2025, within the framework of the XX SIIV National Meeting: "Strade, Ferrovie e Aeroporti." The purpose of this volume is to collect the most innovative research in the field, presented during the 10th International SIIV Arena, with a focus on key issues such as digitalization, pavement materials and safety.

A Scientific Jury will award three prizes, each worth €500, in the following categories:

- *Best experimental research activity;*
- *Best innovative idea;*
- *Best methodological approach.*

10th S.I.I.V Arena Scientific and Organizational Director
Prof. Salvatore Antonio Biancardo



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(by alphabetical order)

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10th International SIIV Arena Renato Lamberti (S.A. Biancardo)

In memory of Professor Renato Lamberti



Renato Lamberti was an incredibly brilliant mind, a curious traveler who explored the most remote corners of the earth, an exceptional professional who, with dedication and commitment—and without ever wasting time on empty talk—helped this country grow, and a university professor who carefully trained hundreds of students and colleagues.

Testing the reliability of T2Go device for skid resistance assessment on non-asphalt pavement surfaces

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Abstract

This study evaluates the reliability of the T2GO device for measuring skid resistance on polyurethane-based, non-asphalt monorail surfaces. Traditional point-based methods, such as the British Pendulum Tester and laser profilometer, were used as references. A total of 88 measurement points were analysed under dry and wet conditions. Comparative analyses showed strong correlation between μ and MPD in dry conditions, and moderate correlation with PTV in wet conditions.

Keywords

Skid resistance, Surface texture, T2Go device

1 Introduction

Skid resistance is a key parameter for ensuring the safety and functionality of road and transit infrastructure. It refers to the ability of a pavement surface to maintain tire adhesion, particularly under wet or adverse conditions. This property is influenced by pavement texture, which consists of microtexture (wavelength < 0.5 mm) and macrotexture (0.5–50 mm) [1, 2]. Microtexture primarily affects grip at low speeds and braking, while macrotexture supports water drainage and skid performance at higher speeds [3].

Accurate assessment of these texture components is essential. Traditional point-based tools, such as the British Pendulum Tester (BPT) and laser profilometers, are widely used due to their standardization and reliability [4]. However, they are time-consuming, sensitive to local surface irregularities, and offer limited spatial coverage [1, 3].

This research aims to evaluate the reliability of the T2Go device as a continuous friction measurement system for the assessment of pavement skid resistance. To this purpose, comparative analyses were conducted against established point-based methods, namely the British Pendulum Tester and laser profilometry.

2 Methodology

This experimental study was carried out along the 5 km elevated track of the People Mover monorail system in Bologna, Italy. The surface consists of steel beams coated with a polyurethane-based textured overlay, which is traversed by rubber-tired vehicles under high-frequency service and exposed to challenging operational conditions such as weathering, surface contaminants, and mechanical wear.

To evaluate the reliability of the T2Go device, a total of 88 measurement points were investigated, including 76 located along the operational track and 12 on laboratory-fabricated slabs made of similar polyurethane-based material. Skid resistance was recorded using both the T2Go (μ) and the British Pendulum Tester (PTV) under dry and wet conditions, while Mean Profile Depth (MPD) was measured with a laser profilometer in dry conditions only. Unlike the static readings of BPT and profilometer, T2Go collects continuous data at 3 cm intervals. To align these data sets, a harmonization procedure was implemented: raw T2Go outputs were cleaned by

removing the first and last 30 cm of each run, and average μ values were calculated over 1-meter sections centred around the reference points of the point-based instruments.

Correlation analyses were conducted to assess consistency between methods, including μ vs. MPD (dry), μ vs. PTV (dry and wet), MPD vs. PTV (dry), and intra-method comparisons between dry and wet conditions for both μ and PTV. Each correlation was evaluated using correlation coefficient (r), coefficient of determination (R^2), standard error (SE), and p-value to quantify correspondence and determine T2Go's viability as a reliable skid resistance assessment tool on field.

3 Findings

Table 1 summarize the outcomes of the correlation analysis between T2Go measurements and the conventional assessment methods (MPD and PTV).

Correlation	n	r	R ²	SE	equation	p-value
MPD _d – μ_d	66	0.811	0.658	0.1081	MPD _d = 1.53* μ_d - 0.77	< 0.001
MPD _w – μ_w	66	0.522	0.272	0.1527	MPD _w = 1.86* μ_w - 1.03	< 0.001
PTV _d – μ_d	81	-0.188	0.036	5.8114	PTV _d = -7.43* μ_d + 70.75	0.092
PTV _w – μ_w	76	0.625	0.390	4.5609	PTV _w = 36.14* μ_w - 27.51	< 0.001
MPD _d – PTV _d	64	0.442	0.196	0.1402	MPD _d = 0.012* PTV _d - 0.24	< 0.001
μ_d - μ_w	78	0.842	0.709	0.0726	μ_d = 1.12* μ_w - 0.07	< 0.001
PTV _d - PTV _w	78	0.946	0.895	2.729	PTV _d = 0.88* PTV _w + 12.70	< 0.001
NOTE w = Wet; d = Dry; n = n° elements in IC 95 %						

Table 1. Correlation results

Among the tested relationships, the correlation between μ and MPD in dry conditions ($r = 0.811$, $R^2 = 0.658$) proved significantly stronger than that with PTV, indicating greater sensitivity of T2Go to macrotexture.

Notably, the μ - PTV correlation improved under wet conditions ($r = 0.625$, $R^2 = 0.390$), suggesting that wet testing may enhance T2Go's responsiveness to microtexture.

Figure 2 presents scatter plots comparing T2Go friction values with PTV (wet) and MPD (dry), illustrating the degree of linear correlation across measurement methods.

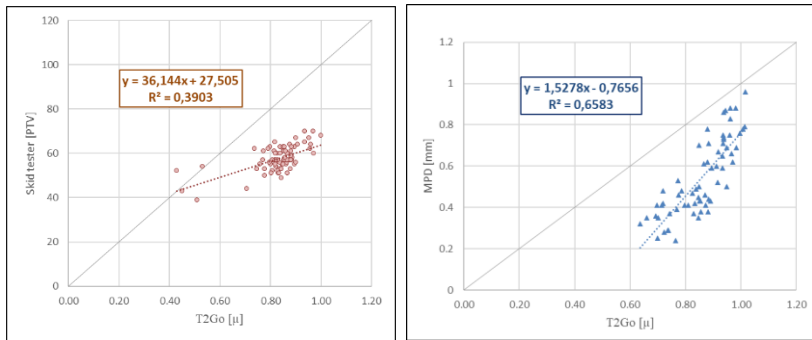


Figure 1. Scatter plot of PTV– μ (wet) and MPD – μ (dry)

The MPD – μ (dry) plot shows a stronger linear fit and lower dispersion, confirming high agreement in dry macrotexture assessments. Conversely, the PTV– μ (wet) plot reveals greater variability, although a moderate correlation persists.

4 Conclusions

This study evaluated the T2Go device as a continuous friction measurement tool on non-asphalt, polyurethane-based surfaces.

Results showed strong correlation with MPD in dry conditions, indicating high responsiveness to macrotexture. Moderate correlation with PTV under wet conditions suggests acceptable sensitivity to microtexture.

The T2Go's continuous output and reduced testing time make it a practical alternative to traditional point-based methods for faster and efficient preventive skid resistance assessment.

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Highly polymer-modified bitumen: focus on fatigue performance

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Abstract

This study involved the analysis of four highly polymer-modified bitumens (HPMBs), featuring varying polymer types and dosages along with different base binders, all of which underwent extensive laboratory characterization. Specifically, a binder phase analysis was conducted, which included short- and long-term aging of the binders, chemical analysis, rheological tests, and adhesion tests. The four binders were then used to produce both open- and dense-graded warm mix asphalt (WMA), to conduct mechanical characterization using both traditional and advanced approaches (Viscoelastic Continuous Damage). This paper will focus on the most significant results obtained from the fatigue tests conducted on both the binders and the mixtures.

Keywords

Pavement, asphalt, polymer modification, styrene polymer.

1 Introduction

The use of styrene-butadiene-styrene (SBS) polymer-modified bitumen (PMB) is now well-established in pavement engineering but presents some drawbacks (e.g., poor storage stability and resistance to heat, oxidation and UV radiation). To address the above limitations, new styrene polymers with high

vinyl content in the polybutadiene, which enable the production of highly polymer-modified bitumen (HPMB), have recently been introduced [1]. However, the limited available studies investigate laboratory-prepared HPMBs, which are not representative of large-scale production. Conversely, studies investigating industrially produced HPMBs often lack detailed binder composition data, limiting the interpretability of the results. In this context, the aim of this study is to characterize both the binder and the mixture properties of an HPMB currently under development for use in Italian motorway pavements (HPMB_A), comparing it with a reference PMB and two HPMBs already available on the market (HPMB_O, HPMB_V).

2 Methodology

The analysis involved extensive laboratory characterization of the four binders under study, which included short-term and long-term binder aging, Fourier Transform Infrared Spectroscopy (FTIR) tests, Viscosity tests, Frequency Sweep tests, Linear Amplitude Sweep (LAS) tests, Multiple Stress Creep and Recovery (MSCR) tests, and Binder Bond Strength (BBS) tests. The Performance Grade (PG) of the binders was also determined based on the results of Dynamic Shear Rheometer (DSR) tests and Bending Beam Rheometer (BBR) tests. Open-graded (OG) and dense-graded mixtures were produced with the four binders, using a chemical warm mix asphalt (WMA) additive. The OG mixtures were subjected to the Indirect Tensile Strength (ITS) test, the Cantabro test, and the Semi-Circular Bending (SCB) test, all performed under both dry and wet conditions to evaluate the effect of water. Meanwhile, the dense-graded mixtures underwent traditional mechanical tests such as ITS, Indirect Tensile Stiffness Modulus (ITSM) tests, and Indirect Tensile Fatigue Tests (ITFT), as well as advanced

mechanical tests such as complex modulus tests and fatigue tests based on the Viscoelastic Continuous Damage (VECD) framework. The main results of the fatigue tests conducted on both binders and mixtures will be presented below.

3 Findings

From the results of the LAS tests, it can be observed that the HMPBs exhibit a continuously increasing stress-strain curve without reaching an apparent peak up to the maximum strain of 30% (Figure 1a). From the damage curves (Figure 1b), it is evident that the PMB accumulates more damage compared to the HPMBs. The fatigue curves in Figure 1c indicate that the HMPBs show a marked improvement compared to the PMB, with a significantly higher number of cycles to failure at high strain values (200-400% greater fatigue resistance).

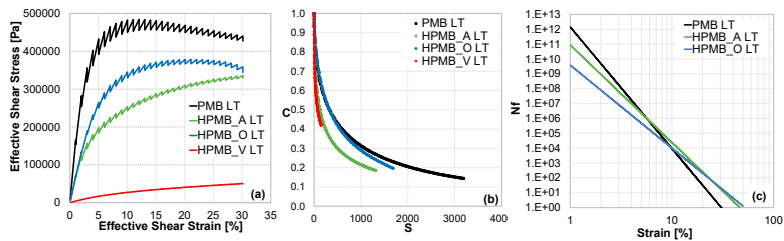


Figure 1. LAS results: (a) strain-stress curve, (b) Damage characteristic curve, (c) Fatigue curve

From the ITFT tests conducted on DG mixtures, no significant performance improvements were observed for the DG_HA and DG_HV mixtures compared to the reference mixture DG_P (Figure 2). Conversely, only the DG_HO mixture showed a clear improvement in fatigue resistance compared to DG_P.

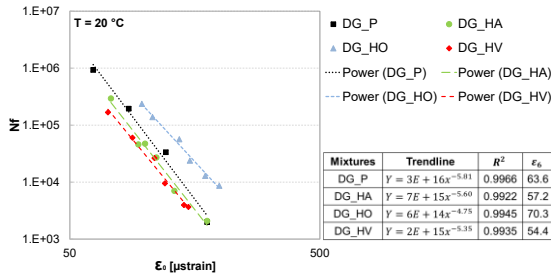


Figure 2. ITFT results at 20 °C

Based on the VECD fatigue test results, it can be observed that the HPMB mixtures exhibit better damage tolerance compared to the PMB mixture, as denoted by lower C (pseudo-stiffness) values at failure (Figure 3a). These findings are confirmed by the D^R values (Figure 3b) -which are higher for the HPMB mixtures- thus indicating a greater capacity to absorb energy before fracture. However, from the S_{app} values in Figure 3c, no improvements are observed for the HPMB mixtures.

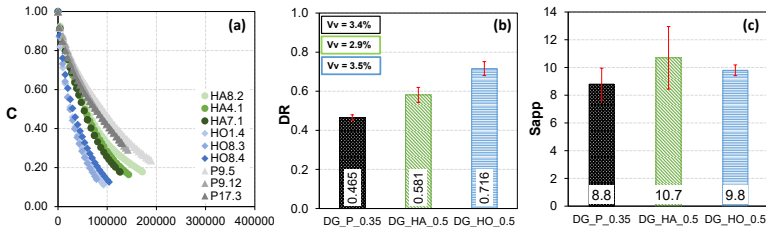


Figure 3. VECD fatigue results: (a) Damage characteristics curves, (b) D^R values, (c) S_{app} values

Some adhesion issues can explain why no significant fatigue improvements were observed for the HPMB mixtures compared to the PMB mixture. In general, as shown in Figure 4, the average POTS (pull-off tensile strength) values of HPMBs are lower compared to PMB. In some cases, such as for HPMB_A and HPMB_V, an adhesive (A) or undesired (U) failure was also

observed. These results may be attributed to the volumetric predominance of the polymer over the bitumen phase.

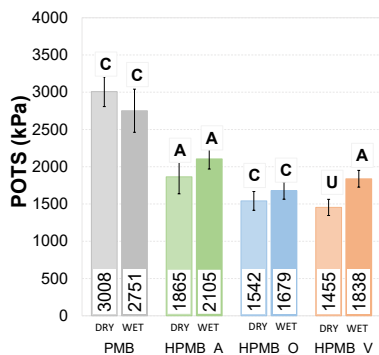


Figure 4. BBS results on virgin limestone

4 Conclusions

In conclusion, the fatigue results obtained from the LAS tests appeared promising, as great improvements were observed for the HPMBs compared to the PMB. However, due to some adhesion issues observed for the HPMBs, the fatigue performance of the related mixtures was partially compromised. Therefore, HPMBs have potential, but their formulation—intended not only in terms of polymer content—represents a critical factor for obtaining high-performing asphalt mixtures.

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Porous Asphalt Pavements with High Content of Secondary Raw Materials

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Abstract

This study examines the introduction of recycled materials in asphalt mixtures, specifically the full replacement of natural limestone sand with recycled artificial sand (RAS) from municipal solid waste incineration residues, and the partial substitution of virgin coarse aggregates with reclaimed asphalt pavement (RAP). Laboratory tests indicate that mixtures with RAS maintain indirect tensile strength comparable to traditional mixtures and reduce rut depth by 67% after 10,000 load cycles, demonstrating improved resistance to permanent deformation. The results confirm the technical feasibility of using RAS and RAP, contributing to enhanced sustainability and performance of porous asphalt pavements.

Keywords

Porous Asphalt Mixtures, Recycled Artificial Sand, Sustainable Pavements

1 Introduction

The road pavement industry is focusing on reducing emissions and enhancing sustainability by using secondary raw materials in bituminous mixtures [1].

Porous pavements, designed with 18–25% air voids, require careful maintenance to ensure durability [2, 3]. Bitumen

aging caused by oxidation reduces lifespan, but inorganic nanomaterials can improve binder resistance to heat and UV [4]. Water stagnation and chlorides promote surface damage, especially in cold climates. Porous asphalt evolves through innovative materials like RAP, industrial slags, incineration sands, and recycled plastics to meet 2024 environmental standards [5]. Mixtures with up to 91% steel aggregates show good water resistance and low Cantabro loss, indicating that recycling milled asphalt is feasible despite binder aging [6]. Due to high performance needs, recycled materials are not yet widely used in porous mixtures, prompting ongoing research.

This study aims to fully replace virgin aggregates with recycled ones from different industrial sources

2 Methodology

Two porous asphalt mixtures were designed and tested: UD1, composed exclusively of virgin aggregates, and UD2, where limestone sand was fully replaced by recycled artificial sand (RAS) from municipal solid waste incineration bottom ash. Both mixtures have comparable particle size distributions (see Table 1 and Figure 1). Prior to mixture design, all aggregates and bitumen were characterized. Laboratory evaluations included Indirect Tensile Strength (ITS) at 25 °C, Indirect Tensile Stiffness Modulus (ITSM) at 10 and 20 °C, Indirect Tensile Strength Ratio (ITSR) at 25 °C, and rutting resistance at 40 °C. Subsequent research phases will involve partial substitution of coarse virgin aggregates with high percentages of Reclaimed Asphalt Pavement (RAP).

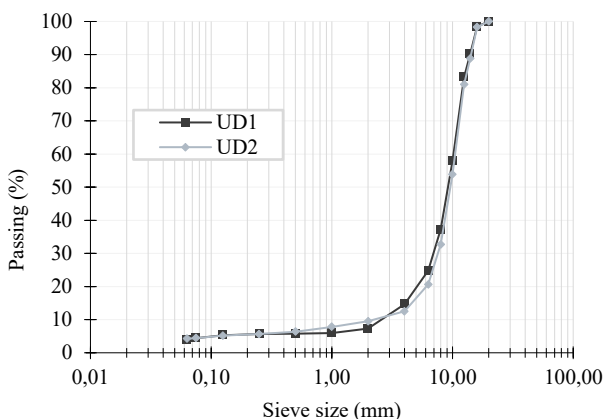


Figure 1. Gradation curves for UD1 and UD2

Components	Mixtures materials	
	UD1	UD2
-	%	%
Basalt 10/15	60	68
Basalt 6/10	18	20
Basalt 3/6	10	0
Limestone 0/4	7	0
Filler	5	4
RAS 0/10	0	8
Bitumen 50/70	3.6 - 4.1	3.6 - 4.1
Fiber	7	7

Table 1. HMA composition

3 Findings/Expected outcomes/Potential applications

The laboratory results in Table 2 show that the UD2 mixture has indirect tensile strength values comparable to UD1, both in the pre-peak and post-peak phases. The rutting depth,

shown in Figure 2, after 10,000 loading cycles is approximately 67% lower than that of UD1. These findings confirm the technical feasibility of fully replacing limestone sand with recycled artificial sand (RAS) in porous asphalt mixtures.

ID Mixture	% of bitumen	Aggregates apparent density [g/cm ³]	ITS @25°C [MPa]	CTI @25°C [DaN/mm ²]	Pre peak Fracture Energy [J/m ²]	Post Peak Fracture Energy [J/m ²]
UD1	4.1	2.780	0.634	56.423	1.26E+04	2.88E+04
UD1	3.6	2.780	0.535	35.140	1.23E+04	2.51E+04
UD2	4.1	2.817	0.630	50.170	1.16E+04	2.92E+04
UD2	3.6	2.817	0.600	52.850	9.53E+03	2.17E+04

Table 2. Indirect Tensile Strength results of UD1 and UD2

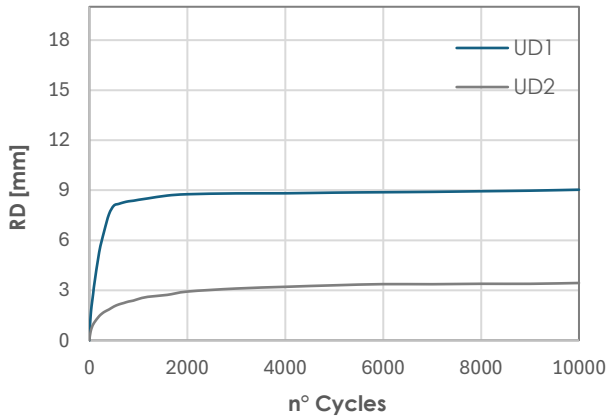


Figure 2. Rutting curves of UD1 and UD2

4 Conclusions

The study shows that using recycled artificial sand (RAS) from municipal solid waste incineration does not reduce the mechanical performance of porous asphalt mixtures; on the contrary, it improves properties like rutting resistance and fracture energy. This confirms the technical feasibility of fully replacing limestone sand with RAS in sustainable pavements. Ongoing research aims to introduce other recycled materials, such as Reclaimed Asphalt Pavement (RAP), to replace coarse virgin aggregates, further boosting the sustainability and performance of porous asphalt mixtures.

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Digital Twins for Proactive Safety of Vulnerable Road Users

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Abstract

The study investigates the use of DTs in Smart Cities to simulate interactions between vehicles and VRUs at intersections with limited visibility. Applying surrogate safety measures, it aims to identify high-risk configurations and support the development of predictive conflict mitigation strategies.

Keywords

Digital Twin, Vulnerable Road Users, Risk Evaluation, Urban Intersection

1 Introduction

Cyclists, as Vulnerable Road Users (VRUs), face increased risks at urban intersections due to limited visibility and complex trajectories [1]. Unlike vehicles equipped with advanced ADAS, bicycle technologies still lack predictive capabilities, relying on passive systems like collision detection [2]. Factors such as geometric constraints and unclear intent signals further reduce the chance of timely evasive actions [3]. This study presents a Digital Twin (DT) framework to simulate these interactions. A controlled test at the University of Catania provided real-world data to calibrate the DT and analyse severe conflicts in a virtual environment.

2 Methodology

This study adopts a simulation-based methodology to analyse interactions between vehicles and cyclists in complex urban environments. A Digital Twin (DT) (Figure 2) of a T-junction located within the University of Catania campus, characterised by limited visibility, was constructed using OpenStreetMap (OSM) data enriched with geometric and physical information [4]. Vehicles were modelled in the SUMO simulator using the Extended Intelligent Driver Model (EIDM) and calibrated with real-world data. Behavioural parameters such as speed, acceleration, and reaction times were represented as probabilistic distributions and integrated into a behavioural model developed in Python within SUMO. This model includes specific reaction times for cyclists [5] and drivers [6], perception based on distance and visibility, and adaptive deceleration [7], allowing the simulation to overcome limitations of traditional microsimulation approaches. To generate a large and representative synthetic dataset, the Latin Hypercube Sampling (LHS) technique was employed [8], and model validation was performed by comparing simulated and real speed profiles using scale- and trend-sensitive similarity metrics (Figure 3) [9]. The resulting simulation environment enabled the analysis of critical interactions and the extraction of risk metrics such as differential time to arrival (TTA_2) and relative speed at the conflict point (Figure 4).

Metri c	Min S	Start S	Cross S	Max S	Min S	Start S	Cross S	Max S	U. M.
coun t	39	39	39	39	6	6	6	6	-
min	1.34	3.45	1.42	5.84	1.53	3.8	3.59	5.91	m/ s
mean	2.92	7.08	2.94	7.4	2.39	6.11	4.75	7.83	m/ s
85°	3.5	7.91	3.5	8.14	2.98	7.14	5.8	9.06	m/ s
max	4.42	8.47	4.42	8.68	3.74	7.77	5.88	9.25	m/ s
std	0.61	1.05	0.6	0.69	0.83	1.36	0.9	1.25	m/ s

Table 3. Real Data Statistics



Figure 2. Digital Twin of the Road Network's Study Area

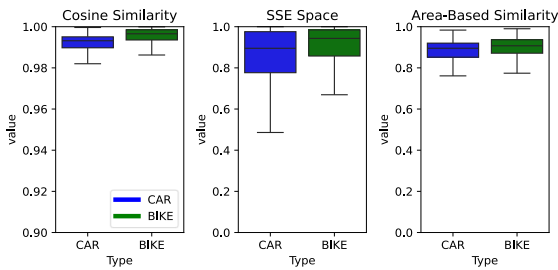


Figure 3. Model Validation Metrics

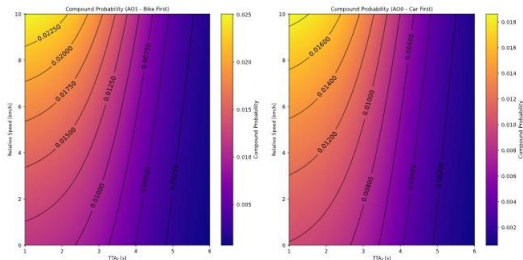


Figure 4. Risk Heatmap Based on TTA₂ and Relative Speed

3 Findings/Expected outcomes/Potential applications

Findings:

- DTs can replicate real-world conditions and support predictive analysis of vehicular conflicts in complex urban scenarios;

Expected outcomes:

- Definition of a synthetic metric for proactive risk assessment in vehicle–cyclist interactions;

Potential applications:

- The DT framework can be used to design and evaluate intelligent safety systems aimed at protecting cyclists in connected urban environments;

4 Conclusions

The study demonstrated the feasibility of using Digital Twins and advanced simulation to replicate real-world interactions between vehicles and cyclists in critical scenarios. This approach provides a solid foundation for developing predictive safety strategies and intelligent mitigation systems to protect vulnerable road users.

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From CAD to Smart Infrastructure BIM: A Visual Programming Approach to Workflow Automation

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Abstract

This research introduces CAD-to-BIM 2.0, an automation-focused methodology developed using Visual Programming Languages (VPL) within Autodesk BIM authoring software. The framework streamlines the digital modeling of road infrastructures by transitioning from traditional CAD designs to parametric BIM models. Through a modular suite of custom algorithms, CAD-to-BIM 2.0 achieves a significant reduction in modeling time and error probability. The methodology was validated on a complex case study, demonstrating its scalability and potential for integration with AI-based enhancements in future developments.

Keywords

BIM, Infrastructure, VPL

1 Introduction

The widespread adoption of Building Information Modeling (BIM) is reshaping the Architecture, Engineering, Construction, and Operation (AECO) industry [1, 2]. In Italy, regulatory mandates such as UNI EN ISO 19650 and Legislative Decree 209/2024 require BIM integration in public works above €2 million by 2025 [3, 4]. However, uptake remains limited due to

costs, training gaps, and technological fragmentation [5]. As a result, BIM workflows in transport infrastructure often rely on converting CAD projects into BIM models [6], reducing BIM to a compliance tool rather than a design methodology.

This research introduces CAD-to-BIM 2.0, an automation-oriented framework developed in a Visual Programming Language (VPL) environment. Its goal is to shorten modeling time and reduce human error when transitioning from CAD artifacts to federated, information-rich BIM models. Building on prior work in procedural parametric modeling [7–9], it delivers a more scalable toolkit for road design and coordination, aligning infrastructure practices with the efficiency, interoperability, and sustainability targets of Industry 4.0.

2 Methodology

The CAD-to-BIM 2.0 framework embeds automation into traditional workflows through Dynamo for Civil 3D and Revit. Input data are prepared by analyzing CAD drawings and organizing key geometry and semantics in Excel. VPL scripts then generate the terrain surface, reconstruct alignments, and reduce noise via filters. Cross-sections are assigned to corridors, which are automatically generated from user inserted parameters. A VPL-driven federation ensures consistency across disciplines, while semantic enrichment via Property Sets (P-sets) secures ISO 19650 compliance. Independent yet integrated modules make the method scalable and adaptable to diverse infrastructure contexts, modelled in compliance with Industry Foundation Classes standard file formats.

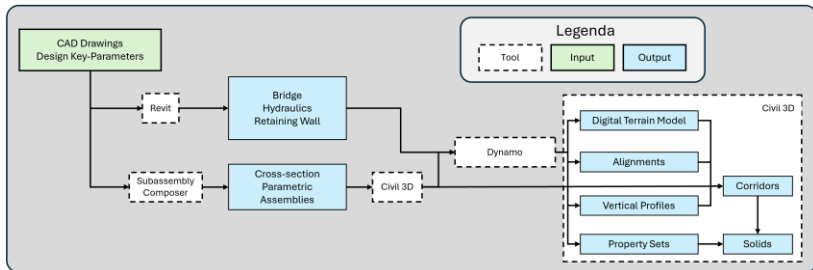


Figure 1. Methodology Graphical Abstract

3 Findings/Expected outcomes/Potential applications

The proposed CAD-to-BIM 2.0 methodology was validated on a real-world infrastructure project: a suburban road network including two main axes and multiple intersections, roundabouts, a bicycle lane, and a viaduct crossing a river. The project also comprised hydraulic works and retaining walls. The application of CAD-to-BIM 2.0 led to a drastic reduction in modeling time, from the initially scheduled 28 working days, to less than one. The case demonstrated the method's robustness in managing geometric complexity, interdisciplinary coordination, and information enrichment within an integrated BIM environment—while simultaneously improving consistency and data integrity. In fact, the geometries are derived directly from those provided in CAD, since the DTM is obtained from the polylines of the contour lines and the 3D solids of the road are obtained from those of the tracings and drawings of the standard sections. A VPL graph allows the federation of the different disciplinary models (Figure 2), while another creates the P-sets and connects the information to the geometric models by reading it directly from the Excel files on which the data models of the contracting authorities are usually provided. Every step of traditional CAD-

to-BIM workflow is streamlined avoiding error-prone manual operations. The workflow also enhanced interoperability between platforms, paving the way for scalable infrastructure modeling.

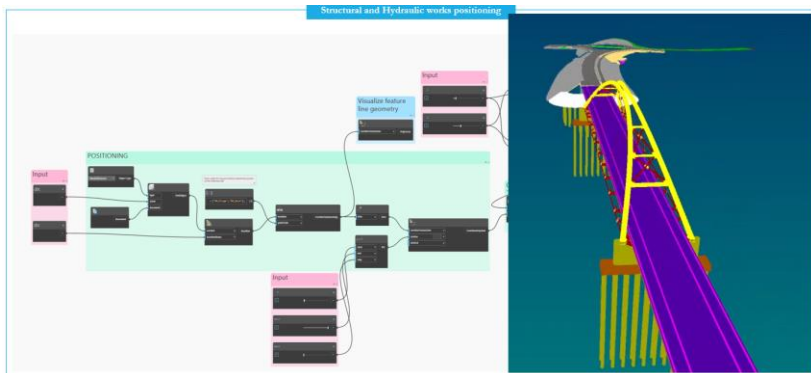


Figure 2. Graph for models' federation (left) and related results (right).

Potential applications include adaptation to railway, tunnel, or airport projects, as well as integration with GIS or asset management platforms. Looking ahead, AI-based extensions could further enhance performance: e.g., machine learning agents trained to classify CAD elements and recommend semantic enrichments or detect missing metadata, thus enhancing robustness in less-structured scenarios.

4 Conclusions

CAD-to-BIM 2.0 presents a significant step forward in the automation and standardization of infrastructure modeling. Its modular VPL-based design enables rapid, error-resistant digital modeling, aligned with the principles of sustainability (SDG 9 "Industry, Innovation, and Infrastructure" and SDG 12 "Responsible Consumption and Production") and digital

transformation. While currently dependent on structured inputs and manual oversight for edge cases, the methodology sets the stage for future developments that include AI-driven flexibility and full end-to-end automation. The demonstrated gains in productivity and quality signal a promising trajectory toward more intelligent and resilient digital design ecosystems.

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Investigation on road pavement instability through visual analysis: a case study in Bari

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Abstract

The research aim is to make road construction and maintenance sustainable. To reach this goal, several factors must be considered, such as, for example, the used material, waste produced and how it can be recycled. In the following manuscript, the first phase of the optimisation of road maintenance activities is illustrated. A primary challenge to improve the sustainability of road infrastructure is the correct management of maintenance activities. Primarily, it is needed to determine when the road pavement becomes unstable. One of the most effective methods is to perform Non-Destructive Testing (NDT) such as the Falling Weight Deflectometer (FWD). However, this process can be expensive in terms of cost and time. To make this cheaper, a correlation between the visual instability on roads and the mechanical characteristics has been hypothesised for this purpose. These analyses are performed on some streets of the city of Bari (Italy). This approach would require a punctual definition of the different types of instability associated with a specific image: an issue solved by employing a machine learning algorithm. Building on these findings, linear and multinomial logistic regression analysis was performed. In this way, it could be possible to define a preliminary evaluation of the mechanical state of the road pavement and hypothesise the maintenance intervention.

Keywords

Pavement Instability, road failure detection, road maintenance activities

1 Introduction

The estimated lifespan of new road pavements is about 20 years [1]. During this period, boundary conditions such as load cycles and meteorological factors can change, leading to unexpected instabilities [2], such as fatigue cracking, potholes, corrugations, alligator cracking, shear failure cracking, longitudinal and crossing cracking, etc [3]. For pavement rehabilitation, the use of NDT deflection basin methodology is recommended, since it allows to accurately determine the in situ effective capacity of the existing pavement under load cycles [4].

2 Methodology

Since one of the main outcomes of a damaged pavement is visible on the road, a machine learning algorithm based on several pavement damage images was used in this study to identify the damage typology.

This model is organised in three steps: training, evaluation and inference. For the first step, a Faster R-CNN (Region-based Convolutional Neural Network, used for object detection) training model was used, avoiding overfitting issues. The model performance was periodically evaluated on an already existing dataset. Hence, for the training phase, a previously tested model was used to perform the following instability analysis: Longitudinal Crack (D00), Transverse Crack (D10), Alligator Crack (D20) and Pothole (D40) in the United States [5].

In the preliminary step, the points to investigate were selected according to their resistances: i.e. only 78 points were

analysed, the ones characterised by resistances lower than the expected ones by design.

The first phase to carry on this study was about the collection of photos and the detection of instability. After that, it was possible to analyse if there is a correlation between instability and the measured mechanical behaviour. The machine learning model was tested using both on-site photos and Google Earth ones, if on-site collection was not possible. The model output includes images with boxes highlighting instabilities, as well as data files reporting the instability category and location.



Figure 1. Instability analysis results

According to these results, it was possible to categorise the type of detected instability. If on sites there were different types of road failure, the final instability category was the combination of them. To estimate the effects of instability on road pavement, the parameters considered were the results of FWD: asphalt modulus, foundation modulus, subgrade modulus, overall modulus of the entire area under the loading plate, and the remaining lifespan of the pavement indicated as cycle loads of 8.2 t.

3 Findings/Expected outcomes/Potential applications

21 out of 78 investigated points showed no sign of instability, probably because the fatigue was not yet visible, or the site presents a different kind of road failure, not detected by visual investigation.

To evaluate the significant variables correlated to the remaining lifespan of the pavement based on load cycles, a linear regression model was used. This model was crucial for determining if the detected instabilities were significant and which moduli were statistically relevant for defining the road pavement condition. The results showed that all instability classes were significant, and the two key moduli were the foundation and overall ones. This result suggests that for the investigated road pavement, the prevalent structural issue was due to the foundation layer. The instability caused by the different stiffness between the asphalt and the foundation layers can be further identified by analysing the overall modulus.

The multinomial logistic regression model was then used to identify the relationship between the significant moduli, analysed before, and the instability types. These are the independent variables, and their benchmark category is no damage. The multinomial model coefficients were converted into odds ratios (Figure 2), then related to the benchmark category: an odds ratio greater than 1 indicates a positive association, while a value less than 1 indicates a negative association, and a value of 1 means no association.

According to Figure 2, an increase in foundation stiffness can mitigate road failure on the road pavement analysed.

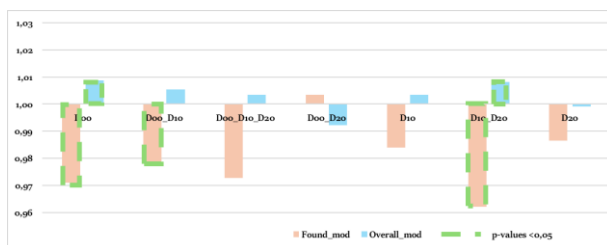


Figure 2. Instability's odds ratio (Y axes) and instability types (X axes).

The analysis also suggests that a percentage of pavement decay is caused by the pavement's high overall stiffness, which diminishes its ductile behaviour. In this way, it's possible to optimise the recovery works. In fact, knowing which layers are damaged, the interventions can be targeted.

This result suggested that punctual interventions could be useful as working on recalibrating the stiffness of the different layers to reduce instability (as introducing geogrids).

4 Conclusions

The maintenance road activities are crucial to ensure safety and comfort for road users. To avoid costly restoration, it's crucial to intervene promptly. This study represents a starting point to extend this approach also to other contexts outside the investigated sites.

In the following steps of the research will be analysed also the effects of the materials on the sustainability of the road.

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Dynamic Per-Arm Lane Control at Commutable Roundabouts: Integrating Safety and Performance for Real-Time Traffic Management

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Abstract

Smart Roundabouts can improve efficiency and safety, yet the interplay among capacity, delay, and crash risk is underexplored. This study presents a framework that generates heterogeneous demand, computes operations via HCM, estimates safety with NCHRP 888 SPFs, and dynamically optimizes per-arm lane assignments. Across 5,000 different traffic scenarios (1-h horizon, 15-min slots, a total of 20,000 time slots), four static configurations are benchmarked against a dynamic policy. Static multi-lane designs cut delay but raise crash risk. The dynamic policy adapts entry and circulatory lanes to traffic, 53% reduction of delay by achieving 17.3 s/veh delay (36.9 s/veh baseline), while increasing expected crashes from 3×10^{-4} to 6×10^{-4} crashes/ h (+97.8%).

Keywords

Roundabout, COM-Roundabout, Dynamic Lane Control, Managed Lane Strategies, Safety-Performance Trade-off.

1 Introduction

Converting stop-controlled or signalized intersections to single-lane roundabouts substantially reduces crashes. Nevertheless, when demand is high or imbalanced, single-lane

designs can become capacity-constrained. On the other hand, double-lane roundabouts, although increasing capacity, have been associated with higher crash frequencies. To reconcile these objectives, recent concepts such as COM-Roundabout use vehicle detection systems (loop or video), smart signage (VMS/LED markers), and simple control logic to activate lanes only when needed [1]. Existing HCM methods typically analyze a fixed lane configuration [2], while NCHRP 888 provides SPFs and CMFs that incorporate lane counts but still assume static geometry [3]. Managed-lane strategies on freeways (reversible lanes, dynamic merge control, or part-time shoulder use) show that reallocating lanes with sensors and lane-control signals can improve performance without permanent widening.

This study extends these principles to smart and commutable roundabouts and evaluates a dynamic per-arm lane control strategy against four static configurations.

2 Methodology

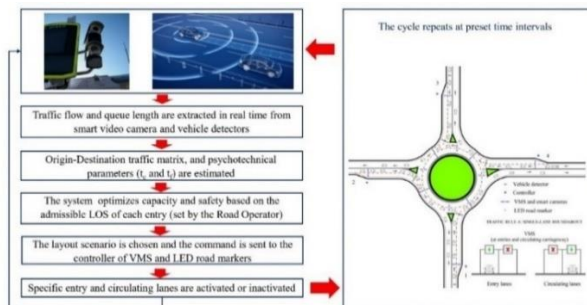


Figure 1. System architecture and control loop for dynamic per-arm lane control (COM-Roundabout)

Figure 1 outlines the sensing–estimation–optimization–actuation loop. The controller runs a sensing–estimation–optimization–actuation loop: measured flows/queues update OD and gap-acceptance parameters; a lane configuration

satisfying LOS rules is selected and issued to VMS/LED markers. The loop executes every $\Delta t = 15$ min over a 1-h horizon.

A four-leg COM-Roundabout was modelled. OD matrices are drawn from Dirichlet distributions, scaled to AADT $\in [20,000; 70,000]$ veh/day with set proper elasticity and a peak-hour factor; arm arrivals follow Gaussian peaks. Scenarios are accepted only if max control delay ≤ 100 s/veh and LOS-F share $\leq 30\%$; 5,000 scenarios pass (a total of 20,000 time slots). Four static layouts were compared—A (1-in/1-circ), B (2-in/1-circ), C (1-in/2-circ), D (2-in/2-circ)—and a dynamic controller.

Performance estimation follows the HCM method. Entry-lane capacity depends exponentially on conflicting circulating flow q_c with lane-configuration-specific parameters A, B, i.e., $c_i = A e^{-B \cdot q_{c,i}}$. Control delay uses the HCM roundabout function (Eq. 1) with $x = q/C$ and analysis period T . Queue estimation, two-lane demand splitting/recombination, approach aggregation, and LOS thresholds follow HCM specifications [2]:

$$d = \frac{3600}{c} + 900 \cdot T \cdot \left[x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3600}{c} \cdot x}{450 \cdot T}} \right] + 5 \cdot \min[x, 1] \quad (1)$$

At each slot, expected leg-level total crashes follow NCHRP 888 SPFs [3]. For a single-lane circulating carriageway, the expected number of crashes per year for a leg with approach AADT appr and circulating AADT circ:

$$E = \exp(a + b \ln(\text{appr}) + c \ln(\text{circ}) + d \text{ area} + e I_{\text{two entering}}) \quad (2)$$

where a , b , c , d , and e are parameters with an $I_{\text{two entering}}$ term for two-lane circulatory roads. Indicators (TwoEnteringLanes / TwoExitingLanes) preserve validity under mixed lane counts. Slot-level crashes scale E by slot length/8,760 h. Over N slots, the state s specifies 1–2 entry lanes per arm and 1–2 circulatory lanes (32 configurations). With delay $d_{rb}(s)$ and crashes $E(s)$, the controller minimizes:

$$J(s) = w_{\text{delay}} \frac{d_{rb}(s) - d_{\min}}{d_{\max} - d_{\min}} + w_{\text{safety}} \frac{E(s) - E_{\min}}{E_{\max} - E_{\min}} + \eta I_{\text{change}} \quad (3)$$

where $w_{\text{delay}} + w_{\text{safety}} = 1$, $d_{\min}$ and $d_{\max}$ are the minimum and maximum intersection delays among candidate states, $E_{\min}$ and $E_{\max}$ are the corresponding crash bounds, η is a switching penalty, and I_{change} is an indicator of whether the current state differs from the previous state. A rule gives priority to arms experiencing LOS F for consecutive slots by requiring additional lanes until LOS improves. This optimization framework reflects multi-objective trade-offs.

3 Results and Discussion

Across 5,000 different traffic scenarios, static layouts show distinct regimes (Table 1). The dynamic policy averages 17.3 s/veh delay (A 36.9, B 10.6, C 27.6, D 8.5) with crashes 6×10^{-4} per h (A 3×10^{-4} ; D 9×10^{-4}), and the LOS F rate for the dynamic scenario did not change compared to scenario A, and LOS F occurred in 25% of the time slots. According to Figs. 2.a&b, it activated entries 3 & 4 from the start to the end, and entry 1 from minute thirty, also peaked near 36 s/veh.

Scenarios	Mean delay (s/veh)	Total expected crash (crashes/h)	Switches (number)	%LOS F	Delay variation (%)	Crash variation (%)
Dynamic	17.3	6×10^{-4}	3	0.25	-53%	97.8%
Scenario A	36.9	3×10^{-4}	0	0.25	0.0%	0.0%
Scenario B	10.6	8×10^{-4}	0	0	-71.3%	167.2%
Scenario C	27.6	4×10^{-4}	0	0.25	-25%	47%
Scenario D	8.5	9×10^{-4}	0	0	-77%	188.8%

Table 1. Comparison of different scenarios with dynamic

Versus A, delay drops 53% with a 97.8% crash increase; versus D, it attains ~68% of D's delay savings at ~52% of D's crash penalty. Sensitivity shows a nonlinear trade-off with a tipping

region near $w_{\text{delay}} \approx 0.5$: $w_{\text{delay}} \leq 0.4$ yields ~ 31 s and 3.5×10^{-4} crashes; at 0.5, 17.3 s and 6×10^{-4} ; by 0.6, ~ 11.8 s, $\sim 7 \times 10^{-4}$, and LOS-F disappears.

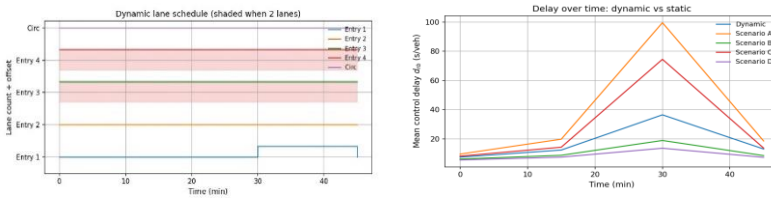


Fig. 2. (a) Lane states; (b) Mean delay—Dynamic vs A–D.)

4 Conclusions

A simulation–optimization framework is presented for dynamic per-arm lane control at COM-Roundabouts. Static two-lane designs minimize delay but raise expected crashes; the dynamic policy retains much of the benefit while moderating safety exposure, and it is deployable with standard detectors and lane-control displays for HDVs. Future works may include: richer safety models (severity, ped/cyclist); multi-objective, adaptive weights (emissions, equity); CAV-enabled control; and extensions to turbo/flower roundabouts equipped with dynamic traffic controller systems.

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Synergistic use of RAP and recycled waste plastics for sustainable asphalt mixtures

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Abstract

The integration of reclaimed asphalt pavement (RAP) and recycled waste plastics in road pavements has garnered attention due to its environmental benefits. This study aims to compare the mechanical properties of sustainable asphalt mixtures containing 50% RAP, a rejuvenating agent, and different dosages of a polymeric compound introduced via the hybrid method, in comparison with a control asphalt mixture modified using the conventional wet method.

The experimentation involved: a mix design optimization, a comprehensive laboratory investigation of mechanical properties, and a plant-scale production to corroborate laboratory findings. Findings highlighted the promising potential of recycled plastics for application in hot-mix asphalt (HMA) with high RAP contents.

Keywords

Reclaimed asphalt pavement (RAP), waste plastics, polymer-modified binder (PmB), asphalt mixture, sustainability

1 Introduction

The scientific community and the asphalt industry are actively researching sustainable technologies to maximize the use of recycled materials, industrial by-products, and wastes in

asphalt production [1]. In this context, Reclaimed Asphalt Pavements (RAP) and waste plastics are increasingly used as base components in asphalt mixtures. However, while diverting non-renewable resources from landfills offers environmental benefits, these sustainable practices must not compromise the performance and durability of asphalt pavements. To date, the synergistic use of high RAP contents and waste plastics has been only marginally addressed in the literature.

Therefore, this research aims to evaluate the mechanical properties of hybrid-modified asphalt mixtures containing 50% RAP, a rejuvenator, a neat 50/70 bitumen, and a polymeric compound, sourced from waste plastics, incorporated via the hybrid method at two different dosages: 0.3 % (in MIX 1) and 0.5% (in MIX 2) by total mixture weight. A control asphalt mixture (named MIX 0) prepared with a polymer-modified bitumen (PmB), served as the baseline to compare the effects of polymeric modification via the hybrid method with those of standard modification via the wet method. Part of the experimental program was carried out at CTU University in Prague (Czech Republic, CZ), and the entire project was co-financed by MUR – DM 352.

2 Methodology

During the mix design phase, thirteen asphalt mixtures with different binder dosages were assessed in terms of workability and performance-related characteristics. Workability was calculated using the Construction Densification Index (CDI), whereas the volumetric characterization included, among others, the evaluation of air voids content at 10, 120, and 200 gyrations. Mechanical properties were evaluated through indirect tensile modulus (ITM) tests at 10 °C, 20 °C, and 40 °C, and indirect tensile strength (ITS) at 25 °C. The optimal composition of each mixture family was selected according to

an Italian technical specification commonly adopted in the highway sector. Subsequently, the optimized asphalt mixtures were compared in terms of (i) fatigue in stress- and strain-controlled test configurations by using 4-point bending [2] and indirect tensile fatigue tests, both at 20 °C and 10 Hz, (ii) and rutting resistance on compacted slabs at 60 °C in air.

Moisture susceptibility at 15 °C and fracture toughness at 0 °C (K_{IC}) were analysed at CTU laboratory; therefore, different base materials were employed. Such an investigation involved the production of two additional hybrid-modified mixtures to assess the influence of the rejuvenating agent in comparison with a softer 70/100 neat bitumen. Moreover, two different reference mixtures were included: a control mixture without any modification process, and a wet-modified mixture containing a PmB with enhanced SBS content (named PmB RC, mandatory in CZ when the RAP content exceeds 15% by the total mixture weight). The main characteristics of the investigated asphalt mixtures are summarized in Table 1.

Finally, MIX 1, MIX 2, and MIX 0 were also produced at the plant scale to validate the laboratory findings obtained in the second phase. In this last phase, such mixtures were evaluated through ITM, ITS, and indirect tensile fatigue tests.

Mix Code	Modif. proc.	Binder type	Polym. comp. (%)	Rejuvenator (%)	TBC (%)
MIX 1	H	50/70	0.3	0.15	4.8
MIX 2	H	50/70	0.5	0.15	5.0
MIX 0	W	PMB 45/80-70	-	0.15	4.5
MIX A	-	P 70/100	-	-	4.5
MIX H1 WO	H	P 70/100	0.3	-	4.8
MIX H1	H	P 50/70	0.3	0.15	4.8
MIX H2 WO	H	P 70/100	0.5	-	5.0
MIX H2	H	P 50/70	0.5	0.15	5.0
MIX W RC	W	PMB 25/55-65	-	-	4.5

Table 1. Main properties of the investigated asphalt mixtures (TBC = total binder content including bitumen, rejuvenator, and polymeric compound; H = hybrid; W = wet; neat bitumens with "P" indicate neat binders sourced in CZ)

3 Research outcomes

Due to space limitations, only selected research outcomes are presented in this section.

Figure 1 illustrates some key findings from the mix design phase. MIX 0 and MIX 1 exhibited similar workability (on the left), whereas higher polymer contents required additional virgin bitumen to achieve the target compaction level. Hybrid-modified mixtures demonstrated greater stiffness (on the right), particularly at elevated temperatures. Figure 2 summarizes the fatigue performance in the 4PB configuration and rutting resistance. Overall, all mixtures showed high rutting resistance, mainly due to the elevated RAP content. In terms of fatigue, MIX 2 and MIX 0 manifested similar ϵ_6 values. Increasing the polymer content improved both fatigue and rutting performance.

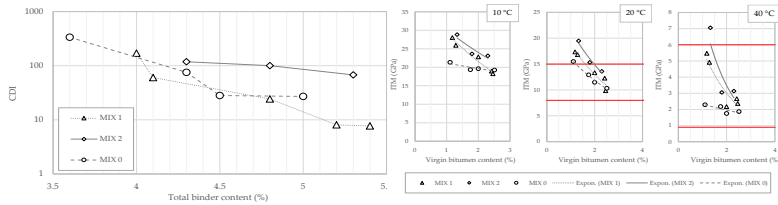


Figure 1. CDI and stiffness moduli at different temperatures in mix design phase.

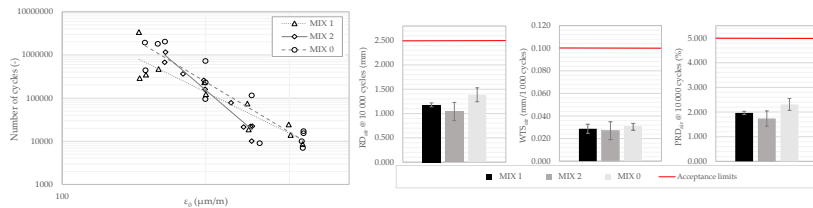


Figure 2. Fatigue and rutting resistance (RD=rut depth; WTS=wheel tracking slope; PRD=proportional rut depth) of the optimized asphalt mixtures.

Figure 3 displays the moisture susceptibility (assessed according to European and AASHTO standards) and k_{IC} of the investigated mixtures. Moisture damage emerged as a critical

concern: wet-modified mixtures exhibited the lowest resistance, whereas the incorporation of the rejuvenator seemed to enhance moisture resistance. Increasing the polymer content improved k_{IC} .

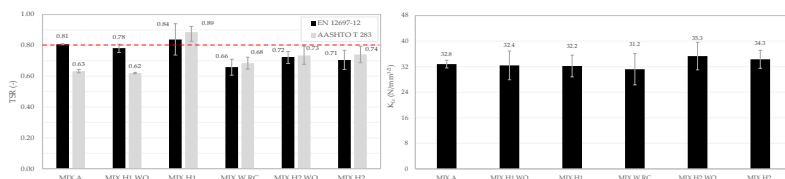


Figure 3. Moisture susceptibility (with CZ acceptable limit for EN standard) and k_{IC} .

4 Conclusions and potential applications

The experimental outcomes indicated that incorporating recycled waste plastics via the hybrid method shows strong potential for their application in HMA with a high RAP content. Despite the predominant role of the RAP in the mechanical properties, higher polymer dosages enhanced stiffness, fatigue resistance, rutting performance, and low-temperature crack initiation resistance. On the other hand, it may reduce workability and moisture resistance. Nevertheless, the use of a rejuvenating agent may mitigate some drawbacks.

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Characterization of asphalt sub-ballast through punching test

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Abstract

Asphalt mixtures are increasingly used for railway sub-ballast in high-speed and high-capacity lines, offering structural, functional, and economic benefits. Traditional road-based test methods do not fully capture railway-specific conditions, particularly the interaction between ballast and sub-ballast. This study presents a new experimental punching test using an adaptive indentation plate (AIP) to simulate ballast particle loads on cylindrical asphalt specimens ($\phi 150$ mm) under different temperatures (5, 20, 35 °C) and deformation rates (5.08, 25.4, 50.8 mm/min). Validation with two mixes of different stiffness showed the method effectively evaluates plastic deformation and indentation behaviour, providing complementary information to standard tests for assessing sub-ballast performance.

Keywords

Bituminous sub-ballast, asphalt indentation, railway maintenance.

1 Introduction

In ballasted railway lines, improving track performance has led to the use of asphalt sub-ballast, an intermediate layer that enhances stability, distributes loads, protects the subgrade from moisture and freeze-thaw effects, mitigates ballast fouling, and reduces maintenance costs [1, 2]. While laboratory tests

derived from road pavement design, such as Marshall stability, indirect tensile strength, and dynamic modulus, are commonly used to characterize these mixtures, they do not fully capture the specific mechanical interactions with the overlying ballast. Concentrated loads from ballast stones induce local stresses and indentation effects not considered in conventional testing. This study proposes and validates a dedicated laboratory methodology to evaluate asphalt sub-ballast under realistic ballast interaction, providing insights for more effective and sustainable railway design and maintenance.

2 Methodology

Indentation in asphalt has been widely studied for road pavements using sharp or blunt indenters, following EN 12697-20/21, to assess viscoelastic and plastic behavior and, occasionally, the resistance of waterproofing bituminous membranes to aggregate-induced deformation [3, 4]. In railway applications, aggregate indentation has primarily been studied for elastic elements in the superstructure (e.g., under sleeper pads, under ballast mats). Standardized methods evolved from flat steel plates to geometric ballast plates (GBP) with raised nodes simulating ballast contact (EN 16730, EN 17282). Spanish studies [5] tested ballast indentation in asphalt sub-ballast using real aggregates, providing realistic contact but with limited reproducibility due to aggregate variability and wear. This study introduces a lab-scale punching test using a steel ballast plate to replicate ballast-sub-ballast interaction, enabling controlled and repeatable characterization of asphalt sub-ballast under realistic railway loads.

2.1 *Novel punching test for asphalt sub-ballast*

To reproduce the ballast indentation phenomenon, the contact area between ballast aggregates and the underlying

asphalt layer was experimentally measured using frozen ballast slabs and image analysis, showing an average footprint area of 9.2% of the analysed surface. This informed the design of an adaptive indentation plate (AIP), composed of a pre-perforated metal plate with five truncated pyramidal metal tips carefully shaped to replicate the geometry, angularity, and contact area of ballast stones (Figure 1). The punching test was developed to evaluate the mechanical behaviour of asphalt mixtures used as railway sub-ballast under localized ballast loads. Cylindrical specimens ($\phi 150$ mm) were tested on a universal testing machine equipped with a climatic chamber and the AIP.



Figure 1. AIP for punching tests: Geometric design. All measurements are in mm.

Tests were conducted at three temperatures (5 °C, 20 °C, 35 °C) and three deformation rates (50.8, 25.4, and 5.08 mm/min) to simulate quasi-static conditions and evaluate the influence of temperature and loading rate on the mechanical response of the sub-ballast layer [6]. During testing, displacement-controlled axial loads were applied up to 15 mm penetration. Two Italian-standard asphalt sub-ballast mixes were tested: SSB with B50/70 binder and HSB with polymer-modified bitumen (PmB 45/80-65). Standard Italian mechanical characterization tests were then performed on both mixes. Specimens for the punching test were 150 mm×120 mm cylinders, prepared to match field sub-ballast thickness. Force-displacement curves showed three phases: initial tip

adaptation, linear increase to peak force (F_{max}), and post-peak failure (Figure 2). Higher deformation rates increased F_{max} at smaller displacements, while lower rates allowed more viscoelastic deformation. Temperature also affected behavior, with stiffness and F_{max} decreasing from 5 °C to 35 °C. HSB is stiffer with higher peak force and less deformation, while SSB is more ductile.

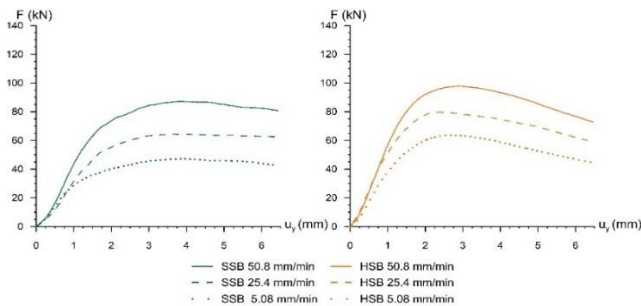


Figure 2. Punching test: SSB and HSB at 20 °C.

3 Expected outcomes

Since F_{max} only reflects peak pre-collapse strength and not real conditions, additional parameters were adopted: the force at 1.5 mm deflection ($F_{u,1.5}$), within the linear zone and below the 2 mm drainage limit, and the secant slope (m) between 1.25-1.75 mm to describe stiffness. Results show that $F_{u,1.5}$ and m increase with deformation rate and decrease with temperature, reflecting stiffer responses under faster loading and softer behavior at higher temperatures. HSB consistently exhibits higher $F_{u,1.5}$ and slope values than SSB, indicating greater strength and lower sensitivity to temperature and rate changes. The lowest deformation rate (5.08 mm/min) proves to be the most suitable for highlighting the viscoelastic behavior of the asphalt mixture, whereas higher rates do not adequately capture the interaction mechanisms typical of such materials.

4 Conclusions

The study developed and validated a punching test with an adaptive indentation plate to simulate ballast/asphalt sub-ballast interaction. Cylindrical specimens of two Italian-standard mixes (SSB and HSB) were tested at different temperatures and deformation rates, analyzing force-displacement curves to extract F_{max} , peak displacement, $F_{u,1.5}$, and secant slope. Results highlighted binder-dependent differences in stiffness and deformation, with the lowest deformation rate best representing quasi-static railway loads. The method is simple, repeatable, compatible with standard equipment, and effective in differentiating mixture behavior.

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Human Information Processing in Driver Road Interaction: Implications for Driving Behaviour and Road Safety

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Abstract

This driving simulation study examined the impact of basic driving information (speed, lateral position and front clearance) transmitted via an innovative head-up display to the driver. The display was designed based on the stages of human information processing, and its effectiveness was evaluated in various road contexts and at different levels of vehicle automation. The study aimed to understand how different methods of conveying such basic driving information impact driver behaviour and road safety.

Keywords

Human information processing, Road safety, Driving simulation, Human factors

1 Introduction

Driving is a complex task involving (i) navigation, (ii) guidance and (iii) control [1]. In certain situations, drivers also need to look at in-vehicle displays while driving. This distracts them from the road environment, and reduces their ability to control speed, maintain a safe distance from the vehicle in front, and stay centred in their lane. With the increasing presence of in-vehicle

technologies, competing visual and manual activities can overload attention and delay responses to critical events.

Head-Up Displays (HUDs) aim to mitigate these risks, by projecting essential driving information onto a transparent surface near the windshield, reducing the need for drivers to look away from the road. However, excessive or poorly designed visual information can lead to cognitive overload and visual clutter [2], reducing situational awareness.

Effective HUDs must be designed to assist drivers in their human information processing (HIP) [3]. When applied to driving, this model suggests that drivers (i) gather information that is useful for driving, (ii) interpret this information, (iii) make decisions, and (iv) implement actions. Automating these four stages can support drivers without replacing their expertise, preserving situational awareness and reducing cognitive load.

This driving simulation study aimed to evaluate the most effective way to convey essential driving information, such as speed, lateral position and safety distance, through a new generation of HUDs designed according to the stages of the human information processing model. The assessment considered driver behaviour, safety, and user preferences.

2 Methodology

In a multi-level mixed factorial design, thirty-two participants (age: $M = 38.6$ y, $SD = 12.0$ y; 16 females) drove in five HUD configurations, i.e., a baseline without HUD (level 0) and the four HUD interfaces (levels 1 to 4). Table 1 presents all the experimental factors. A Qualtrics survey, distributed via Facebook, Instagram, and LinkedIn, collected preferences from 154 drivers to design the HUD symbols (Figure 1), following usability principles. The HUD included information about three key driving variables, i.e., speed, lateral position, and distance to the preceding vehicle.

Table 1. Experimental factors involved in the experiment (Cat. = categorical; WS = within-subject; BS = between-subject; Cov. = covariate).

Experimental factors	Levels	Type
HMI level	5 (baseline + 4 different HUD configurations)	Cat., WS
Gender	2 (male, female)	Cat., BS
Age	-	Cov.

In the Information Acquisition level (1), the HUD provides real-time values. In the Information Analysis (2), data are processed, and the HUD alerts the driver. In the Decision Selection (3), the HUD suggests the most appropriate action to the driver. Finally, in the Action Implementation (4), the system executes the manoeuvre. The first three levels are driver controlled (SAE level 0), while the fourth involves partial automation (SAE level 2).

The road scenario was designed to investigate the driving behaviour in an urban area, a rural road, and a motorway section (Figure 2), considering several interactions with other road users (e.g., pedestrians in the urban environment, cyclists in rural context).

Linear mixed-effects models and ANOVA were used to statistically analyse data from driving behaviour and post-driving questionnaires about subjective usability and workload.

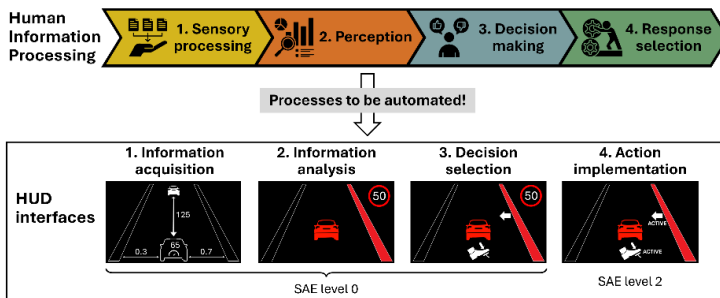


Figure 1. HUD interfaces based on human information processing.

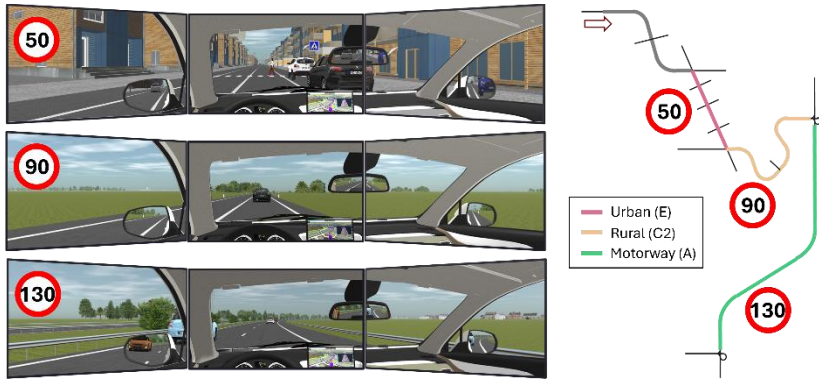


Figure 2. Experimental road scenario.

3 Findings and conclusions

Significant improvements in speed control (Figure 3, left) and safe distance were observed in high-speed environments, i.e., rural areas and motorways, particularly with HMI requiring lower cognitive resources (levels 1 and 4). In contrast, HUDs had a limited impact in urban environments, where high complexity and frequent interactions with other road users reduced their effectiveness. There was only a slight effect of HUD on lateral position, though it offers little practical benefit. Random effects were significant in all statistical models, indicating that individual differences, e.g., driving style, experience and risk perception, strongly influenced driver performance.

Post-drive questionnaires results (Figure 3, right) showed that level 4 was associated with the highest mental workload according to the Rating Scale Mental Effort (RSME) and the lowest usability (System Usability Scale - SUS). Levels 2 and 3, the most cognitively demanding, were judged as less demanding and with much higher usability.

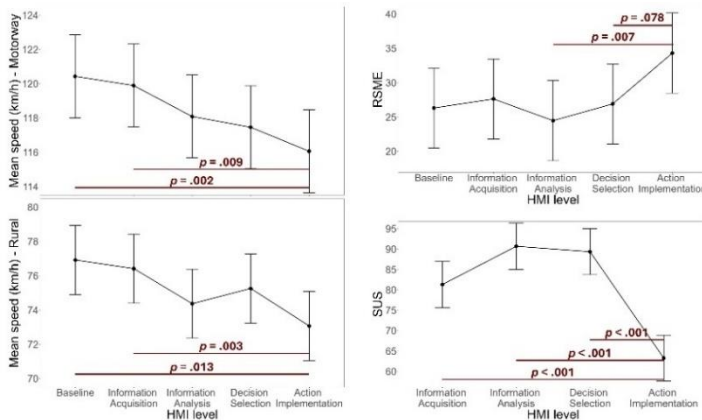


Figure 3. Results of the models. On the left side, mean speed in motorway and rural environment. On the right side, RSME and SUS scores.

Although levels 1 and 4 improved driving performance the most, subjective preferences favoured levels 2 and 3. Although HUDs can enhance driving behaviour, driver satisfaction and usability depend on the cognitive demands of the interface. Individual differences further influence driving performance, emphasizing that ecological and user-friendly interfaces must be designed to avoid overburdening the driver's cognitive resources.

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A Multi-Sensor Scan-to-BIM Approach for Non-Destructive Monitoring of Bridge Infrastructure

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Abstract

Italy's aging bridge network faces critical safety challenges, further emphasized by the Ministry of Infrastructure and Transport's Decree of July 1, 2022, which mandates a multi-level risk-based monitoring approach. This contribution presents an integrated Non-Destructive Evaluation (NDE) framework combining Terrestrial Laser Scanning (TLS), Unmanned Aerial Vehicles (UAVs) with RGB/LiDAR payloads. The fusion of these multi-source datasets within a Building Information Modeling (BIM) environment enables the creation of semantically enriched Digital Twins. This unified model not only ensures compliance with the new guidelines but also enhances inspection efficiency, supports accurate risk classification, and provides a scalable foundation for long-term predictive monitoring of critical infrastructure.

Keywords

Bridge monitoring, Terrestrial Laser Scanning (TLS), Building Information Building (BIM), Digital Twin

1 Introduction

The Italian territory faces a significant and pressing challenge in monitoring its vast and aging bridge infrastructure.

For many structures, there are no original design drawings, no as-built records, or no historical maintenance logs. This data deficit hinders effective risk prioritization, long-term maintenance planning, and informed decision-making, potentially leaving critical vulnerabilities undetected. This contribution proposes a methodology designed to directly address this problem by enabling the rapid and comprehensive collection of high-fidelity geometric and diagnostic data. The proposed approach does not replace visual inspections but powerfully augments them by providing inspectors with a rich, pre-acquired, and objective digital dataset [1-2]. This allows for targeted and informed field verification, drastically improving the efficiency, accuracy, and safety of the entire inspection process.

2 Methodology

The proposed methodology is based on an integrated multi-sensor approach designed to capture the external geometry of bridge structures efficiently and safely. For structures where access is feasible, Static Terrestrial Laser Scanning (TLS) is employed as the primary tool for geometric documentation. The scanner is positioned under the bridge deck and around piers and abutments, capturing millions of measurement points per second from multiple set-ups. This process generates a millimeter-accurate, high-resolution 3D point cloud of the entire visible structure, effectively creating a definitive digital record of its current as-is geometry. In addition to geometric accuracy, TLS data provide intensity (reflectance) values that can serve as indirect indicators of material conditions. Variations in reflectance may highlight localized anomalies such as moisture infiltration or surface deterioration, supporting early detection of potential defects.

In scenarios where physical access is dangerous or impossible, such as over deep ravines or busy highways, Unmanned Aerial Vehicles (UAVs) provide a safe and effective alternative. Drones equipped with high-resolution RGB cameras perform photogrammetric flights to create detailed 3D models and orthophotos. Furthermore, payloads incorporating lightweight LiDAR scanners can be deployed to directly capture topographic point clouds, which are particularly effective for mapping complex geometries and penetrating minor vegetation around the structure.

3 Results and Data Integration

The multi-sensor survey produced a heterogeneous dataset comprising geometric and diagnostic information. A critical step in the workflow is the integration of these data into a unified digital environment. This integration is implemented through the Scan-to-BIM methodology, where the dense, georeferenced point cloud acquired from Terrestrial Laser Scanning (TLS) and UAV-based LiDAR provides the geometric backbone for the creation of an object-oriented 3D model within a Building Information Modeling (BIM) framework (Figure 1). Beyond the generation of a three-dimensional representation, this process enables the development of a functional Digital Twin. In this environment, each structural component is reconstructed as a semantically enriched object. Sensor-derived information is systematically associated with the BIM elements via tailored property sets (Psets). Beyond geometric and photographic attributes, reflectance values derived from TLS measurements can be incorporated into the BIM model as diagnostic layers. This enrichment allows the correlation of material properties with structural elements, enhancing the potential for automated defect recognition.

As a result, individual objects such as bridge girders or piers can be linked with comprehensive health records, including surface condition imagery (e.g., cracks, spalling) and precise geometric descriptors (e.g., layer thicknesses, deflections).

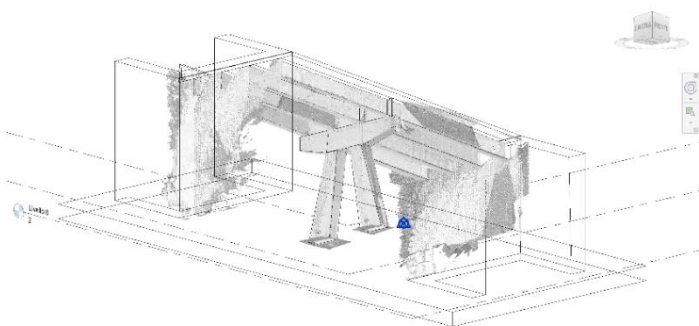


Figure 1. BIM model generated from the integrated TLS and UAV-LiDAR point cloud

The integrated BIM model thus functions as a centralized and persistent information repository, supporting both visualization and engineering analysis. Importantly, it provides inspectors with the ability to perform virtual navigation of the structure prior to on-site operations, enabling the pre-identification of critical areas. Field inspections can therefore be targeted and verification-oriented, reducing survey time and improving the efficiency of structural assessment.

Conclusions

This study has presented an integrated methodology for the non-destructive evaluation and digital documentation of bridge infrastructure, specifically addressing the data deficit affecting Italy's existing network. The combined use of Terrestrial Laser Scanning (TLS) and UAV-based photogrammetry/LiDAR

provides a comprehensive and efficient approach for capturing the external geometry of structures under diverse accessibility conditions.

The successful implementation of the Scan-to-BIM workflow has demonstrated how raw survey data can be transformed into an intelligent, semantically enriched Digital Twin. This model functions as a decision-support tool by consolidating heterogeneous diagnostic information within a contextualized 3D representation of the asset.

The proposed workflow represents a significant advancement over traditional inspection practices. By providing a robust and quantifiable baseline, it supports a transition from reactive, subjective maintenance toward proactive, data-driven asset management. Ultimately, this approach contributes to the optimization of inspection resources, the prioritization of interventions based on objective evidence, and the enhancement of safety and service life of critical transportation infrastructure.

Future developments of the workflow could leverage reflectance data to support the automated detection of defects such as moisture-induced anomalies, further strengthening the role of the Digital Twin as a monitoring tool.

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Private connected vehicles data to support the implementation of urban PMS: the case study of the City of Palermo

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Abstract

This work aims to explore the potential of leveraging big data—particularly that generated by private connected vehicles—for extensive monitoring of road infrastructure in urban areas. Central to this exploration is the following research question: are data collected from connected vehicles (CVs) reliable and cost-effective source for road condition monitoring within urban Pavement Management Systems? In order to give an answer, at first characteristics of the few encountered urban PMS in literature were identified. On this basis, a prototype of urban PMS, leveraging connected vehicles as source of pavement condition monitoring was designed and applied to a case study within the city of Palermo (Italy). The application was validated by comparing these results with an additional visual monitoring operated by using the PASER method. Overall, the comparison supports the potential of using CVs data as a viable and scalable alternative for pavement monitoring in urban contexts; in fact, measurement accuracy is considered adequate to the level of precision realistically possible to obtain a cost-effective solution in such a dynamic and complex environment such as urban road pavements.

Keywords

Private connected vehicles, urban PMS, proactive maintenance

1 Introduction

Road infrastructures are strategic assets that require periodic monitoring and maintenance. This highlights the need to shift from reactive management methods, often ineffective and costly, to proactive and predictive approaches [1]. A key tool in this direction is the Pavement Management System (PMS).

Documented experiences of PMS in urban contexts [2-4] show the intention to move beyond traditional approaches toward progressive digitalization and rationalization of processes. Among the evaluation tools, the International Roughness Index (IRI) is one of the most widely used indicators to assess surface regularity [5]. Depending on the perceived ride comfort [6] or the vehicle's operating speed [7], threshold values can be defined as targets for planning maintenance interventions. Different technologies are employed to determine these indicators: profilers, highly accurate but expensive and less practical in urban context [8]; smartphones, which are more cost-effective and reliable [9]; and sensors installed on connected vehicles (CVs), which represent an innovative, frequent, and trustworthy source. Several studies have demonstrated a strong correlation between CVs data and traditional methods, making this option particularly promising for urban pavement monitoring. The study proposes a proactive maintenance approach based on IRI data from connected vehicles, aimed at assessing their reliability and economic sustainability for monitoring urban pavement conditions.

2 Methodology

The system is structured into four main components, defined on the basis of studies on Urban PMS, with an additional final phase dedicated to validation. These are:

- Preliminary phase: case study identification.
- Monitoring and data collection: CV data (geo-referenced IRI values) were provided by NIRA dynamics, segmented into 25 m road sections and classified into five functional categories. (Only class 3 and class 5 roads are included in the case study)
- Data analysis: datasets collected weekly over two years were filtered and cleaned by eliminating outliers. The network was then divided into homogeneous sections, considered the minimum management units for maintenance.
- Decision-making process: classification thresholds were established using the percentile method, generating five surface condition categories (excellent–critical). Each section was assigned a condition level based on the monthly average IRI (Tab.1), leading to the creation of a digital quality map (Fig.1a).
- Validation: CV-based results were compared with PASER assessments, which are based on visual inspections and a 1–10 rating scale.

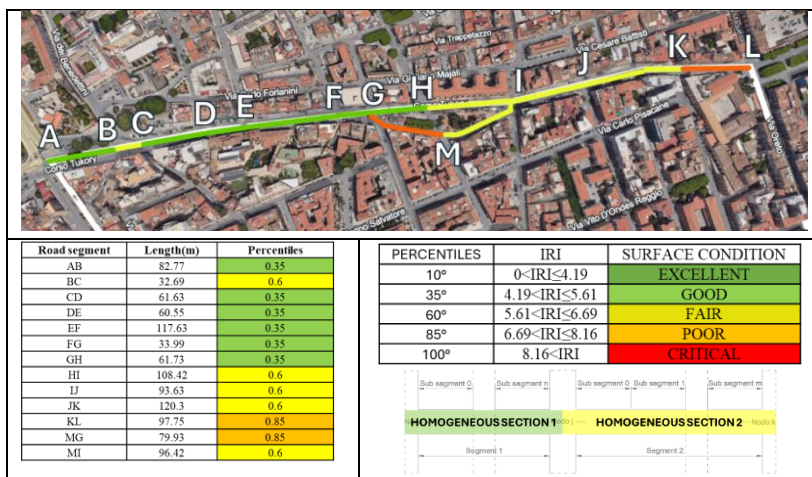


Table 1. Surface condition classes based on the IRI thresholds obtained



Figure 1a. CV-based Digital quality map of the case study

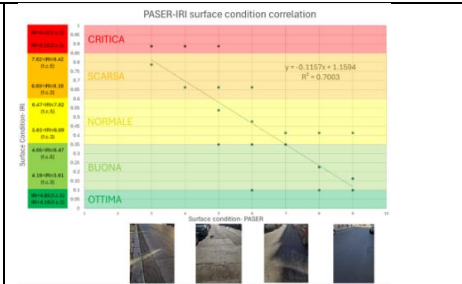


Figure 1b. PASER-IRI comparison

3 Findings/Expected outcomes/Potential applications

The output of the study consists in the creation of digital maps of pavement quality (Fig.1a). The comparison with PASER inspections revealed a positive correlation ($R^2 \approx 0.7$) between the two approaches, with about 70% of the variability explained by IRI data (Fig.1b). In particular, a correlation of 78% was found for class 3 roads and 61% for class 5 roads, which is consistent with the fact that class 3 roads, being more heavily trafficked, allow for greater accuracy. Only a few cases showed significant discrepancies, thus confirming the validity of using CVs data for urban pavement monitoring. Moreover, the pay-per-kilometer purchase of CVs data proves to be much more convenient than the use of specialized vehicles.

4 Conclusions

The study explores the potential of data generated by CVs for monitoring urban road infrastructure. One of the first prototypes of an Urban CV-PMS was developed and applied in Palermo, validated through comparison with PASER method. The results show that CV data represent a suitable solution for the urban context, where road monitoring information is often limited, offering a scalable and economically sustainable

approach capable of ensuring continuous network coverage and fair assessments between primary and secondary roads. The approach proves adaptable to the needs of individual cities and provides a promising foundation for future developments, particularly toward the integration of predictive methods.

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A Multi-Source Digital Twin Approach for Infrastructure Monitoring

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Abstract

Transport infrastructure is the backbone of modern societies, yet much of it is aging and increasingly exposed to natural hazards and rising traffic demands. Conventional inspection techniques remain important but are limited by their subjectivity, cost, and inability to provide continuous updates. In this study, we present a framework that combines remote sensing, non-destructive testing (NDT), and Building Information Modeling (BIM) within a Digital Twin (DT) environment. The system integrates terrestrial laser scanning, GNSS surveys, and multi-temporal interferometric SAR (MT-InSAR) data to build a dynamic and multi-scale representation of infrastructure and its surrounding environment. A case study on a masonry bridge in Lazio, Italy, demonstrates how the framework can capture millimetric displacements, correlate them with landslide risk, and support predictive maintenance. By bringing together diverse datasets in a single, evolving digital space, this approach shows how DTs can make infrastructure management more proactive, resilient, and cost-effective.

Keywords

Digital Twin, BIM, Remote Sensing, NDT



1 Introduction

Much of Europe's transport infrastructure was built in the 1960s and 70s and now operates under heavy stress. Ensuring its safety and durability has become a pressing challenge, especially as climate change increases the frequency of extreme events such as floods and landslides. Traditional monitoring relies heavily on visual inspections and destructive testing. These methods are not only costly and disruptive but also struggle to capture subtle, progressive changes that may signal deeper problems.

Over the past two decades, new technologies have offered alternatives [1]. BIM has become a powerful tool for managing infrastructure data [2], while satellite Earth Observation and ground-based remote sensing allow engineers to monitor networks over wide areas. Digital Twins bring these strands together, creating digital models that evolve alongside their physical counterparts. In practice, however, building such twins for transport assets is far from straightforward. Data arrive from different sources, at different scales, and at different times. Making sense of it all requires robust integration workflows.

This study proposes one such workflow, designed to be both scalable and practical. By merging high-resolution terrestrial surveys with wide-area satellite data, and embedding both in a BIM-based DT, it aims to provide infrastructure managers with tools that are richer, timelier, and easier to act upon.

2 Methodology

The framework follows four key phases. The first step is (1) multi-source data acquisition: TLS surveys provide millimetric geometric detail of the structure; GNSS ensures georeferencing

accuracy; MT-InSAR contributes wide-area displacement measurements with millimetric sensitivity. Complementary datasets such as national landslide inventories (IFFI) enhance environmental contextualization.

Subsequently, (2) data integration and processing are carried out: datasets with heterogeneous coordinate systems and acquisition timelines are standardized into a common spatial-temporal framework (WGS84). Automated algorithms import, filter, and harmonize Persistent Scatterer (PS) points from Sentinel-1 (and potentially higher-resolution missions such as COSMO-SkyMed), linking them to BIM environments.

The third phase is the (3) dynamic Digital Twin development, where a BIM-oriented model is enriched with TLS-derived geometry and InSAR-based displacement data, transformed into adaptive 3D parametric cells through computational design scripts. These dynamic objects evolve with each new acquisition, enabling near-real-time updates.

Lastly, the (4) validation and multi-source monitoring phase is carried out. In particular, cross-comparison between TLS-derived geometric deformations and InSAR displacement trends ensures reliability. The DT environment provides a multi-layered representation of structural and environmental conditions, supporting targeted investigations and risk assessment.

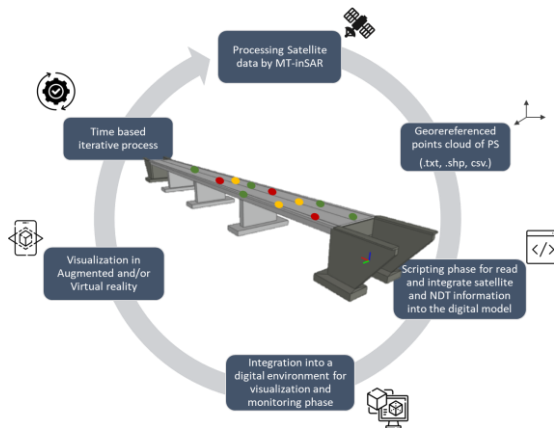


Figure 1. Methodology approach

3 Findings and potential applications

The methodology was tested on a masonry bridge located Lazio region, Italy, and highlights the value of combining multiple datasets. TLS provided detailed geometry, while InSAR revealed displacement trends at the millimeter scale. Together, they painted a clearer picture of the bridge's health and its interaction with surrounding geomorphological processes.

The system is designed to evolve with every new data acquisition. The modular nature of the workflow also means that other technologies, such as GPR, or IoT accelerometers, can be plugged in as needed.

This makes the framework useful well beyond a single structure. Road authorities could use it to prioritize maintenance across networks, while concessionaires could track assets in landslide-prone regions. By linking structural data with environmental risks, it supports not only maintenance planning but also long-term resilience strategies.

4 Conclusions

This study demonstrates how Digital Twins can be more than static models. By integrating TLS, GNSS, MT-InSAR, and environmental datasets in a BIM environment, we created a dynamic and extensible monitoring tool. The approach is semi-automated, scalable, and capable of supporting decision-making at both the asset and network level. Future developments will focus on greater automation, integration of IoT sensor data, and the use of AI for pattern recognition. As nanosatellite constellations and low-cost sensors become more widespread, the vision of real-time DTs for infrastructure is moving within reach. For infrastructure owners and public agencies, this means a shift from reactive inspections to proactive stewardship—improving safety, extending service life, and making better use of resources.

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A Novel Approach for 3D Modelling of Obstacle Limitation Surfaces (OLS) at Airports

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Abstract

In this study, the authors developed a methodology for 3D modelling of obstacle limitation surfaces (OLS). This approach was applied to 11 airports in north-western Italy. The results provide valuable support to the competent authority for assessing potential hazards related to new constructions near airport areas.

Keywords

Obstacle limitation surfaces, aerodrome surroundings, aerodrome safety

1 Introduction

The aviation system is inherently complex and requires the integration of multiple competencies to ensure safe ground and flight operations [1]. Among the critical factors, obstacle management within and around aerodromes plays a crucial role. To address this issue, ICAO introduced obstacle limitation surfaces (OLS) in 1950, a measure also enacted at the European and national levels [2,3,4]. The OLS define the airspace around aerodromes that must be kept free of obstacles to enable intended aircraft operations to be conducted safely at the aerodromes. OLS are determined according to the type and category of runway as well as the intended use (e.g., precision

or non-precision approaches). In EU countries, the design and the implementation of OLS are covered by the Easy Access Rules (EAR) for Aerodromes Regulation (EU) No 139/2014 of the European Aviation Safety Agency (EASA) [3], which sets the geometric parameters and safety criteria for each surface. The main surfaces are the approach surface (AS), the take-off climb surface (TOCS), the inner horizontal surface (IHS), the conical surface (CS), the transitional surface (TS), and the outer horizontal surface (OHS).

In Italy, the authorization process for new constructions is well established, as obstacles must be assessed by the competent authority to determine their impact on air navigation [5,6]. However, type B obstacle charts in the Aeronautical Information Publication (AIP), commonly used for such evaluations, are available only for certified airports, while OLS charts are generally unavailable for non-certified airports.

The objective of this study is to develop a novel methodology for the 3D modelling of OLS that can be applied to both certified and non-certified airports, and to demonstrate its effectiveness through practical implementation.

2 Methodology

This work involved the 3D modelling of five certified and six non-certified airports. Table 1 shows the list of airports with the specific characteristics affecting the dimensions of the OLS. A reproducible GIS-based workflow to generate 3D representations of all OLS components was developed, using the geometric features prescribed in EASA EAR Reg. 139/2014 (CS ADR-DSN.H.405, Table 10) for each of the eleven study aerodromes.

Airport	ARP	ARC	Elev. (ft)	Flight Rules	Run- way
<u>Torino/Caselle</u>	45°12'09"N 007°38'58"E	4E	989	IFR	P
<u>Cuneo</u>	44°32'51"N 007°37'23"E	4E	1267	IFR	P
<u>Genova</u>	44°24'48"N 008°50'15"E	4E	13	IFR	P
<u>Aosta</u>	45°44'18"N 007°22'03"E	2C	1796	IFR	P
<u>Albenga</u>	44°02'45"N 008°07'32"E	2C	149	IFR	P
Torino Aeritalia	45°05'04"N 007°36'11"E	2C	943	VFR	P/U
Alessandria	44°55'30"N 008°37'31"E	1A	299	VFR	U
Biella	45°29'45"N 008°06'09"E	3C	920	VFR	P
Vercelli	45°18'40"N 008°25'03"E	1A	417	VFR	U
Casale Monfer.	45°06'40"N 008°27'22"E	2B	377	VFR	U
Novi Ligure	44°46'48"N 008°47'11"E	2A	607	VFR	U

Table 1. Airports data used to determine the dimensions of the OLS. Certified airports are underlined. (ARP = Aerodrome Reference Point, ARC = Aerodrome reference code, P = Paved, U = Unpaved).

The modelling process for each aerodrome began with georeferencing the runway using known threshold coordinates and elevation values. Where applicable, stopways and clearways were also included. The *Set Z Value* tool was then used to assign specific elevations to reference points in order to accurately define these surfaces, while the *Points Along Geometry* tool was used to distribute additional vertices along linear features to improve interpolation and surface modelling. The same tools were then used to generate the Approach Surface (AS), the Take-Off Climb Surface (TOCS), and the Inner Horizontal Surface (IHS). Where applicable, the Outer Horizontal Surface (OHS) was also generated. The Conical Surface (CS) was modelled as a series of concentric rings that matched the footprint of the IHS. Incremental height steps of 5 metres allowed the prescribed slope of the conical surface to be recreated. Additionally, the Delaunay triangulation tool was employed to generate 3D surfaces from scattered elevation points, ensuring smooth and precise interpolation. This method was particularly useful for modelling transitional surfaces (TS). By applying

Delaunay triangulation, we were able to create a precise representation of the surface accounting for variations in elevation between points. The tool effectively connects the points so that no point lies inside the circumcircle of any triangle. This results in a surface that is mathematically robust and visually seamless.

3 Findings, Potential applications and Conclusions

Figure 1 illustrates the outcomes obtained from modelling the OLS for the airports of Torino/Caselle and Albenga.

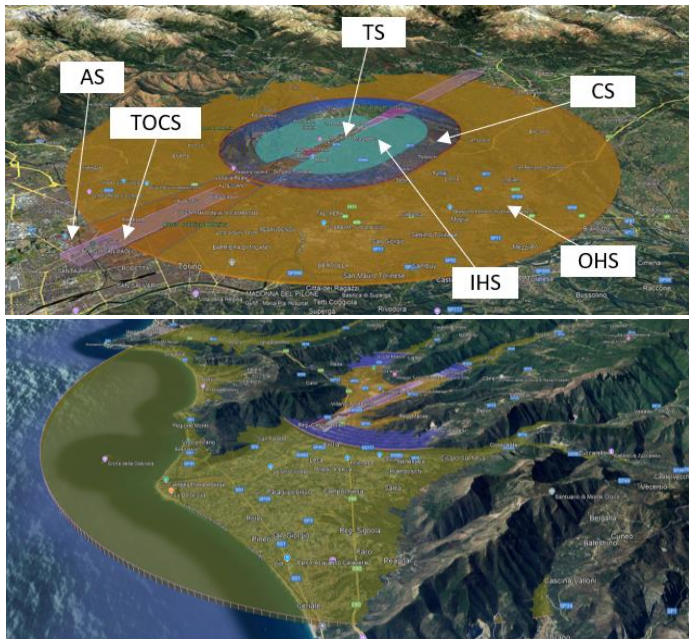


Figure 1. 3D OLS for the airports of Torino/Caselle (top picture) and Albenga (bottom picture). Due to geomorphological constraints, it can be seen that, in some cases, the terrain penetrates the OLS.

In addition to defining useful tools for 3D modelling of OLS in a GIS environment, these results build the foundation for practical applications. The 3D OLS models will enable rapid, geolocation-based checks, allowing competent authorities and local permitting bodies to semi-automatically verify whether any newly proposed structures would penetrate the OLS of airports. This will dramatically speed up the permit decision-making process and reduce manual error. They can be integrated into Aeronautical Information Products and GIS platforms to support obstacle mitigation planning, inform procedure design and airspace safeguarding, and provide clear visualisations for stakeholder consultations.

Finally, this methodology can be applied to the newly proposed ICAO OLS, which are classified as either Obstacle Free Surfaces (OFS) or Obstacle Evaluation Surfaces (OES) [7].

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Life Cycle Assessment of different asphalt pavement scenarios

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Abstract

The increasing relevance of climate mitigation and sustainable resource management highlights transport infrastructure as a critical sector for reducing greenhouse gas (GHG) emissions and advancing the transition toward a circular economy. The use of Reclaimed Asphalt Pavement (RAP), waste plastics, and Warm Mix Asphalt (WMA) technology in road pavement is extensively investigated in terms of performance. However, from an environmental perspective, studies evaluating the combined use of all these solutions in a single pavement are still limited and/or not exhaustive. Life Cycle Assessment (LCA) methodology represents a key approach to comprehensively assess the environmental impact of pavements incorporating these materials. Preliminary results from the incorporation of RAP and WMA technology are promising, and further studies are currently being carried out to also assess the incorporation of waste plastic.

Keywords

Life Cycle Assessment, Asphalt mixture, Recycled materials

1 Introduction

Road pavement construction and maintenance consume large quantities of natural resources and materials [1],

generating significant greenhouse gas emission [2]. It is therefore crucial to identify alternatives that reduce environmental impacts while preserving performance.

In this sense, the LCA methodology enables the evaluation of the environmental impacts of a product by considering all stages of its life cycle. Within the broader framework of Life Cycle Sustainability Assessment (LCSA), LCA represents the environmental dimension, while the economic aspect is assessed through Life Cycle Costing (LCC) and the social aspect is evaluated using Social Life Cycle Assessment (SLCA) [3].

This research project aims to evaluate, using the Life Cycle Assessment (LCA) methodology, the environmental benefits and burdens associated with the use, in road pavements, of Warm Mix Asphalt (WMA) technology, as well as the incorporation of recycled materials, including Reclaimed Asphalt Pavement (RAP) and post-industrial plastic waste.

2 Methodology

In this investigation, a preliminary study was conducted to evaluate the environmental impacts of Hot Mix Asphalt (HMA) and WMA pavements with and without RAP.

The study followed a '*cradle-to-grave*' approach, taking into account the stages of raw material supply, asphalt mixture production, pavement construction, maintenance (including rehabilitation), end-of-life and related transport (Figure 1).

The LCA was conducted in accordance with the methodological principles outlined in the international standards, including EN ISO 14040 and EN ISO 14044, as well as EN 15804, the European standard that defines the rules for construction products. The primary data adopted in the LCA study includes:

- asphalt plant thermal energy consumption and electricity;
- productivity and fuel consumption of construction equipment;
- transport distances;
- quantities of materials used in the mixtures for the different pavement layers.

The remaining data were obtained from the Ecoinvent database. The impact assessment method used was "EN 15804 + A2". However, in this first analysis, performance differences between HMA and WMA, both with and without RAP, have not been considered. This aspect will be addressed in greater detail in subsequent research. After this preliminary study, a more in-depth LCA analysis is currently in progress, focusing on the comparison of HMA and WMA pavements incorporating also waste plastic added with dry method in asphalt concrete mixtures. In this case, in order to evaluate the influence of materials on the pavement service life, the analysis will consider performance parameters derived from laboratory tests performed on the mixtures.

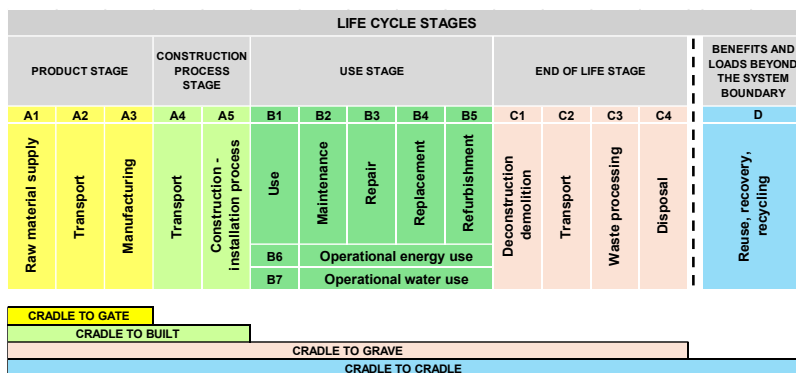


Figure 1. Life cycle stages for construction products according to EN 15804 and system boundaries

3 Findings/Expected outcomes/Potential applications

The LCA results indicate that, when considering the phases up to pavement construction, raw material supply is the most environmentally impactful stage, followed by asphalt mixture production. However, when subsequent stages are included over the pavement's service life, the maintenance stage becomes the most impactful, in accordance with [4]. The use of Reclaimed Asphalt Pavement (RAP) as a partial substitute for virgin aggregates, along with the reduction of production temperatures, was found to provide environmental benefits [4].

The addition of plastic waste inevitably entails an environmental burden associated with the grinding process, which could be offset when considering the environmental benefits of avoiding landfill disposal. Moreover, it is important to point out that the use of plastic waste may influence the service life of the pavement, either positively or negatively, thereby affecting the outcomes of LCA analysis [5].

4 Conclusions

In line with the objectives of the 2030 Agenda for Sustainable Development and the European target of achieving climate neutrality by 2050, the use of recycled materials and warm mix technologies emerges as a promising strategy to reduce the environmental impacts associated with asphalt pavements.

Furthermore, it is essential to clarify that the results are highly sensitive to the definition of system boundaries and allocation methods for environmental burdens related to recycled materials. Equally crucial is a correct performance assessment of materials employed, as they significantly affect the overall efficiency of the pavement structure.

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10th International SIIV Arena

“Renato Lamberti”

(S.A. Biancardo)

The S.I.I.V. Arena is a forum for discussion where Ph.D. students and young scholars from various universities present their research on topics of particular interest to the Scientific Disciplinary Sector CEAR-03/A “Roads, Railways and Airports.” The 10th S.I.I.V. Arena will take place in Naples on 21 November 2025, within the framework of the XX SIIV National Meeting: “Strade, Ferrovie e Aeroporti.” The purpose of this volume is to collect the most innovative research in the field, presented during the 10th International SIIV Arena, with a focus on key issues such as digitalization, pavement materials and safety.

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