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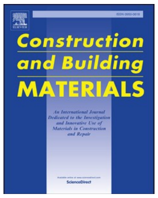

Review

Under tie (sleeper) pads – A state of the art review

Brett Myskowski, Arthur de O. Lima*, J. Riley Edwards

Rail Transportation and Engineering Center – RailTEC, Dep. Of Civil and Environmental Engineering – University of Illinois at Urbana Champaign, 205 N. Mathews Ave., Urbana, IL 61801 USA

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ABSTRACT

Under tie pads (referred to as under sleeper pads outside the United States) are elastic components that deliver a conformal resilient layer between the crosstie (sleeper) and the ballast. Track designs for heavier and faster trains have resulted in a need for more complex systems to decrease required maintenance and improve system reliability and utilization. They have demonstrated success in delivering on these requirements and have been a topic of substantial research over the past twenty years, though no standard understanding of their performance and behavior has been achieved. With this in mind, this paper provides a comprehensive review of the state of under tie pad (UTP) research and use. It introduces UTP technology, examines the physical, mechanical, and chemical properties of UTPs as well as how material selection affects in-track performance and discusses the different uses of UTPs. Based on the literature reviewed, UTPs can provide a reduction in substructure stresses, settlements, ground-borne noise and vibration, crosstie bending demands, and increase in track lateral resistance. UTPs can also result in increased rail bending stresses and track superstructure displacements. The paper also provides recommendations for future research to fill knowledge gaps currently in the literature.

1. Introduction

Under tie pads (UTPs) are elastic layers, typically made of rubber or polyurethane, that are placed between the crosstie (sleeper) and the ballast, as shown in Fig. 1. They are installed with the intention to provide benefits that include a more uniform track stiffness and a reduction in railway track structure degradation that should in turn lead to a reduction in maintenance costs as well as a decrease in railway noise and vibration [1].

One of the earliest known uses of UTPs dates back to the mid-1970s in Japan on the Tokaido Shinkansen Line [3]. While some experimental installations of UTPs were performed over the next twenty years, obtaining reliable materials proved to be challenging so they were not used widely until the 1990s [4]. In Europe, UTPs were first tested in Switzerland in 1986 [5], and Germany and Austria began using them in the 1990s [6]. The success of UTPs in reducing maintenance costs on rail lines in the three countries led to their acceptance and eventual adoption as a standard on the Austrian Railways (OBB) by 2009 [6]. A European Norm (EN) for the testing of UTPs was published [7] and recommendations for use and selection of UTPs were published based on European experience by the International Union of Railways (UIC) in 2018 [8]. As environmental concerns have become more prominent, research has investigated the environmental impacts associated with railways constructed with and without UTPs [9,10], and studies have evaluated UTPs made from recycled materials [11–13]. While using UTPs has become common practice on the passenger and freight mainlines of Central Europe, the effects of their use in other domains remains an open research question. To this end, researchers and railroads in Norway [14], South Africa [15], Russia [16] and the United States [17–21] have studied the use of UTPs in heavy-axle load (HAL) environments. Researchers in Europe [22–27] have investigated UTPs for high speed and very high-speed rail where train speeds exceed 300-400kph (186-248mph). In China, Jin and Liu [28] and Qu et al. [29] have also studied the use of UTPs in ladder track.

Under tie pads are most often classified by their static bedding modulus c_{stat} and dynamic bedding modulus c_{dyn} following the EN [7], though some older papers and some papers from outside Europe use different parameters. A summary of the different classifications available in the literature is provided in Table 1.

Due to their choice of units, some publications use static bedding modulus for classifying UTPs in their study but report it as stiffness rather than the static bedding modulus [29,45–47]. Young et al. [48] appears to refer to the static bedding modulus as the “stiffness modulus.”.

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* Corresponding author.
E-mail address: aolima@illinois.edu (A. de O. Lima).

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Most of the current railway industry standards for UTPs only address classification and quality control [7] so infrastructure owners are free to select the UTP type and material that they deem to be best for their railroad. Some railroads such as Korail [49] and Deutsche Bahn [34] require UTPs with a certain c_{stat} or c_{stat} range depending on their use. While Austria is believed to be the only country to have UTPs as a standard part of design for all mainlines [6], the UIC does provide recommended stiffnesses based on the purpose of the UTP installation [8]. These recommendations provide a good starting point for the selection of UTP stiffness and are shown in Table 2.

The EN standard requires a set of tests to be run on UTPs before their delivery. A static bedding modulus test and dynamic bedding modulus tests at 5 Hz and 10 Hz are required to ensure that the material properties are as advertised. A pull-out bond strength test of the UTP while it is attached to the crosstie, a fatigue test of the UTP on a concrete block and verification of the mass and dimensions of the UTP round out the set of required quality control checks [7]. In addition, the standard has a list of optional tests that the purchaser can require. The standard is focused on the application of UTPs to concrete crossties. For a study on the effectiveness of a UTP installation in the field, the UIC recommends a minimum study period of two years and 100 million gross tons (MGT) of rail traffic [8].

2. Material characteristics

This section discusses the different types of materials that have been used for UTPs and how differences in materials and material characteristics affect the behavior of a UTP.

2.1. Material selection

The two most common base materials for UTPs are rubber, which is typically elastic, and polyurethane, which is typically elastoplastic. While there are exceptions, rubber is the prevailing material used in UTPs in Japan, while polyurethane is more common in Europe [41]. Branson et al. [43] tested neoprene-based materials as UTPs, Kaewunruen et al. [50] investigated closed-cell polymers as UTPs, and Pucillo et al. [27] experimented with ethylene-vinal acetate (EVA) and ethylene-propylene diene (EPDM) pads in addition to polyurethane pads. Researchers have also tested UTPs made from scrap rubber tires with an emphasis on the sustainability of the practice [11–13,51].

In limited comparison testing, research suggests varying the stiffness or thickness of a UTP has more of an effect on bearing pressure and contact area than switching between polyurethane, neoprene and rubber [43,52]. EPDM and EVA pads provided less lateral track resistance than polyurethane pads [27], and EVA UTPs increased contact area by less than polyurethane pads [53]. Kaewunruen's [50] study on closed-cell polymers as UTPs concluded that they are not useful as UTPs because the static bedding modulus is too low when dry and increases when it is exposed to water, making them susceptible to degradation from climate.

While less pronounced than differences due to stiffness or thickness, research has also identified differences in elastic UTPs made from rubber and elastoplastic UTPs made from polyurethane. Branson et al. [52] found that while UTPs of both materials increased ballast-crosstie contact area, UTPs made from polyurethane increased contact area more than those made from rubber while Branson et al. [43] found that there was no significant difference in the performance of polyurethane and neoprene UTPs under laboratory loading. Rubber UTPs tend to be less susceptible to decay from exposure to the elements, particularly saturation and freeze–thaw cycles [41,54], while polyurethane UTPs seem to be better at embedding into the ballast and keeping it in place, possibly reducing ballast migration, which is important at grades and curves [55]. While it would be logical that the embedment of the ballast into the UTP would result in damage to the UTP, Gräbe et al. [15] found that when the polyurethane UTP is removed from service for 24 hours, the severe indentations and even some tears recovered almost entirely to their initial condition. Omodaka et al. [41] found that elastoplastic urethane pads resulted in track with 1.5% higher lateral resistance than track constructed with crossties having elastic rubber pads. In summary, the literature indicates polyurethane UTPs provide marginal benefits to the track structure related to increased crosstie-ballast contact area and pressure as well as increased lateral track stability while rubber UTPs are less susceptible to decay resulting from exposure to the elements.

2.2. Material stiffness

The stiffness of the UTP, whether given by the bedding moduli, or less commonly by the stiffness or spring stiffness, is currently the most common property used to define a UTP and is the basis on which most design recommendations are made [8,34,49]. In addition, changes in the bedding moduli are often the most important sign of issues or failure of the UTP itself [11,41,51,54]. Procurement of UTPs in Europe requires end users to specify c_{stat} and c_{dyn} values for UTP suppliers to meet [7]. Since many studies on UTPs vary the stiffness, specific references to and discussions on UTP stiffness are interwoven into the entirety of the

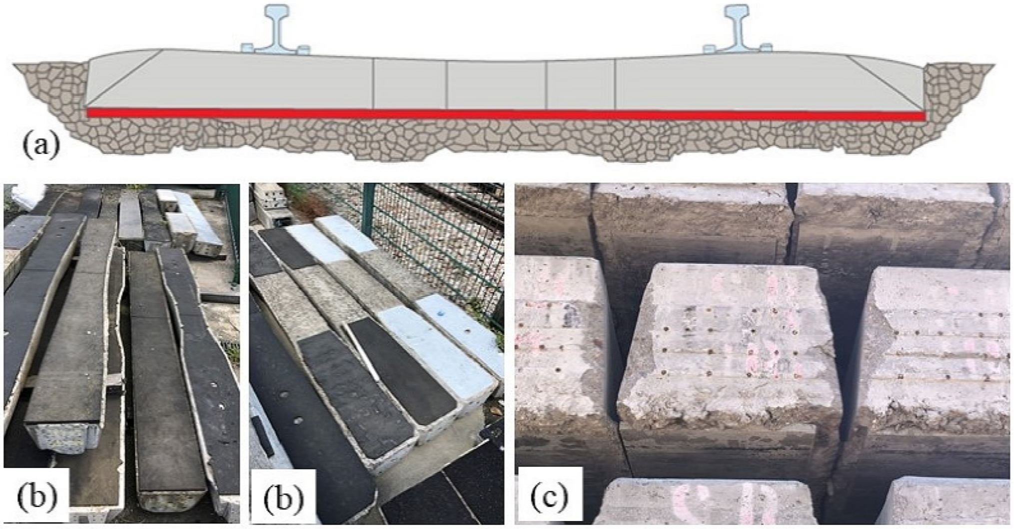

Fig. 1. (a) A graphic profile of a crosstie with UTP [2]; (b) concrete crossties with different types of UTPs in storage in France; (c) padded concrete crossties for installation on a freight railroad in the United States.

paper, but a high-level overview of the effects of stiffness is provided here. In short, decreasing the stiffness of the UTP makes the presence of the UTP more pronounced. Crosstie-ballast contact area increases [36,56], ballast forces decrease [39,57], ballast degradation decreases [58–60], and track settlement decreases [12,60,61] with a reduction in UTP stiffness. Conversely, crosstie acceleration [32], crosstie displacement [32,56], rail bending [32], and rail displacement [32] increase with a decrease in stiffness. Emissions from ground vibration decrease [62–64], and the resonant frequency of the track is lowered [62,63] with decreasing UTP stiffness. While these results hold for concrete crossties, there is currently not enough research to conclude that they hold for other types of crossties such as wood, steel or composite.

Table 2
UTP Applications, from UIC IRS 10713–1, 2018 [8].

UTP Application	UTP Type		
	Soft	Medium	Stiff
Improvement of Track Quality		Primary	Primary
Switches and Crossings (Turnouts)		Primary	Primary
Transition Zones	Secondary	Primary	Primary
Areas with Reduced Ballast Thickness		Primary	Primary
Reducing Long-pitch Rail Corrugation		Primary	Primary
Reducing Ground-borne Vibrations	Primary	Secondary	

2.3. Other material properties

UTP thickness has a major influence on its performance, with an increase in thickness having similar results to decreasing the UTP stiffness [11,12,16]. In testing recycled rubber pads, Esmaeili et al. [12] found that increasing pad thickness from 7 mm (1/4 in) to 13 mm (1/2 in) reduced the c_{stat} by half while Sol-Sánchez et al. [11] found that increasing pad thickness from 5 mm (0.20 in) to 10 mm (3/8 in) decreased both c_{stat} and c_{dyn} by about 40%. Laboratory testing revealed that for all UTPs with a thickness of 1/8 in. (3.2 mm) or greater, the pressure on the ballast and on the concrete was below the thresholds for concrete fatigue crushing and ballast particle crushing [43]. Though mechanical fatigue resistance and other parameters need to be considered, this indicates that pads thinner than the typical 10 mm (3/8 in.) could provide benefits by eliminating the use of excess material.

Increasing the hardness of a UTP has little effect on the performance of a UTP compared to the stiffness and thickness, but can result in an increase in the pressure distribution in the ballast by 20–60% [43]. Katoh and Kakegawa [3] attempted to create a UTP with an ideal hardness value using vibration testing and settled on a Shore Hardness value of Hs 87 +/- 5. A numerical model created for the purpose of optimizing UTPs for a bridge to open track transition zone varied the shear modulus of the UTP instead of the stiffness to create an optimal transition [36].

Table 1
Classification of UTP Properties.

Publication(s)	Classification	Units	Very Soft	Soft	Medium	Stiff
EN Standards [7] UIC Recommendations [8] Abadi et al., 2015 [30] Cao et al., 2014 [31] Johansson et al., 2008 [32] Paixão et al., 2015 [33] Italian Standards, from [27] Deutsche Bahn Standards [34] Others	Static Bedding Modulus c_{stat}	N/mm^3 (lb/in^3)	< 0.08 [7] (<295)	0.08 to 0.15 [7] (295 to 553) 0.10 to 0.15 [27] (368 to 553)	0.15 to 0.25 [7] (553 to 921) 0.15 to 0.25 [27] (553 to 921)	0.25 to 0.45 [7] (921 to 1658) > 0.25 [27] (>921)
EU Standards [7] UIC Recommendations [8] Paixão et al., 2015 [33] Italian Standards, from [27]	Dynamic Bedding Modulus c_{dyn} at 5 Hz	N/mm^3 (lb/in^3)	< 0.09 [7] (<332)	0.09 to 0.25 [7] (332 to 921) 0.16 +/- 0.24 [27] (589 +/- 884)	> 0.25 [7] (>921) 0.25 +/- 0.55 [27] (921 +/- 2026)	> 0.25 [7] (>921) 0.56 +/- 0.95 [27] (2063 +/- 3500)
Chinese Standards, from [35] Akhtar et al., 2006 [17] Dahlberg, 2010 [36] Johansson et al., 2008 [32] Mottahed et al., 2018 [37] Others	Stiffness	kN/mm (lb/in)	50 [36] (285,500)		400 [36] (2,284,000)	3000 [36] (17,130,441)
Krishnamoorthy and Salaheen, 2019 [38] Witt, 2008 [39]	Vertical Stiffness	kN/mm (lb/in)	50 [39] (285,500)		400 [39] (2,284,000)	3000 [39] (17,130,441)
Çati et al., 2020 [40] Krishnamoorthy and Salaheen, 2019 [38] Witt, 2008 [39]	Young's Modulus	MPa (ksi)	10 [39] (1.45)		100 [39] (14.5)	1000 [39] (145)
Dahlberg, 2010 [36]	Shear Modulus	GPa (ksi)	10 to 180 [36] (1,450 to 26,107)			
Katoh and Kakegawa, 1977 [3] Omodaka et al., 2017 [41] Stahl, 2005 [22]	Spring Constant	MN/m (k/in)	6.5 to 9.0 [41] (37.1 to 51.4)			
Katoh and Kakegawa, 1977 [3] Navaratnarajah et al., 2015 [42] Deutsche Bahn Standards [34]	Tearing Strength	MPa or N/mm^2 (ksi)	Average $\geq$ 0.5 [34] (Average $\geq$ 0.0725)			
Branson et al., 2020 [43] Katoh and Kakegawa, 1977 [3] Lakušić et al., 2010 [44]	Hardness	Shore Hardness	48A to 70A [43]			
Çati et al., 2020 [40]	Poisson's Ratio	N/A	Not Specified	Average 0.35 [40]	Not Specified	Average 0.45 [40]
Wan et al., 2014 [45]Akhtar et al., 2006 [17]	Damping Parameter	kN*sec/m^3 [45] (lb*sec/in^3) kN*sec/in (lb*sec/in) [17]	10 to 300 [45]; (0.0368 to 1.105)			

2.4. Recycled materials

With an eye toward environmental sustainability, research has been devoted to studying the effectiveness of using scrap tire treads as UTPs. Because tire treads are used instead of new materials, the tires themselves limit the thickness of the resulting UTPs to between about 5 mm to 13 mm (0.2 in to 0.5 in) and the types of UTPs to soft and medium [12]. While most published research in this area centers on the direct use of tire treads as UTPs, UTPs can also be manufactured by grinding and bonding scrap tire rubber into UTPs, which eliminates these thickness restrictions. Tire-based UTPs decrease settlement [11–13], increase contact area [51], dissipate more energy from loading [13], decrease lateral displacement [13], and decrease ballast breakage [12,13] compared with track without UTPs. These are similar to the desired improvements that one hopes to obtain from installing UTPs with non-recycled materials. When tested for fatigue and thermal/environmental conditions, the characteristics of the UTPs did change [11,51] but the changes were often similar to or less than the changes in material properties that Omodaka et al. [41] and Kraskiewicz et al. [54] found in UTPs made from new materials. It should be cautioned that the only direct comparison between UTPs from recycled and new materials was described by Sol-Sánchez et al. [11], which does find UTPs from recycled tires to be potentially useful. An emerging development is to use asphalt as a material in UTPs, but such an innovation is currently only in research and development and has not yet been tested [65].

3. General mechanisms and applications

The primary purpose for installing UTPs is to create a railroad track structure that deteriorates more slowly and consistently, thereby improving safety and increasing maintenance intervals. This section describes the effects of UTPs on each component of the track structure considering a typical section of open track.

3.1. Rail acceleration and bending

Introducing UTPs into the track system has been found to increase rail acceleration [66], bending, and displacement [32]. Decreasing the stiffness of UTPs results in an increase in rail bending and displacement [32]. Excessive rail bending and displacement is one of the primary concerns regarding the use of UTPs [22,25], so Ngamkhanong and Kaewunruen [56] have proposed a new extremely stiff UTP with c_{stat} $1N/mm^3$ $(3684lb/in^3)$ that provides some of the benefits of ordinary UTPs with less of an increase in rail deflection and bending. Tests on German railway lines found that track with UTPs shows more consistent rail deflection over distance, with variations similar to those found in slab track after installation and after three years of service [22].

Research results are divided as to whether UTPs have no effect on wheel-rail contact forces or if they slightly decrease them. One model found no clear relationship between UTPs and wheel-rail forces [32], while another model found that wheel-rail contact forces and the variance in wheel-rail contact forces to be similar for a crosstie without UTPs, with stiff and soft UTPs, but lower for a crosstie with medium-stiffness UTPs [39]. Johansson et al. [32] found no relationship between UTPs and railseat forces while laboratory experimentation by Ngamkhanong and Kaewunruen [56] found that UTPs decrease wheel-rail contact forces from impact loads by approximately 10%.

3.2. Crosstie behavior

There is a general agreement that introducing UTPs increases crosstie acceleration. Analytical and numerical models [32,67,68], a laboratory test [69], and in-service field testing in Switzerland [66] all concluded that using UTPs increases crosstie acceleration while only Katoh and Kakegawa [3] found that UTPs reduce crosstie acceleration, albeit by only 3%. Notably, the degree to which crosstie accelerations are thought to increase vary widely between studies, with some concluding the increase is on the order of 30% [32] while others find that it doubles or triples [66,69]. Johansson et al. [32] found that decreasing UTP stiffness increases crosstie acceleration further. Under impact rather than cyclic loading, lab testing found that introducing UTPs increased crosstie acceleration by about a factor of ten [69].

Another area of research into how crosstie behavior is affected by UTPs is crosstie displacement, the amount of vertical movement the crosstie undergoes as a result of passing train axle. Modeling [32,56,70,71] and laboratory experimentation [69] have found that introducing UTPs results in higher crosstie displacement than track without UTPs and decreasing UTP stiffness results in a further increase in crosstie displacement [32,56].

Additionally, studies have found that introducing UTPs results in a decrease in crosstie bending [6,66], which is likely the mechanism that results in a decrease in crosstie damage and deterioration found in literature [38] despite the aforementioned increase in crosstie acceleration and displacement. To this end, laboratory testing [72] and field testing in Switzerland [66] have found lower strains in crossties with UTPs. A study subjecting crossties to impact loading has found lower Von Mises stresses in padded crossties, particularly under the rail seat [56]. One study attempted a deeper investigation of this behavior by modeling crosstie movement and rotation resulting from a train pass, finding that softer UTPs can allow excessive crosstie rotation [73].

A summary of the studies on crosstie behavior is shown in Table 3.

3.3. Crosstie-Ballast interface

By providing a soft and flexible layer between the crosstie and the ballast, UTPs increase the contact area between these two components, theoretically resulting in a reduction in track degradation rates and maintenance costs [1]. Several studies have measured the contact area at the crosstie-ballast interface, the results of which are summarized in Table 4; example diagrams and tests are shown in Fig. 2.

Decreasing the stiffness of UTPs further increases crosstie-ballast contact area [30]. By modeling contact points instead of contact area, Kumar et al. [70] found that introducing UTPs increases the number of crosstie-ballast contact points from about 40 to 65, and the size of those contacts increases enough that the contacted ballast no longer yields or breaks. In addition to the findings on contact area, both stiff and soft UTPs were determined to eliminate crosstie center-binding in laboratory testing [61]. Further, studies have also linked an increase in contact area and an enhancement of the frictional resistance at the crosstie-ballast interface to improvements in track lateral and longitudinal stability [27,55,61,69,75,76]. Further discussion concerning the effects of UTPs on track lateral and longitudinal behavior is presented in Section 3.8.

When UTPs are introduced, the increase in crosstie-ballast contact area results in a reduction in crosstie-ballast contact pressure, as shown through findings from modeling [36,56,77] and laboratory testing [15,30,69,78]. Reductions in pressure ranged from 12% [78] to 80–90% [30], but were generally in the 15–30% range. UTPs can also reduce the crosstie-ballast forces from impact and cyclic loads [56]. Decreasing the stiffness of the UTP decreases the crosstie-ballast pressures further, by as much as 45–80% [36,56]. Results from laboratory shear testing demonstrate that the introduction of UTPs reduced the friction angle between ballast and crosstie, bringing it closer to the friction angle between ballast and an unpadded wood crosstie compared to ballast and an unpadded concrete crosstie [79]. Two studies, one in the laboratory [30], and one in the field [55] suggested that ballast particles at the crosstie-ballast interface have higher accelerations, more movement over time, and more rotation when UTPs are present, particularly for stiff or rubber-based UTPs.

Table 3
Summary of Studies on UTP Effects on Crosstie Behavior.

Publication	Parameters Evaluated	Crosstie Type	Loading Type	UTP Properties	Key Findings
Ferreira et al., 2013 [66]	Acceleration	Monoblock Concrete (HSR)	Simulation of train pass at 300 kph (186 mph)	Stiffness 70 kN/mm (400 kip/in)	Maximum accelerations obtained in the crossties may be increased
Ferreira et al., 2019 [68]	Acceleration	Monoblock Concrete (HSR)	Simulation of train passes at 300 and 400 kph (186 and 249 mph)	Optimization of rail pad and UTP stiffnesses	Soft UTPs (<150 kN/mm [856 kip/in]) lead to increase in crosstie acceleration. This acceleration approximately doubles when stiffness is decreased from 150 to 50 kN/mm (856 to 285 kip/in).
Guo et al., 2020 [69]	Displacement	Half Concrete Tie (Chinese Type III Monoblock)	Cyclic Loading	Polyurethane, Thickness: 6.0 mm (0.24 in), Stiffness:	Crosstie deflection doubles with the introduction of UTPs, typically from about 1.0 mm (0.04 in) to 2.0 mm (0.08 in)
	Acceleration		Impact Loading	0.212 N/mm^3 (780 lb/in^3)	Crosstie accelerations with UTPs approximately 10x compared to crossties without UTPs
Johansson et al., 2008 [32]	Acceleration Displacement	Concrete Monoblock	Time-based DIFF and frequency-based GroundVib models	Stiffnesses: 0.1, 0.2, and 0.3 N/mm^3 (370, 740 and 1110 lb/in^3)	Crosstie accelerations increase by 2.5-6x when UTPs introduced, with greater increases for softer UTPs in DIFF; increases less dramatic in GroundVib Crosstie displacements increase by about 1.5x in GroundVib
Katoh and Kakegawa, 1977 [3]	Acceleration	Concrete Monoblock	Vibrogir repeated loading	Hs 87 +/-5 Spring Constant 88 tons/cm (447 lb/in); applied at railseat	Crosstie vibrational acceleration decreased by 3%
Kumar et al., 2019 [70]	Displacement	Concrete Monoblock	Conical Damage Model	Elastic Modulus 0.02 GPa (2.90 ksi)	Crosstie displacement 0.1 mm (0.004 in) without UTPs compared to 0.78 mm (0.031 in) with UTPs
Ngamkhanong and Kaewunruen, 2020 [56]	Bending Displacement	Prestressed Concrete Monoblock	High-intensity Impact Loading modeled in LS-Dyna	Thickness 10 mm, C_{stat} varied from 0.15 to 1.00 N/mm^3 (550 to 3700 lb/in^3)	Displacement increases by 3-4x with the introduction of stiff UTPs and 4.5–7.5x for soft UTPs. Notes that "this study confirms field measurement data that sleepers with UTPs tend to have lesser flexures"
Ngo and Indraratna, 2020 [72]	Bending	Concrete Monoblock	Cyclic Loading by Dynamic Element Model	Stiffness 5.2x10^5 kN/m (356 k/ft)	After 10 cycles, plastic strain for crossties with UTPs is 0.71 mm (0.03 in) compared to 1.20 mm (0.05 in) without UTPs
Schneider et al., 2011 [66]	Acceleration Bending	Concrete Monoblock	In-situ testing in Switzerland	$C_{stat} = 0.30$ N/mm^3 (1107 lb/in^3)	Crosstie accelerations increased by 2-3x with the introduction of UTPs. Crosstie strains decreased 10–15% with the introduction of UTPs.
Shih et al., 2019 [71]	Displacement	Network Rail (UK) G44 Sleeper	Cyclic Loading by FE Model	Vertical Stiffness varied from 50 to 3000 kN/mm (285 to 17,150 kip/in)	With the introduction of UTPs, crosstie displacement increases due to a reduction in confining pressure

Table 4
Summary of Laboratory Tests on Crosstie-ballast Contact Area.

Publication	Crosstie Type	% Contact without UTPs	% Contact with Stiff UTPs	% Contact with Medium UTPs	% Contact with Soft UTPs
Abadi et al., 2015 [30]	Monoblock Twin-block	0.18% 0.53%	1.64% 2.91%		1.05% 4.75%
Guo et al., 2020 [69]	Monoblock	2.9%	16.2%		
Jayasuriya et al., 2019 [59]	Monoblock	18.8%	47.2%		
Loy et al., 2018 [74] *	Monoblock	2–8%	30–35%		
Pospischil and Loy, 2018 [53] *	Monoblock	1.4%	5.9% (EVA); 27.8% (Polyurethane)		
Sol-Sánchez et al., 2014 [51]	Monoblock	2.51%	12.1% (UTPs from Used Tires)		

*Testing conducted by a UTP supplier.

3.4. Ballast degradation and behavior

Ballast degradation is measured using ballast breakage, ballast forces, and ballast strains. Ballast breakage decreases with an introduction of UTPs whether defined by ballast yielding or failure [77], an index of ballast breakage [13,42,59,60,79–81], by measuring the percent fines in the ballast after experimentation [3,15], or by measuring the D_{50} of the ballast before and after a laboratory test [15]. Breakage also decreases further with a reduction in UTP stiffness [58–60]. Nevertheless, UTPs have no effect on ballast breakage defined by mass loss [15,30]. Cui et al. [77] modeled the mechanics of ballast breaking in more detail and found that the ballast breakage in the upper half of the ballast layer is dominated by crushing while the ballast breakage in the lower half of the ballast layer is dominated by sharp edges and corners breaking off. Introducing UTPs was found to reduce forces within the ballast, whether modeled using particle-on-particle forces [39,47] or the number of expected ballast particle failures [47,77], or by calculating a general ballast force, stress or pressure [18,42,57]. Softer UTPs resulted in lower ballast forces than stiff UTPs [39,57]. The standard deviation of the ballast forces also decreased when using UTPs [57]. Ballast strain, whether measured by shear strain or volumetric strain, decreased when using UTPs [42,59,80,81].

Studies present conflicting results on the effects of UTPs on ballast movement. Abadi et al. [61] found that UTPs reduce the lateral spread of ballast in the shoulder and Stahl [22] found that UTPs prevent ballast under the crosstie from moving while Gao et al. [55] found that UTPs resulted in an increase in ballast movement from the high side to the low side of the curve in a field test. Guo et al. [69] found that UTPs caused lateral ballast acceleration to decrease but vertical ballast acceleration to increase, while Ferreira and Lopez-Pita [67] found that UTPs reduced vertical ballast acceleration but increased ballast vibration in high-speed rail track. Stahl [22] determined that UTPs reduced ballast vibration above 16 Hz but increased it below 16 Hz. Sol-Sánchez et al. [58] used tamping and stoneblowing cycles as a proxy for ballast degradation in a lab test and found that using UTPs increased the time between cycles.

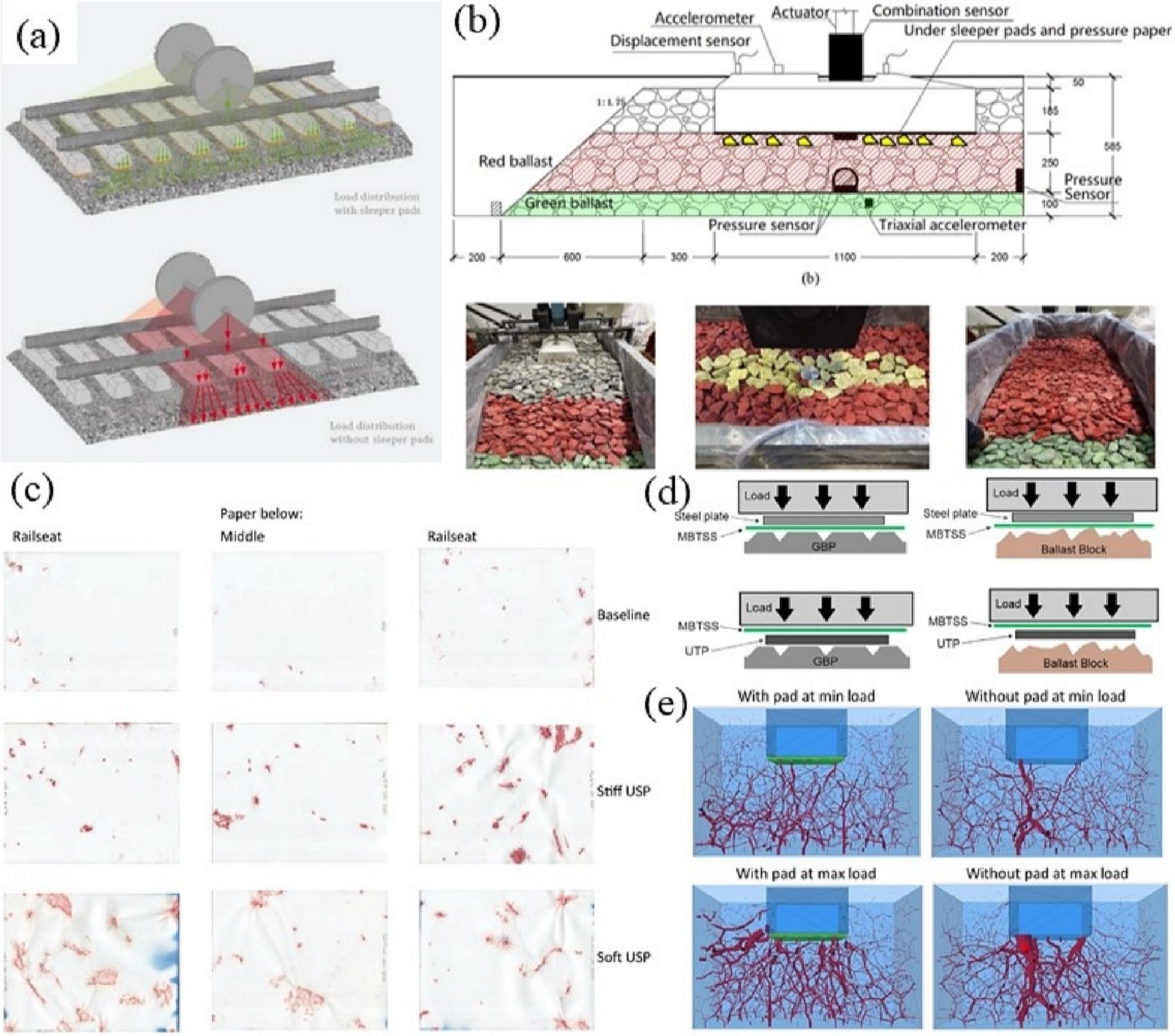

Fig. 2. Examples of crosstie-ballast interface contact measurements. (a) Expected changes in vertical force distribution in track due to including of UTPs [4]; (b) Example laboratory test apparatus for analyzing contact area and pressure changes in crossties with and without UTPs [69]; (c) Semi-quantitative results for UTP contact area using contact tape [30]; (d) Laboratory evaluation of different supports for testing UTP contact area and pressure [52];(e) Ballast force chain distributions for a crosstie and ballast with and without UTPs using DEM [47].

Overall, while the literature provides no clear conclusion on the effects of UTPs on ballast movement, it indicates that the resulting decreases in ballast contact forces and ballast strains results in an overall net benefit to ballast performance, whether in terms of ballast degradation or maintenance (e.g., tamping/stoneblowing) cycles. A quantitative summary of the studies on the effects of UTPs on ballast behavior is presented in Table 5.

3.5. Subballast and subgrade

Research into the effects of UTPs on the subballast and subgrade is currently limited, and findings often contradict one other. Laboratory experimentation and one field study found that UTPs decrease the forces at the ballast-subballast and ballast-subgrade interface [18,78], and a model of UTPs for HSR applications agrees, also finding that subballast and subgrade particle accelerations were reduced [67]. On the other hand, a laboratory study found that ballast-subgrade pressures for standard monoblock concrete crossties are approximately equal with and without UTPs while ballast-subgrade pressures increased with UTPs for twin-block concrete crossties [30]. One model and two laboratory studies found no difference in subgrade pressures based on the presence of UTPs [3,69,70]. A model looking at the effects of UTPs on changing pore water pressures for soil drainage found that UTPs can reduce excess pore water pressure buildup by up to 50% [31].

3.6. Track stiffness

The introduction of an elastic element such as UTPs to the track structure will inevitably change the stiffness of the track structure, and research has determined that the presence of UTPs decreases the stiffness of the track structure [46,47,58,61,68–70,83,84] and the resilient modulus of the track structure [59]. All else equal, research indicates track structure stiffness decreases with a decrease in UTP stiffness [47,59,61], or an increase in UTP thickness [12]; example data demonstrating this relationship are shown in Fig. 3. Research also indicates that the track stiffness will be slightly less variable with UTPs

Table 5
Summary of Studies of UTP Effects on Ballast Behavior.

Publication	Experiment Type	Parameters Measured	Loading Type	UTP Types	Key Results
Abadi et al., 2015 [30]	Laboratory	Ballast-crosstie contact pressure Ballast-subgrade contact pressure	Cyclic, 3 to 6 million cycles	UIC Soft and Stiff	UTPs result in an 80–90% reduction in ballast-crosstie contact pressure. UTPs result in little change in ballast-subgrade contact pressure for monoblock crossties and cause the pressure to approximately double for dual-block crossties. Soft UTPs have about 15% less ballast-crosstie and ballast-subgrade contact pressure than stiff UTPs.
Cui et al., 2021 [77]	Model	Ballast Breakage Mechanisms Ballast Stress	FEM Ballast Box Model	Not Specified	UTPs particularly useful at reducing breakage from overall damage that is likely to occur in top half of ballast layer UTPs result in a reduction in ballast breakage from ballast tensile and shear failures UTPs reduce maximum ballast stress by 26% and average ballast stress by 3%.
Davis et al., 2011 [18]	Field (United States)	Ballast Stress Ballast-Subgrade Interface Stress	Heavy Haul Revenue Service	Not Specified	UTPs reduce the vertical stress in the ballast by 20–50% with greatest reductions under center of crosstie. UTPs reduce the vertical stress at the ballast-crosstie interface by 15–30%, uniformly across the profile of the crosstie.
Esmaeili et al., 2022 [60]	Laboratory	Ballast Breakage Index	Cyclic, 200,000 cycles	UIC Soft and Stiff	Stiff UTPs reduce ballast breaking by about 3% while soft UTPs reduce ballast breaking by about 9%.
Gräbe et al., 2016 [15]	Laboratory	Percent Fines Mass Loss D_{50} Static Pressure Dynamic Pressure Static Contact Dynamic Contact	Cyclic, 1 million cycles	UIC Medium	Introducing UTPs reduced the accumulation of fines by 25%, eliminated the reduction in D_{50}; reduced static and dynamic pressures by about 75%, approximately tripled static and dynamic contact, and had little effect on mass loss.
Grossoni and Bezin, 2015 [57]	Model	Ballast Forces Variation in Ballast Forces	Simulated Train Pass	Stiffness ranging from 30 to 150 MN/m (171 to 856 k/in)	The stiffest UTPs reduce ballast forces by about 8% while the softest UTPs reduce ballast forces by about 17%. The standard deviation of ballast forces decreases with the introduction of UTPs and further decreases as the UTPs become softer.
Indraratna et al., 2014 [80]	Laboratory	Shear Strain Volumetric Strain Ballast Breakage Index	Impact Testing	UIC Medium	Ballast shear and volumetric strains decrease about 40% with the introduction of UTPs. The ballast breakage decreases by 45–65%, with the greatest benefits occurring for hard subbases.
Indraratna et al., 2021 [13]	Laboratory Recycled Materials	Ballast Breakage Index	Cyclic Loading	Not Specified	UTPs reduced ballast breakage by "more than 50%".
Jayasuriya et al., 2019 [59]	Laboratory	Shear Strain Volumetric Strain Ballast Breakage Index	Cyclic Loading	UIC Medium	UTPs reduced volumetric and shear strain by 15–50%, with the greatest reductions at low loading frequencies and the least reductions at high loading frequencies. UTPs reduced ballast breakage by 7 to 40%.
Katoh and Kakegawa 1977 [3]	Field (Japan)	Ballast Vibrational Acceleration	Train Pass	Hs 87 +/-5 Spring Constant: 88 tons/cm (447 kip/in); applied at railseat only	Track installed with UTPs reduced vibrational acceleration by 22% immediately after installation and by 51% 23 days after installation
Li et al. 2018 [82]	Model	Ballast Modulus	Simulation of Train taking a Turnout	UIC Medium	UTPs result in a reduction of the equivalent ballast modulus by about 50%.
Navaratnarajah et al., 2015 [42]	Laboratory	Shear Strain Volumetric Strain Ballast Breakage Index	Cyclic, 500,000 cycles Impact Load	UIC Medium	Under impact loading, UTPs reduce shear and volumetric strain by about 17% for hard subbases and about 28% for soft subbases. Under cyclic loading, introducing UTPs reduces ballast breaking by about 75% at the top, middle and bottom of the ballast layer.
Navaratnarajah et al., 2020 [79]	Laboratory	Ballast Breakage Index	Direct Shear Test	Not Specified	The ballast breakage at the crosstie-ballast interface was reduced by 75% with the introduction of UTPs.
Sol-Sánchez et al., 2016 [58]	Laboratory	Tamping Cycles Ballast Breakage Index	Cyclic Loading, 200,000 cycles	UIC Stiff and Soft	Without UTPs, tamping was required 4 times over the course of the 200,000 cycles. With stiff UTPs, it was required twice and with soft UTPs it was required only once. The introduction of UTPs reduced ballast breakage, and soft UTPs reduced ballast breakage more than stiff UTPs.
Venuja et al., 2021 [81]	Laboratory	Shear Stress Ballast Breakage Index	Direct Shear Test	UIC Medium	When the shear strain is held constant, UTPs reduce the resulting shear stress by about 25%. UTPs reduced ballast breakage by about 40%.
Witt 2008 [39]	Model	Ballast Contact Forces	Load Section of Track with Variable Stiffness	Young's Modulus 10 to 1000 MPa (1.45 to 145 ksi)	Decreasing UTP stiffness decreases ballast contact forces

than without [83]. Thus, it is theoretically possible to select a UTP thickness or stiffness to target a desired track stiffness. While research attempting this is relatively lacking, Esmaeili et al. [12] selected a 11 mm (0.43 in) thick pad to obtain a desired track stiffness for a laboratory experiment and Ferreira et al. [68] created a model to optimize the railpad/UTP combination ideal for a HSR route with train speed between 300 and 400 kph (186 and 250 mph).

Decreasing the track stiffness results in an increase in energy dissipated per unit volume by the track structure [60,85], and this energy dissipation rate increases as UTP stiffness decreases [58–60]. This increase in energy dissipation results in a decrease in track settlement [85].

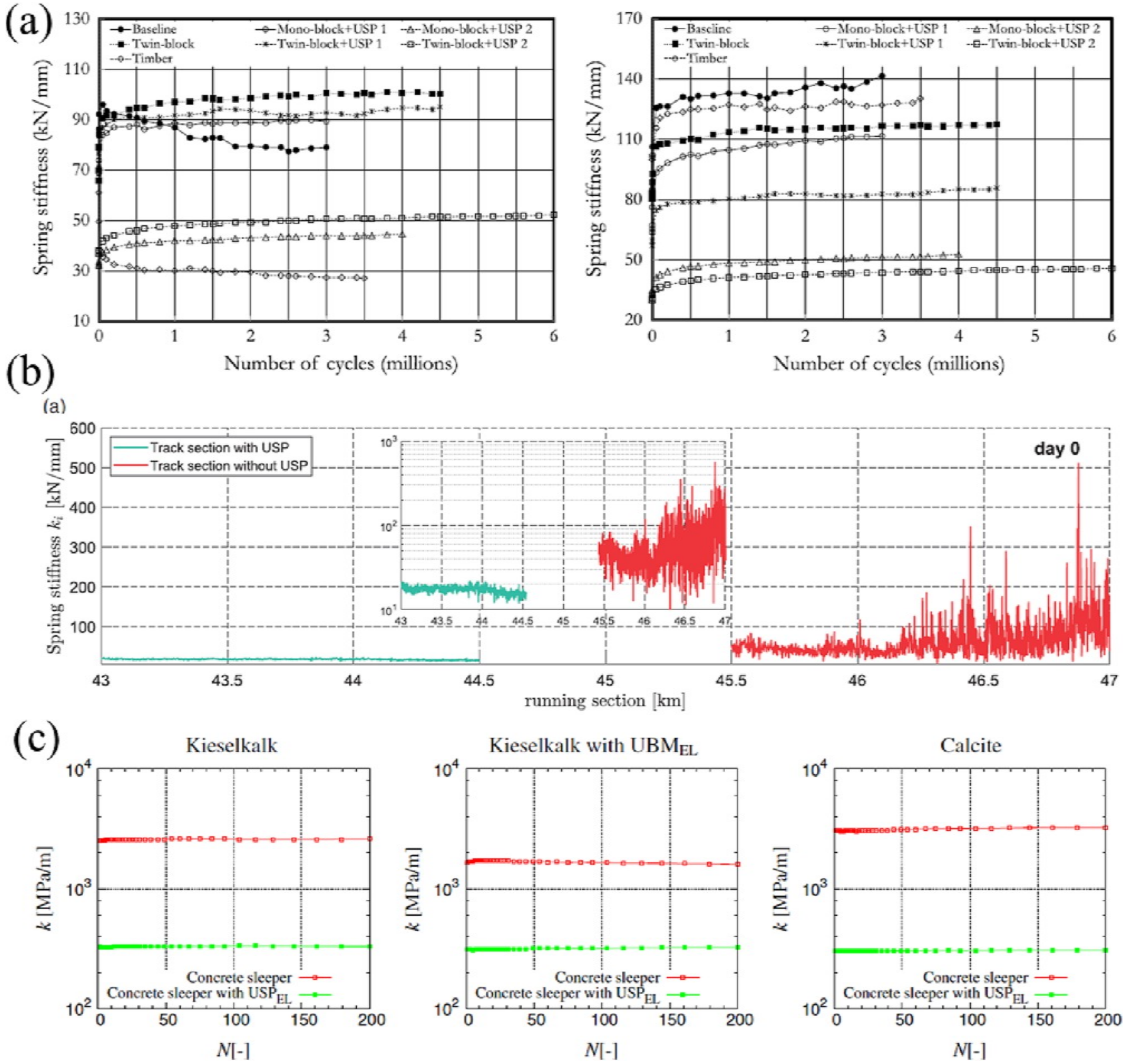

Fig. 3. Influence of UTP introduction to track stiffness; (a) Changes in the overall track spring stiffness of a crosstie at the ends (left) and over the entire crosstie (right) as a result of changing UTP stiffness [61]; (b) Stiffness estimation of a section of track in Austria with and without UTPs through computer modeling [84]; (c) The difference in track stiffness (k) resulting from using UTPs in two different types of ballast and with the introduction of under ballast mats (UBMs) [70].

3.7. Track settlement

Under tie pads have been shown to reduce track settlement through modeling [67,70,77] and laboratory testing [3,12,15,41,60,61,69,78]. A field study by a UTP supplier on the Austrian Railways found that settlement for track with UTPs was on average lower than that of track without UTPs [53]. As the stiffness of the UTP decreases, track settlement will decrease as well [12,60,61]. In laboratory testing, using UTPs reduced settlement for all sections of the crosstie: the center, the railseat and the shoulder [69], and also reduced settlement in conditions where the crossties had no center support [3]. Li and McDowell [47] found that the settlement from a single train pass was lower with UTPs than without. Tests looking at the variability of settlement in track are limited as they require a substantial length of track to test, with one study on an ore line in Norway showing no differences in settlement standard deviation in a curve at 47 MGT [86].

A quantitative summary of the studies on the effects of UTPs on track settlement behavior is presented in Table 6.

3.8. Lateral and longitudinal resistance

Lateral and longitudinal track resistance to movement is an important part of a good track structure, particularly as related to track buckling resistance. Laboratory experimentation found that UTPs decrease the longitudinal resistance at the crosstie center but increase it at the rail seat [61], while another laboratory experiment found that UTPs increase longitudinal track resistance, particularly under high forces [69]. Thus, additional research is still required to understand the effect of UTPs on longitudinal resistance. Results from laboratory [13,41,51,59,78] and field experimentation [27,53] are consistent that UTPs result in an increase in lateral resistance and a decrease in lateral movement over time, with only Guo et al. [69] dissenting that UTPs have little effect on lateral resistance. An increase in lateral resistance from UTPs is further evidenced by a North American freight railway

Table 6
Summary of Studies of UTP Effects on Track Settlement Behavior.

Publication	Experiment Type	Loading Type	Track Settlement			
			Without UTPs	Stiff UTPs	Medium UTPs	Soft UTPs
Abadi et al., 2019 [61]	Laboratory	Cyclic, 1 M cycles	5.7 mm (0.22 in) (monoblock) 4.21 mm (0.17 in) (dual-block)	3.9 mm (0.15 in) (monoblock) 4.03 mm (0.16 in) (dual-block)		4.0 mm (0.16 in) (monoblock) 3.96 mm (0.16 in) (dual-block)
Esmaeili et al., 2020 [12]	Laboratory, Recycled Materials	Cyclic, 200,000 cycles	6.0 mm (0.24 in)			5.0 mm (0.20 in)
Esmaeili et al., 2022 [60]	Laboratory	Cyclic, 200,000 cycles	7.8 mm (0.31 in) (S Ballast) 4.4 mm (0.17 in) (K Ballast)	5.4 mm (0.21 in) (S Ballast) 3.5 mm (0.14 in) (K Ballast)		4.5 mm (0.18 in) (S Ballast) 3.1 mm (0.12 in) (K Ballast)
Gräbe et al., 2016 [15]	Laboratory	Cyclic, 1 M cycles	55.1 mm (2.17 in)		31.1 mm (1.22 in)	
Guo et al., 2020 [69]	Laboratory	Cyclic, 1 M cycles	7.9 mm (0.31 in) (center) 6.6 mm (0.26 in) (railseat) 1.4 mm (0.06 in) (shoulder)		6.4 mm (0.25 in) (center) 4.3 mm (0.17 in) (railseat) 1.1 mm (0.04 in) (shoulder)	
Katoh and Kakegawa, 1977 [3]	Laboratory	Cyclic, 1.5 M cycles	72 mm (2.83 in) (no center support) 51 mm (2.01 in) (center support)	48 mm (1.89 in) (no center support) 39 mm (1.53 in) (center support)		
Kumar et al., 2019 [70]	Model	Dynamic, 200 cycles	1.42 mm (0.06 in) (without UBM) 2.90 mm (0.11 in) (with UBM)	1.28 mm (0.05 in) (without UBM) 2.60 mm (0.10 in) (with UBM)		
Navaratnarajah et al., 2018 [78]	Laboratory	Cyclic, 500,000 cycles	22 mm (0.87 in) (20 Hz / 145 kph) 13 mm (0.51 in) (15 Hz / 110 kph)			17 mm (0.67 in) (20 Hz / 145 kph) 9 mm (0.35 in) (15 Hz / 110 kph)
Omodaka et al., 2017 [41]	Laboratory	Cyclic, 200,000 cycles at 7 Hz	0.44 mm (0.02 in) (strong subgrade) 1.22 mm (0.05 in) (weak subgrade)	0.33 to 0.44 mm (0.013 to 0.017 in) (strong subgrade) 1.18 to 1.32 mm (0.046 to 0.052 in) (weak subgrade)		
Plasek et al., 2014 [86]	Field (Czech Republic)	47 MGT Revenue Service	7 to 14 mm (0.28 to 0.55 in)		7 to 13 mm (0.28 to 0.51 in)	
Pospischil and Loy 2018 [53]	Field (Austria)	Revenue Service	12.5 mm (0.49 in)	7.5 mm (0.30 in)		

successfully using UTPs to prevent lateral track movement from changes in temperature in a curve [21]. A full-scale field study found that the increases in lateral resistance occur for both loaded and unloaded track sections [27]. In installing UTPs in a tunnel on a mainline track in Japan, Katoh and Kakegawa [3] found no change in lateral track movement but did see a reduction in track twisting.

3.9. *Effects of different railway and track properties*

The previous discussion in Sections 2 and 3 has centered on the use of UTPs on concrete crossties and how changing the properties of the UTPs affects track behavior. However, changes in the track structure itself will change how UTPs affect track behavior. This subsection summarizes findings from research addressing changes in six relevant track structure elements – crosstie type, crosstie support, train speed, ballast type, subgrade quality, and the presence of other elastic elements – and how they influence how UTPs affect the track structure. It should be noted that research into many of these topics is partial or limited, and additional investigation should be undertaken.

While most research into UTPs was conducted on concrete monoblock crossties, studies have investigated alternative crosstie materials and geometries. Laboratory testing conducted into dual-block concrete crossties found that while UTPs have the same positive effects for dual-block crossties, these benefits are less pronounced [30,61]. Laboratory testing of steel, timber, and composite crossties found that, similar to concrete crossties, the introduction of UTPs reduced the stiffness and the settlement of the track structure [46]. Field experimentation at a test track in the United States comparing wood tie turnouts with and without UTPs found that the turnout with UTPs settled 33% less after accumulation of 80 MGT [20]. Very soft UTPs with wood ties were installed in a low-tonnage passenger line tunnel in Switzerland in 1986, and researchers have found no evidence of track stability or UTP material deterioration after 20 years of in-service use [5]. The steel switch crosstie with a specially designed UTP shown in Fig. 4d was developed for and successfully installed on the Guangzhou-Shenzhen Railway to allow safe tamping at points of switch while maintaining track lateral resistance [87].

Modeling and laboratory experimentation has been used to investigate the effectiveness of UTPs in preventing and mitigating issues related to improper crosstie support. Laboratory testing found that UTPs were effective at eliminating center-binding issues related to cyclic loading [61] and in situations where crossties were lacking center support, UTPs reduced settlement by 33%, greater than the 24% reduction for crossties with center support [3]. A model was created for situations where crossties were hanging – lacking support altogether – and found that the presence of UTPs reduced the forces in the ballast significantly, up to a factor of five for three hanging crossties in a row [39].

Studies that vary train speed appear to suggest that similar benefits are achieved from UTPs across all speeds, with most research done at speeds corresponding to inter-city passenger rail [59,88] and high-speed rail [22–25], while research at lower freight speeds is more limited. In laboratory experimentation simulating train passes between 97 and 160 kph (60–100 mph), UTPs showed the most reduction in settlement and ballast deterioration at the lower loading frequencies corresponding to lower train speeds [59]. Cao et al. [31] modeled the effects of UTPs on pore water pressures above and below the critical ground wave speed,

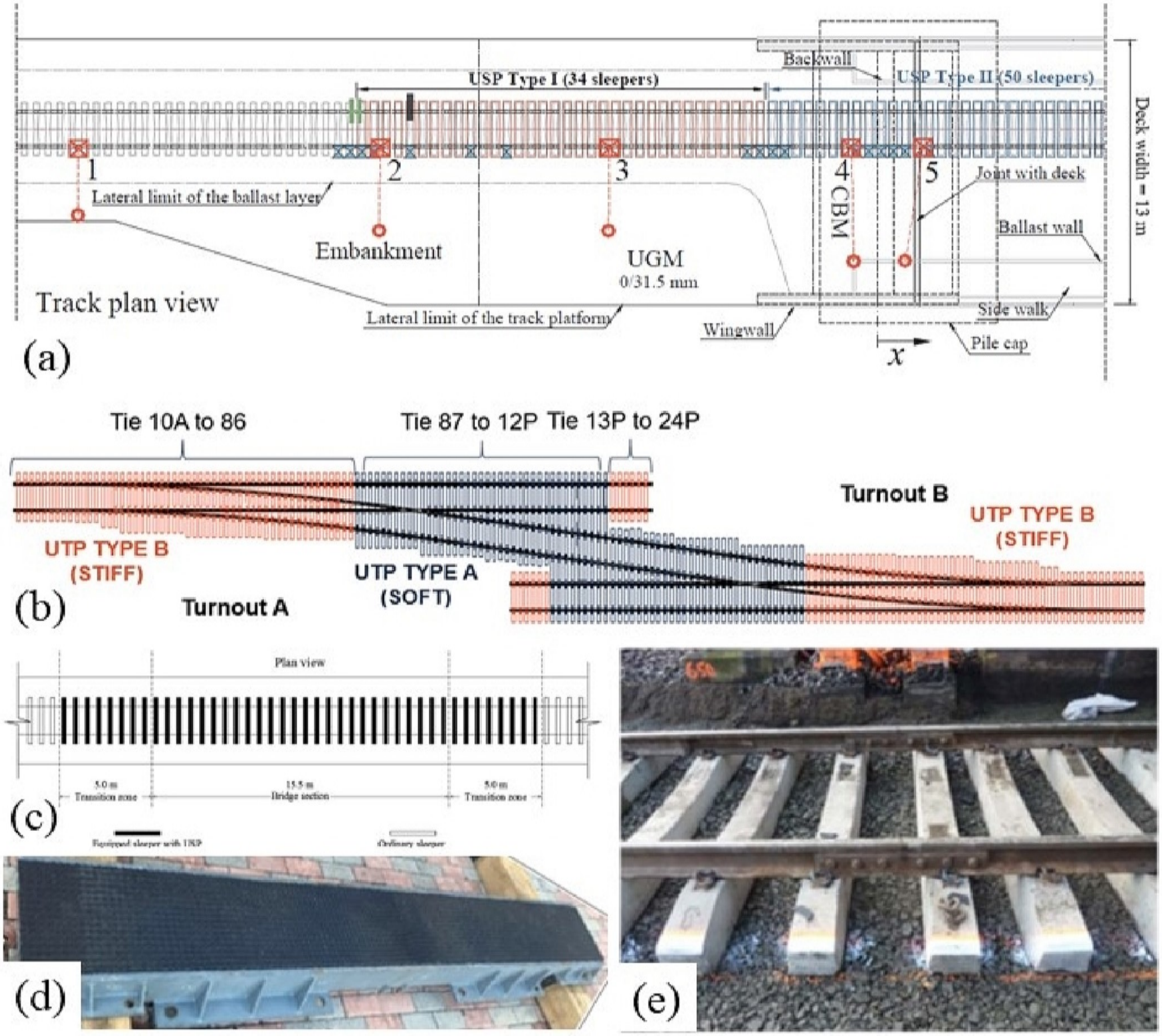

Fig. 4. Different applications for UTPs in special track: (a) a transition from open track to bridge [109]; (b) a wood-tie crossover optimized for American freight traffic [116]; (c) a bridge in Iran [106]; (d) a specially designed steel switch tie [87]; (e) an installation at an insulated joint in Australia [4].

250 kph (155 mph), and found UTPs to be more effective below critical ground wave speed because UTPs are better at dealing with dynamic effects than static effects, and dynamic effects dominate below critical ground speed while static effects dominate above critical ground speed. Vanhonacker and Masoumi [89] found that UTPs do not reduce ground-borne vibrations for trains below about 75 kph (46 mph) but did not investigate their ability to improve geometry and reduce maintenance at these lower speeds.

A model [70] and laboratory experiments [12,60] investigated the effect of ballast type on UTP performance. The least track settlement occurred with the hardest ballast available and the softest UTP available [12,60], though the effect of UTPs decreased as ballast hardness increased [60]. Kumar et al. [70] notes that different ballast types will settle differently primarily based on their initial packing when UTPs are present, but did not draw any conclusions about how the difference in ballast types affected the performance of the UTPs. These components may also be used to reduce the railroad ballast thickness [1,8]. While there is little study on the effects of ballast thickness on the performance of UTPs, improvements in the understanding of how changes in ballast affect the track structure [60,90] should provide a greater understanding into how changes in ballast affect UTP performance as well.

The stiffness and quality of the subgrade is likely an important parameter in the performance of UTPs and selecting the correct UTP stiffness. Laboratory experimentation compared the effects of using UTPs on different subgrades, finding that UTPs consistently provide benefits for stiff and well-supporting subgrades [41,42,80]. For a soft subgrade and UTPs, the ballast degradation and impact forces are reduced [42,80], but there does not appear to be a reduction in settlement anymore [41]. In a life-cycle cost analysis on a railway corridor in the United Kingdom, there are locations where the UTPs are considered to have a net detrimental effect because the subgrade is particularly soft [48].

4. Under tie pads in special track applications

4.1. Curves

UTPs are used in curves to maintain geometry and reduce track structure deterioration in the same way they are used in tangent track. Installation of UTPs in curves in Austria since the 1990s has resulted in reduced ballast forces, reduced crosstie bending forces, and reduced track settlement [6,91]. In addition, UTPs reduced ballast voids beneath the edge of the crosstie, an issue more concentrated in curves [91]. When installed in a curve in the Czech Republic, UTPs were credited with maintaining track geometry better than a nearby curve without UTPs after 47 MGT [86]. In the United States, UTPs installed on a five-degree curve decreased the variance in surface roughness at 190 MGT [18]. They were also used to eliminate curve breathing on a United States freight railway curve subject to large temperature fluctuations [21].

There are other studies that conclude that installing UTPs results in little change or may have negative effects on the behavior of curves. Two test curves in the Czech Republic, one with UTPs and one without, saw no differences in track settlement [86]. An installation of UTPs on part of a curve on a freight line in Norway resulted in no differences in concrete crosstie damage or geometry changes between the sections with and without UTPs at 100 MGT [14]. At a test track in the US, more ballast migration from the high side to the low side of a curve was observed with UTPs at 900 MGT [55], a possible drawback to using UTPs in curves.

UTPs have been used in curves to reduce the severity of long-pitch rail corrugation, sinusoidal waves on the running surface of the rail, a phenomenon particularly problematic in curves [8]. Using soft UTPs in combination with premium fastening systems and soft rail pads can reduce the rate of long-pitch corrugation by a factor of five or more in curves with a radius of less than 400 m (1312 ft) [8]. Installing UTPs in Austria successfully reduced rail corrugation when the UTP stiffness was correctly chosen [6,91]. Ferreira et al. [68] found that at 24 MGT, stiff UTPs reduced long-pitch corrugation by about 40% and soft UTPs reduced it by half. A study on long-pitch corrugation in the Czech Republic has led to some promising, if not yet conclusive, results [92].

4.2. *Rail joints*

UTPs have been tested at rail joints to mitigate high impact forces. On a test track in Russia, UTPs were installed at rail joints and have been shown to reduce both the track settlement and track settlement rate at 600 MGT and 810 MGT respectively. Additionally, the joints with UTPs settled very little between 600 MGT and 810 MGT while the joint without UTPs continued to settle throughout the test [16]. In a test installation in Australia (Fig. 4e), track geometry at the joint was more consistent after the installation of UTPs [4]. A study on the Tokaido Shinkansen found that installing UTPs at a rail joint decreased ballast acceleration by approximately half [3]. Installing UTPs at rail joints increased the vibration of the crosstie and other track components [4,56], just as it does in open track.

4.3. *Turnouts (Switches & Crossings)*

The primary goal of using UTPs in turnouts (switches and crossings) is to reduce the abrupt changes in stiffness that occur near the point of switch and the point of frog (point of crossing) and therefore to increase the longevity of the turnout. To this end, modeling [45] and field experimentation [20,93] have found it best to use softer UTPs under the point of frog and stiffer UTPs away from the point of frog. Field testing in the United States found that using such a turnout with timber crossties was successful in reducing stiffness variance, settlement, settlement variance, and wheel-rail load variation within the turnout, but the approaches to the turnout saw slightly higher forces and force variance [19,20]. Padded turnouts installed in the Czech Republic provided improved settlement performance compared to nearby turnouts without UTPs [86,93]. Two studies measured crosstie displacement at a turnout, with one finding that the padded crossties displaced more variably than non-padded crossties [94] and the other finding the padded crossties displaced less variably [88]. Depending on the design of the turnout itself, using UTPs, particularly soft UTPs, may encourage crosstie rotation [88]. Field testing in Switzerland found that adding UTPs to turnouts increased vibrations less than 24 m (78 ft) from the track but decreased vibrations once further away [95], and decreased vibrations at frequencies above 63 Hz but had little effect below 63 Hz [96].

A vehicle-track interaction model based on field crosstie deflection data found that a turnout with UTPs sees a reduction in wheel-rail forces [94,97] and a reduction in force variance [94]. Another model goes further to conclude that the P_2 component of impact forces are reduced more than the P_1 forces when using UTPs [98]. Modeling a turnout with UTPs found reductions in track stiffness by about 31% and crosstie-ballast pressure by about 20% [82]. Modeling found that using UTPs in turnouts increased rail displacement and rail pad deformation, with higher increases in rail displacement occurring for softer UTPs [98]. A model of the environmental costs of a turnout on the Austrian Railways network found that over the life of a turnout, the annual environmental costs of a padded turnout will be €66 less than a non-padded one [99].

4.4. *Crossing diamonds*

Installing UTPs at crossing diamonds is often undertaken with similar goals and methods to that of UTP turnout installations [100]. The authors are aware of only one published study using UTPs with crossing diamonds. A field experiment at a test track in the United States found that a crossing diamond with UTPs did not become a low spot and settled more consistently than an unpadded crossing diamond [100].

4.5. *Transition zones*

As transition zones between low-stiffness and high-stiffness sections of track are widely understood to be locations of rapid track structure degradation [101], UTPs have been used in transition zones to slow this degradation by creating a more gradual track stiffness transition [101]. One solution is to use a single UTP stiffness for the transition zone and then potentially in higher track stiffness areas as well. This solution focuses on reducing contact stresses at the crosstie-ballast interface to tame the negative feedback loop of deterioration at the transition [102,103]. This solution has been modeled [24,25,35,39,104] and attempted in the field as well [33,104–106]. Researchers were able to create track with a stiffness that changed more gradually on an US mainline freight corridor [104], and decrease crosstie acceleration by 9% on a mixed-use corridor in Iran [106]. Another revenue service implementation of UTPs can be found in Argentina, where UTPs were combined with UBMs for a bridge and transition section [107]. Selecting UTPs in a transition must be done carefully to obtain the correct track stiffness profile and ensure that rail acceleration does not increase too dramatically. Two models found that it is best to use UTPs on the stiff part of the track and the backfilled approach but not the transition itself [24,35]; otherwise rail accelerations in the transition can increase excessively, particularly for high-speed trains [25,33]. Using UTPs that are too soft in the transition can cause the wheel-rail forces to be transferred away to the stiff part of the track rather than dissipated as planned [39].

To address these problems, researchers have tried to optimize the UTP transition by gradually decreasing UTP stiffness as the track structure becomes stiffer. This was first modeled in 2010 using five different UTP stiffnesses on the approach [36]. A bridge and approach with multiple UTP stiffnesses was modeled by Paixão et al. [33] using the solution in Alves Ribeiro et al. [108] and later installed in the field in Portugal (Fig. 4a) [109]. The researchers were able to decrease the variability in track stiffness while controlling rail displacements to a maximum of 1.06 mm (0.04 in), compared with about 1.5 mm (0.06 in) before [109]. Theoretical designs using UTPs with multiple stiffnesses were created for a transition between open track and a bridge in Turkey [40] and for a transition between ballasted track and slab track in

Slovakia [110].

4.6. Bridges

Because ballasted bridges are very stiff, UTPs have been used to decrease track stiffness at bridges so that it is similar to adjacent tangent track to improve track geometry and reduce track structure degradation, as shown in Fig. 4d. This was successfully demonstrated on a bridge experiencing geometry and mud-pumping issues on a freight railroad in the United States, resulting in decreased rail forces and accelerations and no special maintenance for 1,200 MGT, compared to 40 MGT for a nearby non-padded bridge [111]. Installing UTPs on a bridge in Iran reduced accelerations on the bridge and transition [106]. In the United States, a revenue-service UTP installation reduced the stress in the concrete crossties and increased the time between tamping cycles [17] and in a test track installation UTPs reduced impact forces and increased tamping cycles from 20 to 35 MGT [112] at 1,400 MGT of traffic.

UTPs have also been installed on bridges with the intention to reduce stress and deterioration on the bridge structure itself, and have been shown to reduce the accelerations, bending moments, and deflections of bridge spans [17,37,106]. A model of a steel girder bridge found that using UTPs will result in changes to the natural frequency and therefore the dynamic response of the bridge [113].

UTPs can also be used on bridges to decrease noise emissions from the bridge. After retrofitting an existing open-deck steel bridge with UTPs, overall sound decreased by 5 dB and vibration in the steel bridge girders decreased by 6 to 12 dB [114]. Bridges retrofitted with UTPs in Germany resulted in minimal changes with medium-stiffness UTPs but reduced vibration by between 3 and 10 dB with soft UTPs while overall sound decreased by about 1 dB for all bridges with UTPs [115]. For a viaduct with ballasted track, introducing UTPs reduced vibrations above 50 Hz by 4 dB and decreased sound emissions by 6 dB immediately beneath the viaduct and by 3 dB at 12.5 m (41 ft) away from the track [3].

4.7. Tunnels

A pair of UTP field studies were initiated in Switzerland in the 1980s with the objective of evaluating vibration reduction in tunnels, and the experimental track has not yet shown any major deterioration [6]. Vibration was reduced by about 14 dB for frequencies above 50 Hz and had little effect at lower frequencies [5]. Additionally, UTPs were installed in the Rokko Tunnel on the Sanyo Shinkansen in Japan to control track geometry and to decrease vibrations, and records kept by JR West show that there was a significant decrease in maintenance work required after UTP installation. In this study vertical track and ground vibration decreased by 4 dB and horizontal track and ground vibration by 3 dB to 5 dB [3].

4.8. Ladder track

Ladder track is a track structure in which each rail is supported by concrete with the two rail support structures connected at regular intervals by steel rods, and is most popular in East Asia [29]. Two studies have been conducted on using rubber pads under the concrete supports in the way UTPs are used for track with crossties [28,29]. Both studies looked exclusively at vibration, rather than track structure issues, and found that using pads decreased ground vibration by 10–25 dB, possibly because of the suppression of end effects, but did not decrease vibration of the concrete support itself.

5. Noise and vibration

The second function of UTPs is to reduce vibration emissions from railway track. The two types of noise and vibration emissions from the railway track are airborne noise emissions and ground-borne vibration emissions [117] and UTPs have been used with the objective of controlling both.

5.1. Ground-borne vibration

Introducing UTPs has the effect of reducing peak ground-borne vibrations from passing trains. These results have been found by modeling [31,62,64,118,119], in the laboratory [44,119,120], and in the field [63,74,121–125]. Reductions in vibration emissions from using UTPs come primarily from reducing vibrations at frequencies above about 30 Hz, while there is typically little effect or a slight increase below 30 dB, though this varies from track to track and model to model [22,31,44,63,74,119–122,124]. Reductions in ground vibration can be as high as 10 dB or 30% at the initial resonant frequency of the track [44,74,119]. While UTPs are useful at reducing ground-borne vibrations at high speeds and high frequencies, their benefits are greatest for speeds below 250 kph (155 mph) [31] and frequencies below about 150 Hz [63,74,121]. Decreasing UTP stiffness will result in a greater reduction of maximum vibrations and will reduce the vibrations from track at lower frequencies [62–64]. For this reason, soft UTPs are recommended for vibration mitigation [8]. A softer UTP is more useful for vibration mitigation with stiff soils than soft soils [62]. A European study found that due to differences in train speed and truck axle construction, freight trains rarely produce peak vibrations greater than 25 Hz, so UTPs are not useful at mitigating vibrations from European freight trains [89]. In addition to decreasing the vibration emissions of track, UTPs reduce the resonant frequency of the track, with a study finding the resonant frequency of non-padded mainline track to be between 50 and 70 Hz and padded mainline track to be 15–30 Hz [123].

5.2. Airborne sound

Studies on the effects of UTPs on airborne sound are limited, with most researchers preferring to focus on ground-borne vibrations. Studies are divided on whether UTPs will increase or decrease audible airborne noise. When UTPs reduce long-pitch rail corrugation in curves, the reduction in rail corrugation also results in a reduction in emitted noise [8,92]. A model of a building adjacent to a Tokyo rail tunnel found that noise in the building increased by 10–15% with the introduction of UTPs, but the noise is outside audible range so there is actually a decrease in net audible frequency [64]. On the other hand, two publications conclude that installing UTPs will slightly increase airborne sound [126,127], possibly because the crosstie-ballast interface vibrates less but the rail itself vibrates more [127]. For intercity passenger rail in Great Britain, it is noted that ground-borne vibration affects areas up to 80 m (262 ft) from the track while airborne noise affects areas up to 300 m (984 ft) from the track [117]. The location of sensitive locations in relation to the railroad could therefore become a consideration as to whether UTPs are installed or not.

6. Life cycle analyses

While it is useful to know that UTPs have benefits and drawbacks in terms of track structure, track maintenance, and vibration mitigation, railroads are often interested in using UTPs to reduce operating and maintenance costs. To characterize and quantify potential savings, researchers have attempted to quantify the life-cycle costs (LCC) of installing UTPs. In the United Kingdom, for a single crosstie, concrete crossties with UTPs were most cost-effective for high-tonnage lines while non-padded timber crossties were most cost-effective for low-tonnage lines [10]. Life-cycle cost evaluations for UTPs have been made on three British Network Rail lines, the London-Portsmouth [127–130], the South West Main Line [117] and the West Coastway Line [48]. The studies, which are similar in nature but use different computational methods, consider purchasing and construction costs, maintenance and reliability issues, passenger ride comfort and noise and vibration emissions. The studies agree that all entities (Network Rail, the infrastructure manager, travelers, and the average non-user) will benefit from the installation of UTPs with only non-users living far enough away from the track to be affected by sound emissions but not vibration emissions seeing a net detriment. All of the studies project an overall net benefit from implementing UTPs as well as both a net social and a net fiscal benefit. A study by Ngamkhanong et al. [131] used the data and corridor from Guedelha et al. [132] to conduct a 30-year LCC analysis and found that installing UTPs during initial construction would result in a net savings of €110 million, or about 13% of the project. An analysis looking exclusively at the vibration effects of UTPs found that if the lifespan of the UTPs is sufficiently long – 25 years for a concrete crosstie lasting 50 years – they are an effective cost-reducing solution [133]. A LCC analysis focusing on extreme weather events from a cost-benefit perspective found that UTPs are negatively affected by extreme temperatures, but not by flash flooding situations [134].

As railroads look to become more sustainable, LCC analyses on UTPs have been conducted in terms of carbon and environmental costs. A British study found that non-padded softwood timber crossties incur the lowest carbon costs for low-tonnage lines and padded concrete crossties incur the lowest carbon costs for high-tonnage lines, though the environmental costs pale in comparison to non-environmental costs [10]. An Austrian study found that the annual environmental cost of a padded turnout is €495 without UTPs against €429 with UTPs, with manufacturing and maintenance contributing to the vast majority of the environmental costs for both cases, and global warming potential the most expensive environmental cost [99]. A study on the London-Portsmouth and Newcastle Edinburgh Network Rail lines found that introducing UTPs will result in a 2.82% reduction in carbon emissions on the London-Portsmouth line and a 0.16% reduction in carbon emissions on the Newcastle-Edinburgh line [9].

7. Conclusion and recommendations

Under tie pads have been extensively studied using models, laboratory and field testing and have been installed in many revenue service environments throughout the world. References to UTPs are also included in prevailing rail infrastructure design practices and recommendations across the globe. This paper provided a compilation and review of UTP research performed to-date. Based on this review the following conclusions can be drawn as to the use of UTPs in concrete crossties:

- The use of UTPs increases crosstie-ballast contact area and can result in a reduction in substructure stresses (e.g., crosstie-ballast pressure and particle contact forces), track vertical settlement, track stiffness, ground-borne vibrations (and lowering the track's resonant frequency), and crosstie bending and strain but increase crosstie acceleration and displacement
- UTPs also result in an increase in rail bending, acceleration, and displacement. This is a critical consideration when selecting materials, and why current recommendations suggest that soft UTPs should be limited to specific cases where noise and vibration reduction is required.
- All aforementioned effects are accentuated with decreases in UTP stiffness
- Current published research results are either inconclusive or contradictory as to the effects of UTPs on:
  - o Ballast acceleration
  - o Deterioration of subballast and subgrade
  - o Airborne noise emissions

A summary of the various material types and parameters as well as the effects UTPs have on the track system is presented in the flowchart in Fig. 5.

Improvements in track structure performance found in locations where UTPs are used likely result from a combination of a reduction in ballast forces, crosstie-ballast contact stresses and crosstie bending, while excessive rail bending, track structure displacement, or excessively soft subballast or subgrade are the most likely culprits when a UTP installation does not improve or worsens track structure performance.

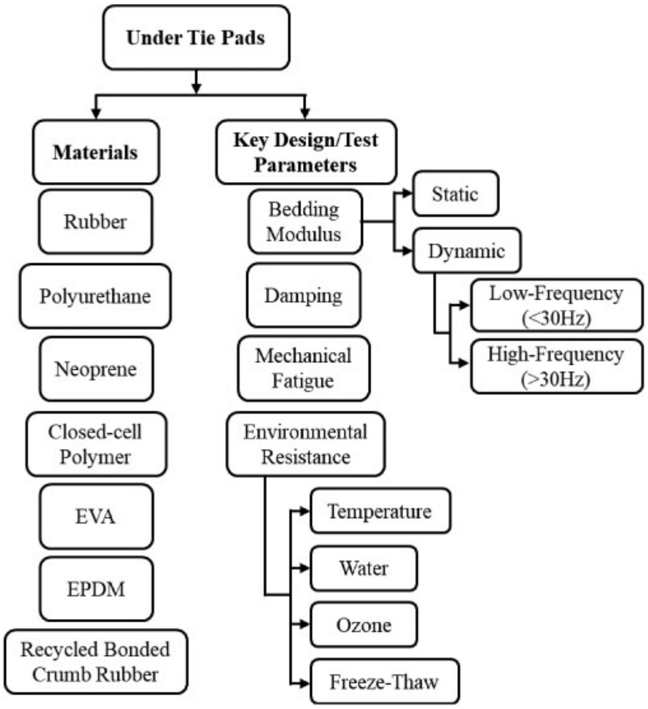

Fig. 5. Summary of UTP materials and key design/test parameters.

Under tie pads may also be used in transition zones to smooth out abrupt transitions in track stiffness such as at bridge abutments, tunnels, turnouts and crossing diamonds. Component characteristics must be carefully selected at these locations. The use of multiple UTP stiffnesses across the transition is typically recommended though constructability should be considered to determine the optimal solution.

Despite the findings summarized in this paper, there is still an incomplete understanding of the benefits and drawbacks resulting from UTP use. Areas that could benefit from future expanded research include:

- Improved understanding and documentation of the effective lifespan of UTPs in-track
- The effect of different materials to UTP properties and performance
- The influence of different ballast, track component types, subgrade characteristics, train speed, and track loading conditions to UTP performance
- Studies that look at the effect of UTPs on the track structure as a system (including train-track interaction) rather than a component-by-component or single-component analysis
- The effect of UTPs in railways with lower operating speeds
- The combined use of UTPs with other elastic components such as under ballast mats or rail pads

Most studies conclude that UTPs will result in improved crosstie performance despite increased crosstie acceleration and displacement. This demonstrates that the reduction in crosstie bending plays a key role in the improvement of crosstie performance (and therefore track performance), and possibly also results in a reduction in the concentration in crosstie-ballast stresses. Specific investigation of these mechanisms is lacking in the literature available. Hence, the field will greatly benefit from studies focused on understanding the effects of UTP reduction in crosstie bending to the track structure performance as well as an investigation of the optimal UTP characteristics for the minimization of crosstie bending.

Because of the lack of knowledge about these complex interactions, there is no uniform standard for selecting a UTP based on the intended design conditions. Railroads currently select the most suitable UTP themselves in consultation with industry suppliers. Improvements to the industry's understanding of UTP behavior and performance should lead to the development of a standard or recommended practice. This should consider track design conditions – e.g., ballast type and substructure bearing capacity, track component types, train speed and loading conditions, and the maximum allowed noise and vibration emissions, if applicable – to recommend an UTP with specific characteristics (or recommend not using UTPs at all). This recommended practice could be advanced later to include specialty application areas like curves, transition zones, special trackwork, bridges, and tunnels.

While UTPs have gained popularity and in some cases become standard practice on railroads with significant rail traffic, opportunities for industry growth as well as challenge lie in expanding their use. For some applications, it may be acceptable to make only minor modifications to the initial UTP design, while in others a specialized UTP may be required to address a unique problem. An additional challenge to the industry is the cost of UTPs, especially if they are to be used in the freight or low volume domains where their cost as a percentage of track will be higher than most passenger railways. The industry has been responding to these changes by improving their rubbers and polymers, and if successful, using recycled rubber or even asphalt as a UTP could decrease costs enough to make them attractive to railroads operating on tighter margins.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arthur de O. Lima reports financial support was provided by BNSF Railway Co.

Data availability

No data was used for the research described in the article.

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