Resilient Railways Using Energy-absorbing Rubber Elements in Track Substructure

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ABSTRACT

Facing the high demand for faster and heavier freight trains in Australia, researchers and practitioners are endeavouring to develop more innovative and resilient ballasted tracks. In recent years, many studies have been conducted by the research team from the Transport Research Centre at the University of Technology Sydney (TRC-UTS) to examine the feasibility of incorporating recycled rubber into rail tracks. This paper introduces two innovative applications using recycled rubber products, such as (1) adding energy-absorbing rubber geogrid made from recycled conveyor belts at the ballast-capping interface, (2) using recycled tyre cells to reinforce the railway capping layer. Large-scale laboratory tests using track process simulation apparatus and field testing were conducted to examine the performance of rail tracks incorporating these innovative inclusions. The test results reveal that the incorporation of rubber geogrid and tyre cells could increase the lateral confinement while improving the energy absorbing capacity of the rail tracks and mitigate the ballast breakage and settlement and lateral movement significantly, hence increasing the track stability. The research outcomes will facilitate a better understanding of the performance of ballast tracks incorporating these resilient waste tyre materials while promoting more economical and environmentally sustainable tracks for greater passenger comfort and increased safety.

INTRODUCTION

Railways are crucial for global passenger and freight transportation. Increasing population, urban expansion, road congestion, and energy demands push the railway industry to develop heavier and faster routes for efficient and cost-effective transport (Selig and Waters 1994). However, traditional ballasted tracks need improvements to handle the stress of increased rail traffic. For over two decades, polymer geogrids have reinforced ballasted tracks, reduced deformation and enhanced track stability (Bathurst and Raymond 1987, Brown et al. 2007, Indraratna et al. 2017, Luo et al. 2023). However, they can rupture under high stress, losing effectiveness and increasing ballast breakage by rigidly confining particles (Hatami et al. 2013, Indraratna et al. 2019). Resilient rubber under ballast mats (UBM) were tested and the results showed that it can reduce ballast degradation, and vibration of rail track through damping but does not reinforce ballast or limit lateral displacement (Costa et al. 2012).

Previous studies have shown that adding artificial inclusions to the track substructure is one possible strategy to reduce ballast breakage and enhance track stability (Sol-Sánchez et al. 2020, Qiang et al. 2023, Ngo et al. 2024). By repurposing them into a more technologically advanced track construction approach, the use of wasted rubber tyres in the track substructure presents an environmentally beneficial alternative to landfill disposal. Over 1.4 billion tyres are sold annually worldwide, which has led to a significant increase in the production of rubber waste (Sienkiewicz et al. 2017). In Australia, between 2009 and 2010, about 50 million equivalent passenger units (EPU) of tyres were disposed of (Mountjoy 2012). Improper waste tyre disposal can lead to severe outcomes, such as transmitting diseases like dengue and malaria as rainwater accumulates in tyre stockpiles, and significant air pollution resulting from tyre incineration (Nuzaimah et al. 2018).

A new solution uses the recycled rubber energy absorbing grid (REAG), which integrates the benefits of conventional polymer geogrids and resilient rubber elements. These rubber grids are produced from discarded rubber conveyor belts from the mining industry (Figure 1a), which are a primary contributor of rubber waste (Nuzaimah et al. 2018). The rubber grid reinforces ballast particles similar to geogrids while also providing damping properties to the rail track (Qi et al. 2024). This novel approach enhances track durability, dissipates energy from repeated train loads, reduces ballast deformation and degradation, and ensures adequate drainage, thereby overcoming the shortcomings of conventional geogrids and under-ballast mats (Siddiqui et al. 2023).

In recent years, there has been pioneering research on the adoption of infilled tyre cells in railway tracks replacing a traditional capping layer, namely, Tyre Cell Track Foundation (TCTF). This substitution aims to enhance the confinement of the track substructure by leveraging the superior damping characteristics and cushioning properties of rubber materials (Indraratna et al. 2018, Indraratna et al. 2022). Although the TCTF method does not necessitate intense mechanical treatment compared to other waste rubber applications, implementing it in rail tracks mandates a thorough geotechnical engineering evaluation of current and proposed parameters to ensure that the design and construction align with the intended purpose. It is worth noting that the TCTF technology is still in its primary research stage and warrants additional research efforts to assess its performance under varying loading levels comprehensively.

ENERGY-ABSORBING RECYCLED RUBBER GEOGRID

Process Simulation Prismoidal Testing Apparatus

The large-scale process simulation prismoidal triaxial apparatus (PSPTA) designed and built at the University of Technology Sydney was used in this study to conduct the cyclic-loading tests. The study utilized fresh ballast, rubber grids (Fig. 1a), capping material, and subgrade as test materials. The fresh ballast, consisting of latite basalt, was sourced from Albion Park Quarry in NSW. The aggregates were thoroughly washed, dried, sieved, and mixed, following the guidelines set by Australian standards (AS-2758.7 2015). High-precision waterjet cutting was employed to create apertures in the rubber conveyor belt panels. The material and engineering properties of the rubber grid can be found in Siddiqui et al. (2023). The rubber grid thickness was between 10 and 11 mm, and the apertures measured 51 mm (Fig. 1b).

The PSPTA replicates the influence zone of a standard heavy-haul track in Australia, incorporating a triaxial chamber that exerts three orthogonal principal stresses and four adjustable vertical walls to simulate ballast movement. The PSPTA's dimensions (600 × 800 mm) represent a unit cell of a straight track section, with a standard concrete sleeper (220 mm width, 200 mm height, 780 mm length) used in the chamber (Fig. 1c). Plane strain conditions were achieved by restricting strains in the longitudinal direction (ε_2=0). The walls in the transverse direction (ε_3) maintained a confining pressure of 15 kPa, reflecting the typical 10-30 kPa range in Australian tracks. Cyclic stress and frequency were controlled by a servo-hydraulic actuator with a 100 kN load cell. A control system monitored and recorded wall movements and applied loads.

A subgrade layer, 350 mm thick, was compacted at the bottom of the testing box to a field density of 1900 kg/m³. A 150 mm thick capping layer was then compacted to 2100 kg/m³, with a woven fabric laid over it to prevent ballast penetration. For tests including REAG, a REAG layer was placed on top of the capping layer. Then the ballast layer was placed in three 100 mm thick layers and compacted to 1560 kg/m³ using a vibratory compactor. A rail-sleeper assembly was centered on the ballast layer, with the surrounding spaces filled with a 150 mm thick layer of crib ballast. Following the tests, the ballast located directly beneath the sleeper was collected for breakage analysis.

Test procedure

The laboratory instrumentations included load cells, linear variable differential transformers (LVDTs), pressure plates and settlement pegs. Load cells on the primary and horizontal actuators were used to monitor vertical and lateral forces. Lateral deformation was tracked with LVDTs on the vertical walls, while the vertical deformation of the ballast was recorded using settlement pegs positioned at the interfaces between the sleeper and ballast, as well as the ballast and capping layers. Preliminary measurements were taken before initiating the cyclic loading tests, with continuous data collected at intervals (e.g., every 20, 50, 100, 500, 1,000, 5,000, 10,000, 50,000, 100,000, …. 250,000 cycles) by data loggers and a host computer. Settlement readings were taken manually using the settlement pegs.

The PSPTA loading program simulated the usual cyclic loading encountered by rail track foundations. A hydraulic actuator exerted force through a 100 mm diameter steel ram, which transferred the load to the ballast through the rail-concrete sleeper setup. The cyclic loading amplitude (A) and maximum cyclic stress ($\sigma_{1cyc,max}$) were based on a simulated 25-tonne axle load, typical for coal freight trains (Indraratna et al. 2010). The maximum stress value (236 kPa for a 25-tonne axle load) was calculated using the AREA (American Railway Engineering) method (Li and Selig 1998). A loading frequency of 15 Hz was utilized to simulate a train traveling at a speed of 110 km/h.

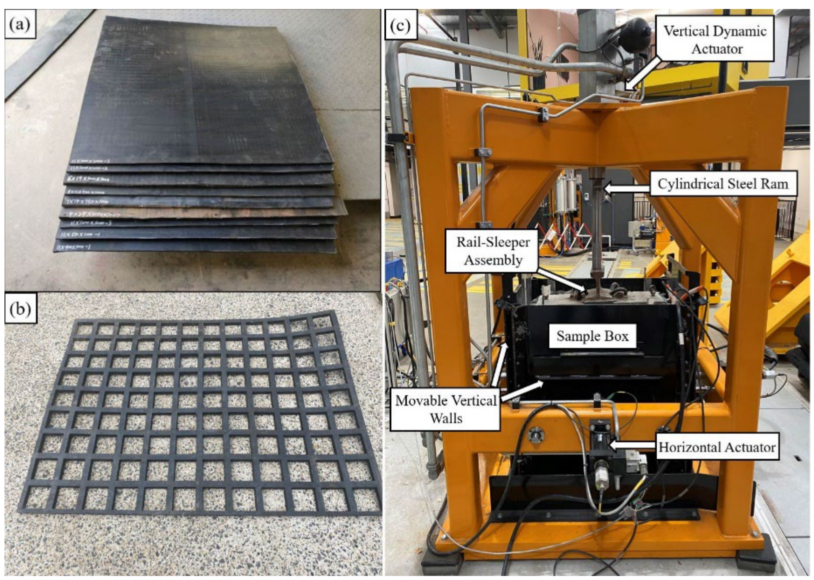


Figure 1: (a) Discarded rubber conveyor belts; (b) Tested rubber grid; and (c) PSPTA

Results and discussion

Lateral and vertical deformation

Figure 2 presents the lateral and vertical deformations of ballast (with and without REAG) over numerous load cycles (N) measured at a loading frequency of 15 Hz under a 25-tonne axle load.

Figure 2a indicates that REAG reduces lateral displacement by approximately 50%, likely due to particle interlocking within REAG apertures. Lateral displacement stabilizes after 10,000 cycles, indicating consistent interlocking with repeated loading. Compared to under-ballast mats (Navaratnarajah and Indraratna 2017), REAG is more effective in minimizing lateral displacement due to its three-dimensional apertures. Figure 2b shows a rapid increase in vertical settlement in the first 10,000 cycles for both unreinforced and REAG-reinforced ballast, followed by a reduced settlement rate. REAG reduces vertical settlement by approximately 60% under a 25-tonne axle load and is more effective than under-ballast mats in reducing vertical settlement (Navaratnarajah and Indraratna 2017).

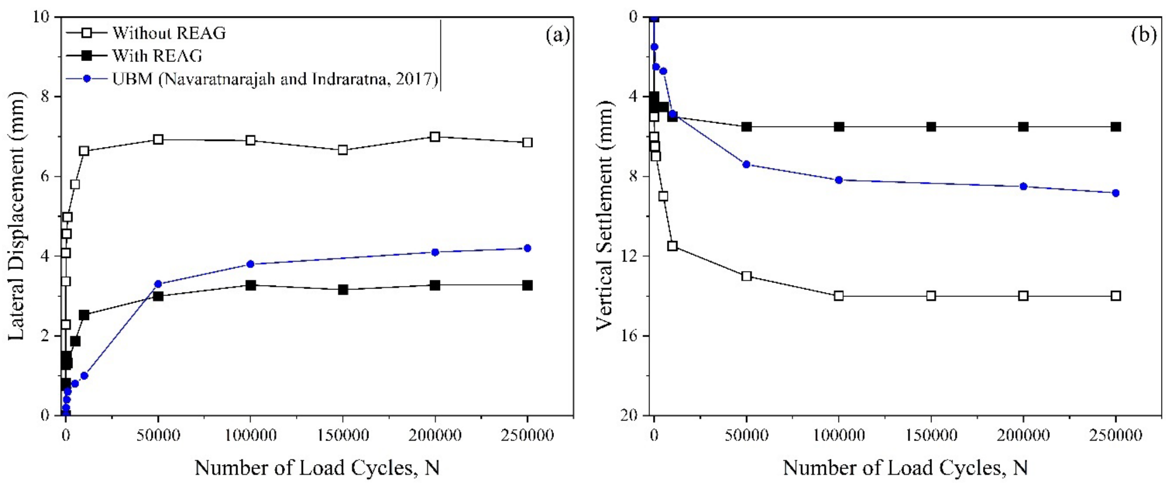


Figure 2: Measured test results: (a) Lateral displacement; and (b) Vertical settlement

Ballast breakage

This study used the Ballast Breakage Index (BBI) developed by Indraratna et al. (2005) for railway ballast. This method analyzes the particle size distribution (PSD) before and after testing against a predetermined maximum breakage limit, as shown in Figure 3. After each test, ballast aggregates were recovered and analyzed for PSD to determine the BBI. Results show a significant reduction in ballast breakage with REAG at the ballast-capping interface. The BBI in the top layer decreased by approximately 20%, and breakage in the middle and bottom layers was reduced by approximately 44% and 48%, respectively. This improvement is due to REAG's dual function of confining particles and providing damping, reducing the stresses transferred to the ballast.

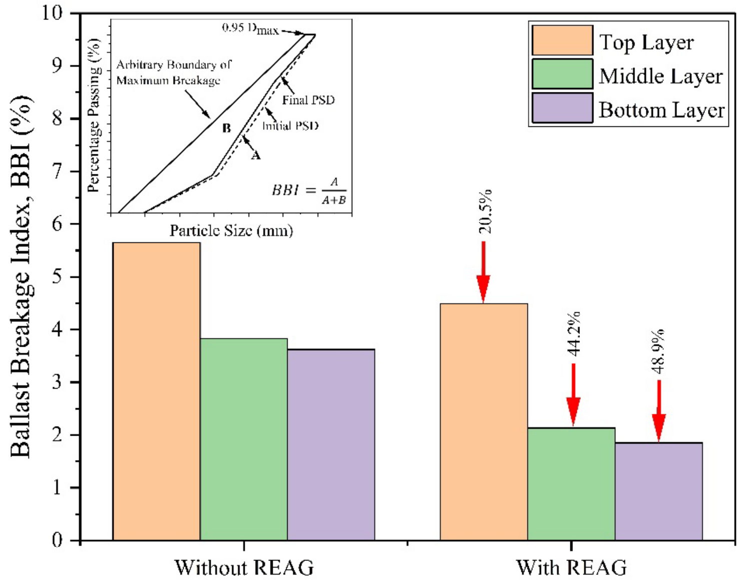


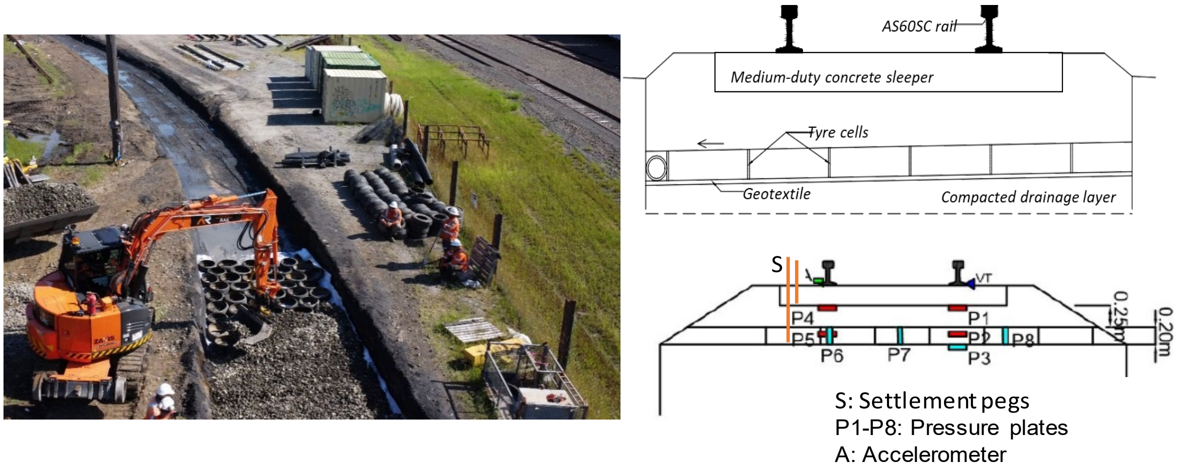
Figure 3: Measured BBI with and without REAG

TRACK USING RECYCLED TYRE CELL IN CAPPING LAYER

In order to persuade railway engineers of the efficacy of utilizing waste rubber tyres on railway tracks, it is imperative to acquire more dependable testing outcomes from practical field experiments to complement test results measured in laboratory conditions e.g., challenges in replicating train loads and inaccuracies stemming from boundary limitations (Indraratna et al. 2018). The field data accounts for the influence of subgrade soil depth, whereas the cubic chamber features a fixed boundary 1m beneath the ballast surface, thus impacting stress propagation due to the nearby non-displacement boundary.

Track construction and loading program

An instrumented track was constructed at a maintenance yard in Chullora, New South Wales, Australia (Fig. 4a), with the collaboration of industry stakeholders, including Transport for New South Wales (Sydney Trains), Bridgestone Corporation, and Ecoflex to implement the laboratory-proven concept of tyre unit cell (Indraratna et al. 2018) in real-life applications. This is the first actual on-the-field test adopting the tyre cell assemblies (20 m long) subjected to real train loading, capturing a maintenance schedule (i.e., rest period). In addition, the trial track includes a section without the inclusion of scrap tyres so that the performance of the TCTF track can be compared with the standard ballasted track (20 m long). This field testing promotes the concept of using the rubber tyre cell assembly (Tyre Cell Track Foundation, TCTF) as a capping layer, offering an engineered solution where scrap tyres, after removing one of its sidewalls, are filled with recycled spent ballast. A cross-section of the TCTF track and instrumentations are schematically shown in Fig. 4b. Given the slowed pace at the maintenance yard, a locomotive with a 22-tonne axle load and two fully laden ballast wagons were used to travel along the trial track at a relatively low speed of 15-20 km/h. More detailed information on the TCTF track can be found in Indraratna et al. (2024)



(a) **(b)**

Figure 4. (a) Track construction; (b) cross-section of track and instrumentations (*modified after Indraratna et al. 2024)*

Measured vertical stresses

Compared to the standard track section (Fig. 5a), an increase in vertical stress was noted at the sleeper-ballast and ballast-capping interfaces in the TCTF track (Fig. 5b). In contrast, slightly reduced vertical stresses were found on the subgrade layer in the TCTF track, highlighting the beneficial effect of TCTF on improving track stability. For example, at N=6000 cycles, the standard track showed a maximum stress level on the subgrade of about 56 kPa, whereas the maximum stresses recorded on the subgrade in the TCTF track were roughly 50 kPa indicating a reduction of roughly 10% in the vertical stresses transmitted to the soft subgrade layer.

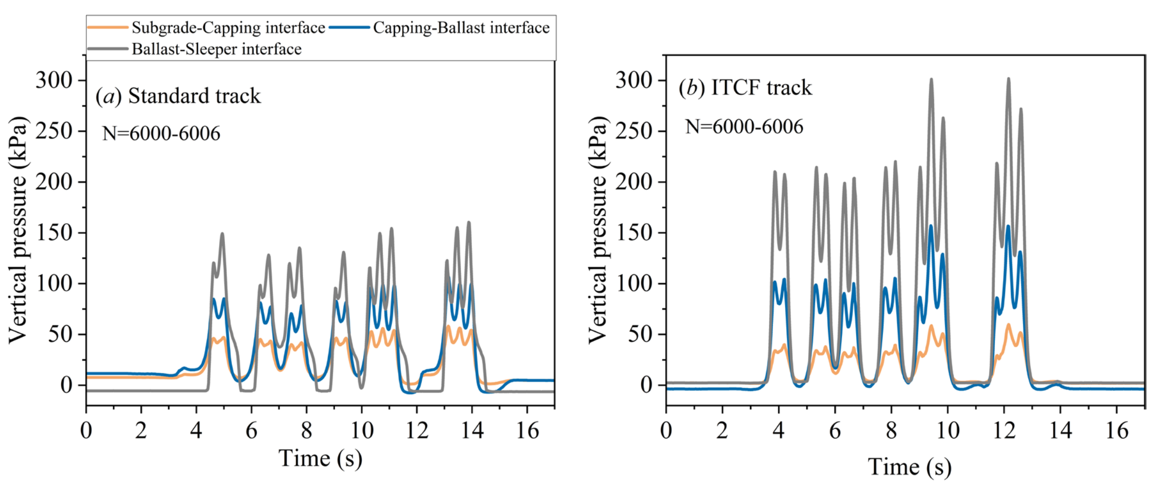


Figure 5. Measured stresses: (a) Standard track; (b) TCTF (*after Indraratna et al. 2024)*

Measured track settlement and acceleration

The comparison of settlements measured for the normal track and the TCTF is presented in Figure 6a. The total settlements in the TCTF section are found to have increased to 8.2 mm during the first N=2000 loading cycles, while they were only 6.1 mm in the standard section. This is because ballast particles displace and recompact during the initial stage of train loading. Furthermore, this can be the result of additional granular infill compaction in the TCTF during the first loading track cycles. At the subsequent cycles of loading, the settlements tend to stabilize for both track sections. Although the TCTF track continues to see further settlements, the rate of settlements is lower than it was at the beginning of the loading stage. At the loading cycle N=6000, the conventional track exhibited a settlement of about 8.2 mm, while the TCTF track's total settlement of around 12.7 mm showed a 35% increase in overall track settlement. The higher settlement of TCTF track is probably due to the inapproporiate compaction of the infilled materials before the test, which generated additional densification during the test. This suggests that a more efficient compaction technique needs to be developed to compact the materials within the tyre cells.

Accelerometers were mounted on the rail of the relevant track sections (Fig. 4b) to measure the vibrations caused by passing trains. The accelerations observed in the TCTF section at the loading (N=6000-6006 cycles) are compared to the standard section, as shown in Figure 6b. It is seen that TCTF track exhibited a higher acceleration (0.026 g) than the standard track (0.014 g). This increased vibration in the TCTF is consistent with the higher settlement observed during the loading phase as discussed earlier.

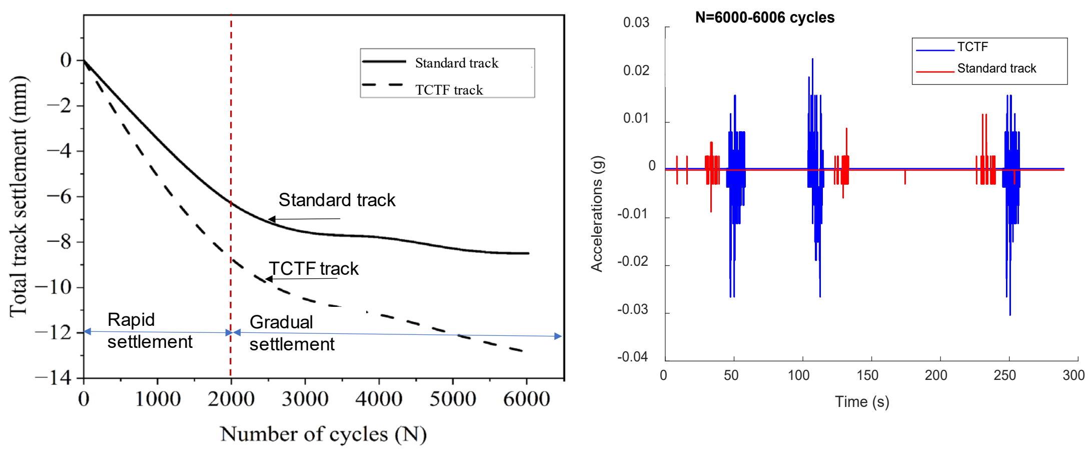


Figure 6. (a) measured track settlement; and (b) measured acceleration (*modified after Indraratna et al. 2024)*

CONCLUSIONS

This paper presented laboratory testing and field trial results on adopting two innovative and sustainable applications using rubber grids and scrap rubber tyres in railway tracks. Based on measured data, the following key conclusions can be drawn:

- The inclusion of REAG significantly reduced both lateral and vertical deformation of ballast under cyclic loading, with a reduction of approximately 50% in lateral displacement and 60% in vertical settlement. The use of REAG also markedly decreased ballast breakage, as evidenced by the BBI reduction of approximately 20% in the top layer and by over 45% in the middle and bottom layers. In practice, this significant reduction in ballast breakage attributed to rubber grids implies the benefits of cost savings for the railway industry and reducing the frequency of track maintenance.
- The field measurement results revealed that although the vertical stresses at the sleeper-ballast interface of the TCTF track section increased, the tyre cell assembly would lessen the amount of vertical stress transferred to the subgrade layer.
- Compared to the conventional track, the TCTF track's total settlement is about 12.7 mm, representing a 35% increase in overall track settlement. Although this may not match the intuitive behaviour that was initially anticipated, a significant decrease in the vertical stress at the subgrade-capping interface would contribute to improved track stability.

The results obtained from this study are expected to offer a scientific advancement within the field of railway engineering that is more robust, environmentally friendly, and economically viable.

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