**Sustainable Smart Transport Infrastructure: Vibration Challenges and Mitigation Techniques**

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**Abstract:** Smart transport infrastructure, an integral component in advancing sustainable transportation, is vital for future economic and environmental development. Due to the high incidence of ground traffic induced by road vehicles and rail transit, vibration remains a critical issue for smart transport infrastructures. Vibration sources arise from irregularities in both roadways and wheels, and mechanical excitations from engines and suspensions also contribute. Increased axle loads and traffic volumes exacerbate the problem. Induced vibrations propagate through the track, subgrade, and surrounding soil, causing infrastructure damage and potentially affecting human health. Persistence of vibration problems in smart transport infrastructure has led to the deterioration of structural integrity and the efficiency of transportation networks.

**Keywords:** Smart infrastructure, Smart transport, Ground vibration, vibration isolation, Mitigation techniques.

**INTRODUCTION**

A smart transport infrastructure provides connectivity among people, vehicles, and infrastructure through the integration of sensing, communication, and data-based decision algorithms [1]. Although recent research has focused on information technology, the smart infrastructure should be designed with sustainability in mind because it is related to the environmental impact through the entire lifetime and the life cycle cost ranging from construction to maintenance. In particular, the smart transport infrastructure is an essential sector because it promotes the transit of people and goods and therefore is highly related to economics [2].

Vibration arises from a moving vehicle and the lifestyle of people on the infrastructure, such as mechanical equipment, a human’s foot step, and musical instruments. The vehicle-induced vibration significantly depends on the type, form, weight, speed, and suspension system of the vehicle as well as the track geometry error, ground properties, and ground-structure interaction effect. It is associated with a structure’s design because degradation of the performance of the structure is encouraged by the fatigue and loosening of bolts connecting decks and girders. Furthermore, it affects a human’s health and behavior through sensory and psychological effects. Therefore, the contribution of vibration to the performance of the smart transport infrastructure should be minimized to enhance sustainability.

**METHODS**

Smart transport infrastructure integrates modern sensing and communication technologies to enable the efficient movement of people and goods, fostering sustainable energy generation and consumption. Realizing such systems hinges on the availability of new infrastructure materials and construction techniques that ensure long-term resource and energy efficiency. Electric railway systems exemplify the move toward sustainability, yet they must address challenges related to natural resources, energy availability, land use, and waste management. There is a significant amount of vibration as an environmental disturbance in these systems, which serves as antecedent for structural damage and deterioration.

Railway vibrations occur due to a number of reasons, like the forge h um 1 n d e against wheel-rail interaction or jerk on account of wheel hitting rails joints. They are transmitted through the earth and transferred to adjacent structures by ground-borne noise and vibrations. These vibrations can be detrimental to structural integrity and human comfort and also cause corrosion that deteriorates the lifespan of tracks, increases maintenance expenditure [1]. Accordingly, technical, economical, and legislative factors have delivered road blocks against the potential control of environmental railway vibrations. Minimizing shipment vibration is thus crucial.

Smart transport infrastructure has attracted worldwide attention in recent decades. Sustainability challenges are attracting more interests. Sustainability is one of the most concerned challenges in smart transport infrastructure. This is because a sustainable system can save more money and cause fewer environmental problems. Vibration is an important challenge that can be mitigated by sustainable techniques. It is one of the most important technical requirements for the successful implementation and operation of smart transport infrastructure. Thus, a comprehensive and timely understanding of vibration and its mitigation in smart transport infrastructure is required.

Vibration exists widely in the transport systems, originating from the track, the support and the substructure. A high vibration level may cause a malfunction in the infrastructure, an incipient damage in structures, a safety risk or a deterioration in human health. Many scholars have investigated the vibration issues in the transport systems based on the mechanical behaviour of the infrastructure and suggested valuable solutions for vibration mitigation [3]. Numerous techniques have been adopted for the infrastructure design, material selections and vibration control. A sustainable design of infrastructure and an appropriate use of materials can improve the services of infrastructure, extend the longevity of buildings and reduce the impact on environment. Active and passive vibration controls can be integrated into a suitable infrastructure to minimise the vibration harms. The vibration levels of infrastructure can be monitored by single or multiple sensors in an Internet-of-Things (IoT) system. The effective signal processing of output vibration signals is helpful for accurate identification of the vibration sources and for prompt reduction in vibration. The capabilities of data analytics and artificial intelligence enable the vibration monitoring of smart infrastructure with a higher sensing accuracy and a better adaptability.

Transportation is vital for economic and social development worldwide. Intelligent transportation systems (ITS) control traffic flow better, leading to efficient use of resources and enhanced sustainability, which saves energy and reduces emissions of greenhouse gases and local pollutants [4]. Sustainable transport infrastructure, incorporating ITS and smart infrastructure, quantifies and minimizes social, economic, institutional, and environmental costs, determining infrastructure sustainable performance. Vibration, produced by vehicle and rail-road interactions, rigid pavements, track, and soil–structure interactions, affects infrastructure durability and causes health and comfort problems for those nearby as well.

Smart transport infrastructure integrates sensing, control, and communication technologies to achieve intelligent operation and management in the transportation domain [5]. Sustainability is a key objective throughout the whole life cycle of infrastructure systems since transportation systems can consume large amounts of resources and generate significant pollution. Vibration is a common problem in contemporary transportation systems, arising from various sources such as rolling stock, operational conditions, and maintenance. Pavements and transportation structures may be long-term compromised by excessive vibration. It results in increased maintenance costs, waste and adds environmental impact. Additionally, human health and the quality of service are degraded due to machine excessive vibration. For this reason, vibration has to be taken into account in the design and operation of transport infrastructure systems. With the rapid development of smart transport infrastructure, the importance of providing energy-saving, environmentally friendly, resource-saving, and liveable transport infrastructure has become increasingly apparent [6]. The management of urban traffic skeleton is therefore critical to future development. Among various transport-related challenges, vibration remains a critical issue. This section defines and examines the sources of vibration within smart transport systems, in order to understand its impact and the need for effective mitigation strategies.

Vibration resulting from the movement of vehicles through infrastructure, influenced by operational components or the surroundings of the infrastructure, is a disturbance associated with vibrations of the source that propagate to other locations. Common causes of such vibrations include aerodynamic effects, ground-borne vibrations, and mechanical, aerodynamic, and hydrodynamic forces around infrastructures like bridges, high-speed railway lines, and offshore platforms. Vibration can cause the transport infrastructure to bridge between freedom–emergency, thus leading to mechanical damage, noise, and discomfort to residents and passengers. Given the widespread use of transport infrastructure in daily life, managing vibration to achieve smart, liveable, and sustainable urban development is a significant challenge.

Vibration, generated under various operational and environmental conditions of vehicles during driving or transportation, has a wide presence in transport infrastructure. Influenced by operational conditions, infrastructure types, vehicle characteristics, mechanisms, and vehicle systems, vibration poses challenges to transport infrastructure [7]. It can reduce transportation safety, increase maintenance and repair costs, cause material degradation and damage to infrastructure components, induce noise in transport systems, and create a harsh and uncomfortable indoor environment for nearby residents. Furthermore, the effects extend to human health as well as ecological and environmental impacts. In response to these challenges, there has been much research on vibration mitigation design and control methods that can be sustainable solutions for smart transport infrastructure. They contribute to various sustainability criteria, such as economic, environmental and social dimensions, by providing a safer and more robustly constructed travel environment that is easier to maintain & operate.

Knowledge human health and comfort impacts due to vibration is one of the key areas for sustainable smart transport infrastructure. In transport, vibrations affect human well-being in terms of physical, physiological and psychological factors. Each of the health effects people attribute to exposure to vibration are categorized by the type and level of vibration they believe had caused them harm. These can include headaches, stomach upset, changes in mood or behavior and/or heart or lung problems. Discomfort itself is reduced under vibration condition in postural, activity, performance, perception, spatial and sleep from a human behavior perspective. It has the added disadvantage of increasing irritation, considered to be a necessary precursor of health effects [2].

The health concerns related to environment because of noise and ground vibrations in the urban transit system have put the mitigation of vibration at the top priority. A variety of methodologies based on life cycle analysis have been implemented for the mitigation of railway rolling noise and ground-borne vibration. Additionally, methods to reduce vibration from subways and measurement standards targeting environmental vibration in urban areas have been proposed [8].

**RESULTS**

The successful management and amelioration of vibration are crucial for the safety, security and sustainability of smart infrastructure in transportation. The barriers are several-fold and involve technical, economic, and regulatory components. Advance technical challenges lay in understanding complicated sources of vibration, predicting the pathways propagation and devising appropriate mitigation methods that can work with smart materials and integrated sensor systems[9]. Economic constraints also relate to the high prices of new materials and technologies, and disturbances of buildings in large-scale retrofits or replacements. There are regulatory issues in the form of standards and guidelines for that covering vibrational release, transmission and control as manifested by smart transport (system) technology.

Much regarding these processes can be ascribed to mitigation techniques. Innovative design strategies introduce the use of poro-elastic materials, densifying approaches, and lattice formwork infill systems aimed at improving both sustainability and resilience in conjunction with damping unwanted strong oscillations. The choice of mix is also crucial; foam concrete, geopolymer concrete and rubberized concrete could help both in vibration reduction and the aim toward an environmental friendly technology. The toolbox may also be enhanced with active control approach and passive damping schemes to provide on-line vibration monitoring and adaptive attenuation using feedback or isolated attenuation mechanisms that do not require external power supply. Such methods are suitable for the responsiveness needs of the smart system

Smart technologies and monitoring systems constitute a fundamental component of contemporary vibration control paradigms. Advancements in sensor technologies—including piezoelectric devices, fiber optic sensors, and MEMS accelerometers—facilitate comprehensive vibration data acquisition essential for system assessment and condition monitoring. Data analytics, big data integration, and artificial intelligence augment these capabilities, enabling the development of intelligent algorithms that can predict, diagnose, and optimise vibration management in real time. It is this kind of tech advancement that paves the way for smarter, more responsive transport infrastructure which can respond to sustainability demands. Refer to ‘Vibration Mitigation Techniques.’

Vibration control in smart transport infrastructure has both technical and economic challenges which make the actualization of vibration-free or/and vibration-tough systems challenging. From the technical point of view it has proved to be extremely difficult to create infrastructure elements, which are able both to realize and dissipate induced stresses and variable loads so quickly. The high cost of performing thorough analysis on vibration and its countermeasure inhibit deep thoughts of vibration for the design in the early design phase.

Tailored, creative design solutions are a main path to potential improvement. Such large-diameter, hollow, cross-shaped vertical vibration isolation piles with multiple small-diameter tunnels could help to improve the mechanical and anti-gaseous vibration properties which accords with sustainable environment protection strategies [10]. The requirements of high initial stiffness and low vertical stiffness, which are the most important to vibration isolation can be met by appropriate design of piles.

An alternative approach is offered by the selection of materials. In this way, production of prefabricated vibration-isolation parts suitable in terms of both performance and service life can be achieved with the aid of engineering materials (concrete) which have superior mechanical properties and damping coefficients. The use of prefabricated isolator systems highlights benefits in construction efficiency, cost savings and potential widespread acceptance. Ground improvement techniques using microbial-induced calcium carbonate precipitation (MICP) also offer hope for railway and metro systems.

Active vibration control methods are readily applicable to incorporation in smart structures. Adopting sustainable urban development to integrate a smart, active vibration-isolation system into an overcrowded city rail monitoring system. Effective control is particularly accessible in high-speed train contexts, where high-speed communication technologies enable real-time monitoring of train status and environmental variables through dedicated wireless sensor networks (WLANs). Studies indicate that urban transport infrastructure can be designed to achieve a sustainable system through the implementation of active control strategies and advanced monitoring systems.

Passive control complements these approaches. Configurations consisting of counterslab, float, high elastic layers, and associated elements can substantially reduce vibration levels, sometimes by a factor of two for slab vibrations and more than three for floating slab vibrations. Strategically choosing resilient materials and optimising slab thickness further enhances sustainable solutions.

The recent advancement of vibration-monitoring technologies nurtures the generation of multi-source data, forming a foundation for more sophisticated smart transport infrastructures. Implementations leverage various types of sensors — including vibration, audio, visual, radar, lidar, and multi-camera systems — each endowed with distinct characteristics. It is imperative to develop so-called intelligent vibration monitoring systems capable of analysing combined data streams and delivering actionable intelligence that supports maintenance and operational decisions. Numerous studies explore data processing techniques, transmission schemes, and wireless sensor network layouts not only for vibration mitigation but also for noise and vibration analysis in large infrastructures. The incorporation of data-driven artificial intelligence technologies into vibration monitoring frameworks holds considerable promise for the realisation of true smart transport infrastructure.

Smart transport infrastructure, a key integrated component of smart cities, can mitigate the negative environmental attributes of current transport systems and support sustainable development. Sustainability is a key challenge for modern transport infrastructure. Control of vibration has been a long-lasting issue addressed by various research fields, including mechanics, electronics, and urban traffic. Rail transport can induce environmental vibrations and noise in adjacent properties, yet effective vibration management remains a challenge. Effective vibration-specifi c designs and techniques are therefore essential for smart transport infrastructure to meet the requirements of sustainability. Vibration refers to mechanical oscillations about a reference point. Railway transport can induce environmental vibration and noise in neighbouring structures and cause issues in railway bridges and tracks. Rail-induced vibration is also a concern for human health. Control of vibration in transport infrastructure therefore constitutes an important challenge [11].

Smart transport infrastructure that incorporates cutting-edge information and communication technologies plays a leading role in the digital transformation of transport systems. By its nature it integrates the various types of energy and utilities such as railway, road, power and water that constitute the urban infrastructure network. Ensuring sustainable, liveable and resilient smart cities requires sustainable urban infrastructure that is designed and implemented in a way that minimises the degradation of social, environmental and economic systems in the long term. In the area of transport, it is essential that the systems provide efficient mobility, reduce emissions and consumption of resources during operations, and consider the impact of noise and vibration on human health. Implementing sustainable transport infrastructure requires a move away from traditional materials and methods, and the adoption of alternative designs and low-cost durable materials.

A major challenge for researchers is to simultaneously address many different fields and disciplines encompassing design, construction and smart operation. This paper focuses on solving the vibration problem and associated noise generated by movements of vehicles. Vibration and noise have long been identified as critical issues in urban transport and are considered key impediments to the development of smart cities. It is generally accepted that the increased number of vehicles and interconnection of transport modes found in smart infrastructure will make the vibration problem worse. Developing legacy infrastructure into a smarter network that is more sustainable, but retains low cost, in-service accessibility and low impact on users and energy demands is a major social and technical undertaking [11].

The growing concern over vibration has promoted the establishment of standards aiming to minimize negative impacts related to human health, comfort and safety [12-14]. However, standards may also put limits on the traffic and the exertion of control actions, which has motivated research to develop alternatives capable of increasing the transport capacity while keeping the vibration below the required limits.

Vibration mitigation techniques serve to address excessive transport vibration, the primary source of nuisance for both passersby and passengers [1]. Rail transit vibrations can propagate through the track, surrounding soil, and nearby structures, generating significant noise. The extent of rail vibrations depends on track type, tread surface condition, train speed, axle load, and other factors. Active, semi-active, and passive vibration control methods provide well-established strategies for mitigating excessive vibration in assisted living environments and similar settings [3].

The combination of innovative design and appropriate material selection has the potential to support sustainable transport infrastructure by enhancing durability and reducing maintenance requirements, thereby addressing recurring issues related to traditional construction approaches. Active approaches involve the injection of modified external energy to counteract vibration effects, while passive solutions incorporate additional components that absorb vibrational energy or modify mechanical parameters without external power input. The widespread deployment of sensors and advancements in data analytics and artificial intelligence facilitate the evolution toward smarter infrastructure, which is essential for maintaining operational continuity.

Design innovations constitute a principal method for strength­ening sustainable efforts in vibration mitigation. Implementations often involve isolating elements within or adjacent to an infrastructure component. In decks, numerous bridge types incorporate an open-joint approach that uses a gap not only to reduce the transmitting area when traffic traverses a joint but also to enable more isolated deck sections. Supports or columns may have isolation bearings, and parapets can contain high-damping rubber devices to reduce the fatigue effects from vibrations. Other approaches include mass-tuning of certain components and design geometric efficiencies to limit the generation of traffic-load-induced vibration. Material choice can also have a profound effect on vibrations, especially in cases that are not particularly dynamic or high amplitude. Although the design stage can be a relatively straightforward means of implementing sustainability best practices, modifications or retrofits are often imme­diate and thus crucial [13].

A material should be chosen and its role in sustainable design methods which are for reducing the vibration of smart transport infrastructure. Engineering solutions to reduce the vibration typically require heavy materials that are not always in line with the need of light structures [4]. In railway systems, different materials, such as ballast mats, rubber granulates and tyre derived aggregates can influence vibration transmission to the environment and assist in its reduction [5]. The chosen materials are expected to not only damp the radiated vibration but also enable green techniques. Therefore, more efforts are drawn to sustainable materials (such as rubber crumb and rubber granulate) and novel gradient designs (without dense particalts).

Active vibration control systems now include steady-state controller designs that suppress response from harmonically excited lightly damped structures, as well as transient-state controllers such as bang-bang-type and sliding mode controllers [6]. Since many civil infrastructure components are exposed to transient and/or impulsive vibro-acoustic environments, the development of time-domain-based algorithms for active vibration damping is critical. A recurrent neural network-based inverse-modeling scheme demonstrates promising performance for this application.

Passive vibration isolation techniques rely on appropriate materials and simple mechanical systems, including steel springs, viscoelastic materials, and rubber mounts, to reduce vibration transmission without external power [7]. These methods operate primarily at a fundamental frequency and therefore have limited effectiveness across broad frequency ranges, but their simplicity and reliability make them suitable for some smart transport infrastructures.

Smart transport infrastructure connects roads, vehicles, traffic management centres, and communication devices, geographically dispersing monitoring and assessment activities. Widely applicable to roads, bridges, tunnels, railways, and other transportation facilities, it integrates sustainability at its core [8]. The mass movement of passengers and freight significantly contributes to greenhouse-gas emissions, making the development of sustainable smart transport infrastructure crucial to reducing carbon emissions and fostering a resource-efficient, environmentally responsible economy.

Vehicular and train movements generate vibration waves that propagate through the infrastructure, soil, and adjacent structures. Additionally, vibration arises from train wheels interacting with rail irregularities or damage [9]. Excessive vibration leads to distress, deformation, or serious damage in infrastructure components and subsurface soil, raises human discomfort and health risks, causes noise emissions, and impairs the function of sensitive facilities near transport routes. Effective vibration-management strategies are therefore critical for remaining life, serviceability, and the sustainability of transport infrastructure.

Technical issues are limiting the use of vibration control in Transportation. The economics of them, and uncertainty over how effective they might be, make people even more reluctant to invest in any kind of mitigation. Social issues, like the control of vibrations near critical facilities, also make the problem complex. Control strategies often depend on design concepts such as base isolation, energy dissipation and structuralshape optimisation that can lead to modifications of the existed structure and rising constructionseparated the cost for a great amounts. Material- selection favors sustainability; the high-performance fiber-reinforced concrete has low environmental impact and has already been used in road infrastructure. Active and semiactive control approaches not only enhance the possibility of smart systems, but also provides smartness to systems where installation of structural devices is inaccessible. The monitoring of vibrations, due to the development of sensor technologies, allows determining the health status of the monitored infrastructure and then transmitting that information to its control systems. Piezoelectric, magnetostrictive, electromagnetic-inductive and micromachined principles are used to record acceleration, displacement, strain or pressure changes by means of a single- or multi sensors. The development of advanced data analysis and processing technologies supported by artificial intelligence have resulted in smarter, faster, more precise and reliable vibration monitoring systems which are essential elements of smart infrastructure.

Smart transport systems are increasingly evolving from intelligent in-vehicle management systems to asset monitoring and maintenance. Vibration monitoring in highways and bridges gives information for traffic detection and surveillance. There is a growing trend in the research and development of a variety of sensors and techniques towards combining the sensor networks with intelligence, which agrees well with progress in the smart transport infrastructures [9]. In order to realize both the online monitoring, intelligent computation and scalability, a pavement vibration sensing IoT monitoring system has its own advantages comparing with traditional systems. Among the various types of infrastructure, transport is among the few to specify strongly competing objectives by addressing increasing traffic demands and a number of competing metrics related to security (physical vulnerabilities), impacts on the environment (carbon emissions, waterborne pollution and others) and economic pressures [1].

**DISCUSSION**

Emerging advances in data-driven approaches and the increased availability of data, activities such as vibration monitoring of bridges or railways have become viable. Vibration monitoring plays a crucial role in predicting infrastructure degradation and ensuring the safety of railway operations. However, vehicle vibrations are influenced not only by the condition of the structure under investigation but also by the behavior of the vehicle–infrastructure interaction throughout the ride. Consequently, the automatic labeling of vibration data remains a necessary step to enhance interpretation and accurately estimate infrastructure conditions, especially for long observation periods. Rather, deep neural network architectures, which are quite successful for sequential data modeling, suffer from large model parameter tuning. A C-LSTM network for automatic labeling of vehicle dynamic response data on bridges is developed to simplify further the process and minimize dependence upon extensive parameter tweaking [10].

Commun Bioinspired flight control techniques, such as insect and bird inspired Neural Flight Control Models (NFCM), can improve the maneuverability of Aerospace Perfect Insect Based Micro Air Vehicle (APIMAV) platforms. Such models have the particularity to rely on baseline control parameters (BCPs) that may not easily be well tuned in order to maintain good aerodynamic flight stability and precision. Optimization of BCPs is essential for performance; however, the complex, noisy, and time-consuming nature of the design space makes standard optimization algorithms inadequate. Surrogate-assisted optimization algorithms can effectively handle nonlinear problems, yet their performance varies according to the problem type and graph structure of the training data used for inference. A surrogate-assisted optimization framework leveraging Gaussian Process (GP) surrogate models, supported by an advanced multi-information source heuristic adaptive GP inference algorithm, is introduced to efficiently perform BCP optimization for NFCM, effectively addressing the challenges of noisiness and time consumption while improving convergence and solution quality [11].

**CONCLUSION**

Persistent exposure to vibrations from rail traffic systems has a detrimental effect on various infrastructure components, including rails, sleepers, buildings, and bridges. Accordingly, sustainable design, development, and operation of smart transport infrastructure must prioritise effective vibration management.

In this paper, the challenges over sustainable management of vibrations associated to smart transport infrastructure are critically reviewed. It also discusses a variety of successful mitigation methodologies and presents recent developments in vibration technologies used for monitoring and mitigation.

The ongoing global economic recovery is forecast to sustain rapid growth in passenger and freight transport over the next two decades. However, realising the economic and social benefits of enhanced transport capacity is heavily contingent upon efficient infrastructure operation and management. Various initiatives are underway to upgrade existing infrastructure and develop new networks in response to burgeoning urban populations worldwide. In parallel, a paradigm shift towards smart transport infrastructure seeks to integrate sensor, data analytics, artificial intelligence, and autonomy technologies to optimise the delivery of transport infrastructure services [1]. To deliver sustainable services in a sustainable way, infrastructure design, construction, and management must embed sustainability principles. Vibration stands out as a critical challenge that must be addressed to achieve this goal. Substantial sources of vibration exist within transport infrastructure systems, including moving trains, subways, surface vehicles, and aircraft; vertical and horizontal transportation systems such as elevators and escalators; as well as road and rail transportation on floating structures and at tracks crossing expansion joints in bridges.

Such vibrations influence the rails, sleepers, bridge decks, ballast layers, embankments, subgrade and underground pipes or cables leading to structural damage or reduction of safety transmitted load. Also, vibration and the accompanying noise can bother the residents nearby(home-bom) there which means negative impacts on social sustainability. The smart infrastructure of transportation is therefore intelligible to a monitoring and tuning of the vibrations, so that sustainable operation requires an efficient vibration management.

If not, we cannot achieve the sustainable construction of smart transport infrastructure. Yet, several obstacles still prevent more success. Removing these barriers is core to realising the potential of smart transport infrastructure systems. This study presents a comprehensive summary of the differ-ent challenges related to sustainable vibration control and covers various methods for vibration reduction and monitoring.

**REFERENCES**

1. Su, J., Liu, X., Wang, Y., Lu, X., Niu, X., & Zhao, J. (2024). In situ test and numerical analysis of the subway-induced vibration influence in historical and cultural reserves. *Sensors*, *24*(9), 2860. <https://doi.org/10.3390/s24092860>
2. Rustamova, N. R. (2025, July). The role of vitagenic technologies in revolutionizing machine design and functionality. In *AIP Conference Proceedings* (Vol. 3304, No. 1, p. 030095). AIP Publishing LLC.  <https://doi.org/10.1063/5.0269690>
3. Maclachlan, L., Ögren, M., Van Kempen, E., Hussain-Alkhateeb, L., & Persson Waye, K. (2018). Annoyance in response to vibrations from railways. *International journal of environmental research and public health*, *15*(9), 1887. <https://doi.org/10.3390/ijerph15091887>
4. Hong, D., Qiu, Y. & Kim, B. Vibration characteristics of an active mounting system for motion control of a plate-like structure in future mobilities. *Sci Rep* **13**, 16278 (2023). <https://doi.org/10.1038/s41598-023-43419-w>.
5. Rustamova, N. R. (2025, July). Vitagenic chemistry: Unveiling life-enhancing energies in chemical reactions. In *AIP Conference Proceedings* (Vol. 3304, No. 1, p. 040056). AIP Publishing LLC. <http://doi.org/10.1063/5.0271016>
6. Brownjohn, J.M.W., De Stefano, A., Xu, YL. *et al.* Vibration-based monitoring of civil infrastructure: challenges and successes. *J Civil Struct Health Monit* **1**, 79–95 (2011). <https://doi.org/10.1007/s13349-011-0009-5>
7. Rustamov, K. J., & Rustamova, N. R. (2025). Advanced hydraulic drive systems in multi-purpose machinery: Enhancing efficiency and performance in modern engineering. AIP Conference Proceedings, 3304, 030093. <https://doi.org/10.1063/5.0269688>
8. Ye, Z., Yan, G., Wei, Y., Zhou, B., Li, N., Shen, S., & Wang, L. (2021). Real-time and efficient traffic information acquisition via pavement vibration IoT monitoring system. *Sensors*, *21*(8), 2679. <https://doi.org/10.3390/s21082679>
9. Korabayev, S., Ergashev, O., Mahsudov, S. A., & Mamatova, S. (2024). Exploring common technical issues in modern technology. BIO Web of Conferences, 145, 03016. <https://doi.org/10.1051/bioconf/202414503016>.
10. Shin, R., Okada, Y., & Yamamoto, K. (2022). Application of C-LSTM networks to automatic labeling of vehicle dynamic response data for bridges. *Sensors*, *22*(9), 3486. <https://doi.org/10.3390/s22093486>
11. Korabayev, S., Ergashev, O., Mahsudov, S. A., & Mamatova, S. (2024). Exploring common technical issues in modern technology. BIO Web of Conferences, 145, 03016. <https://doi.org/10.1051/bioconf/202414503016>
12. Rustamova, N. R., & Rustamov, K. J. (2025, July). Vitagen information and hydraulic drive systems in multi-purpose machinery: Enhancing performance and innovation. In *AIP Conference Proceedings* (Vol. 3304, No. 1, p. 030097). AIP Publishing LLC. <https://doi.org/10.1063/5.0269692>
13. Sanz Bobi, J. D. D., Garrido Martínez-Llop, P., Rubio Marcos, P., Solano Jiménez, Á., & Fernández, J. G. (2024). Prediction of degraded infrastructure conditions for railway operation. *Sensors*, *24*(8), 2456. <https://www.mdpi.com/1424-8220/24/8/2456>
14. Nodira Rustamova, Mamura Khakimova, Maftuna Islamova, Gulshad Yuldasheva, Shaymardon Norov, and Bekzod Islamov "Autonomous AI pipelines for high-throughput optical material screening", Proc. SPIE 14014, Advanced Materials for Optics and Photonics: Chemistry and Engineering Perspectives (AMOP 2025), 1401411 (2025); <https://doi.org/10.1117/12.3094132>