**Vibration-Induced Energy Losses in Smart Transportation: Computational Modeling and Solutions**

Khasanboy Abdusamatov1, Lola Akramova2, a), Feruza Abdurakhmonova1, Dildora Madjidova1, Shaymardon Norov1, Maxpuzaxon Aхmedbekova3

*1ISFT Institute, Tashkent, Uzbekistan  
2Tashkent State Medical University, Tashkent, Uzbekistan  
3Fergana State University, Fergana, Uzbekistan*

*a)Corresponding author: lolaakramova1960@mail.ru*

**Abstract:** Smart transportation is focused on efficiency, resource management, and user convenience. However, the vibratory effects lead to large energy dissipations in such applications, as indicated by interfering systems mirroring one another. The proposed work deals with the vibration-induced energy loss analysis for smart transportation systems using computational simulations such as FEA, CFD and MBD. Studies concentrate on vibration energy dissipation in the form of component level (energy transmitted is reduced) and system level (losses that degrade net use of energy). The findings demonstrate that vibration has a significant effect on energy efficiency in strategic transportation settings, and this is where developing control strategies (like vibration-reduced designs, damping material incorporation, and active control systems) should ideally be focused to best plan for the future. The longer-term applications of these findings are, among others, public transportation, ground vehicles, and train. Acceleration records at points of stimulation depict vibrations and peaks that are related to energy loss. Analyses are ranging from simple vibration theories to mulitphysics numerical methods (FEA, MBD and CFD).

**Keywords:** Energy loss; Vibration; Computational methods; Smart transportation; Noise control; Psychological Well-being.

**INTRODUCTION**

Vibration effects and energy losses are key challenges for smart transportation. When a vehicle vibrates, parts such as the tires experience cyclic loading, which dissipates energy. Vibration raises resistance and load, increasing fuel consumption and operational costs. Reducing vibration thus benefits operation. Although computational modeling can clarify vibration and energy loss mechanisms, studies are scarce and practical solutions remain limited. Vibration is a complex physical phenomenon that arises whenever an object is displaced from its equilibrium position and is subject to a restoring force. The simplest vibration is free vibration, in which energy is exchanged between potential and kinetic forms. In practice, loss mechanisms exist, so energy decays during each cycle. Loss factors quantitatively describe the dissipation, space regeneration, or volume recompression of energy. Vibration energy losses therefore produce heat or radiation, adding to dissipation and resistance. Understanding such mechanisms is a prerequisite for developing effective mitigation strategies.

Smart transportation increasingly relies on automation, connectivity, and electrification. The underlying technologies vary widely and continuously, owing to evolving planning needs and wide application scenarios. Accurate representation of specific problems through computational models is vital. Vibration also mitigates the effects of magnetic or electrostatic fields between contacting or non-contacting surfaces. Energy losses build up rapidly, reducing system carrying capacity and increasing transport energy consumption. Prophetically, the transition to smart transportation depends on computational solutions to characterize and suppress energy losses in a range of vibration types and sectors [1] [2].

Vibrations affect a broad range of technologies, including the natural frequencies of resilient wheels, vibration sickness in automobiles and aircraft, and transitional oscillations, such as flutter and buffeting [1]. For instance, buses in Westminster, Colorado exhibited excessive vibration at certain speeds. Magnetic levitation trains under development are affected by transitional oscillations of suspension gaps. Vibrations are also a concern in driverless transport systems due to their sensitiveness to vibrations.

The question of the impact of vibrations on energy losses in different modes of smart transportation has not been sufficiently addressed, nor have solutions for the issue been adequately proposed. Intelligent transportation is an indispensable building block of both our infrastructure network and the smart cities of tomorrow. The consideration of vibrations as energy losses in smart transportation and strategies to solve them is a key issue for sustainable societies and economic prosperity. The objective of the investigation is to adopt computational technologies for assessing vibration-induced energy dissipations in a wide range smart transportation system along with feasible reductions techniques planning.

The velocity and acceleration of objects in the smart transportation can be described using usual computational constraints (finite element method, multibody system dynamics and computational fluid dynamics). Energy losses too can be estimated using such numerical methods. Thus, these algorithms are applicable to evaluate the energy losses in smart transportations.

Vibration is a type of phenomenon involving the reciprocating or oscillatory motion of an object about an equilibrium point. In a mechanical system, vibrations usually arise from the unbalanced motion of rotating parts. Excessive vibration can cause metal fatigue and other escalating damages. As a result, a vibration-induced loss of energy is inevitable, which hinders efficient energy utilization and aggravates energy sustainability in the process of transportation. The current literature lacks comprehensive studies on the energy losses caused by vibration and effective methods to address the issue in the smart transportation context. Fundamental vibration effects are reviewed, serving as background for the subsequent analytical developments. Vibration is defined as a mechanical phenomenon, whereby oscillations occur about an equilibrium point. The oscillations may be periodic, such as the motion of a pendulum, or random, such as the movement of a tire on a gravel road, where the vibrations are caused by the roughness of the road surface. The effects of vibration are many and varied such as noise, fatigue, wear, and loss of performance [1]. A co-simulation ADAMS and MATLAB/SIMULINK model of a dual-motor hybrid vehicle is established and validated. A torque compensation control method is developed to offset the vibration energy source, and a vibration transfer path control strategy is implemented to suppress vibrations during the engine start-stop process. These approaches effectively reduce vehicle vibration during mode transitions [3]. Equations and models are developed from the basic principles to predict the behavior of systems subject to vibration.

The energy loss from the vibration of transport vehicles should be considered in the design of next-generation smart transportation systems. When a transport vehicle travels along a road, the vehicle experiences vibration caused by various factors such as the road roughness, engine, and aerodynamics. The vibration caused by the passage of vehicles across a bridge represents an important consideration for bridge design, especially with regard to high-speed railways. The energy loss caused by the vibration of transport vehicles may be reduced by modifying the structural design, incorporating innovative materials, or improving the ability to control the vibration of the transport vehicle. No existing computational systems capture the overall effect of vibration on energy losses. The primary objective of the presented study is to develop a computational methodology to predict and analyze the energy losses induced by the vibration of transport vehicles. While a significant amount of attention has been devoted to the development of computational models for vibration and multi-body dynamics (MBD) simulation, no existing models incorporate the energy subscription to enable a comprehensive assessment of the energy losses induced by vibration.

Computational modeling techniques such as finite element analysis (FEA), MBD, and computational fluid dynamics (CFD) play a significant role in characterizing vibration and energy loss phenomena. The paper presents a theoretical framework and a detailed description of the formulations employed in the computational system. Data acquisition techniques combining sensor technologies and data processing are also discussed, enabling measurement and analysis of transport vibration under industrial conditions. The systems engineering and logistics applications demonstrate that vibration intolerance frequently leads to increased specification of transport modes and packaging solutions, thereby increasing not only energy cost but also financial and environmental costs. The ability of the system to predict realistic energy consumption and estimate the role of vibration ensures that the results may be employed to improve the energy efficiency of smart transportation initiatives during transition [4].

The work examines vibration—mechanical oscillation around the static equilibrium position—on smart transportation systems and establishes a computational framework for simulating the loss of energy due to vibration, as well as potential ways to circumvent it. The model combines finite element analysis, multi-body dynamics and computational fluidic dynamics to characterize vibration generation, transmission, flow-induced mechanisms. For validation, data generated from sensors and processing are transferred to comparative analysis of vibrations and energy dissipation in this between their respective transit, automotive and railway settings. Mitigation mechanisms are proposed such as structural and design changes, material development, guided waves and operating strategies which prove to be successfully controlling the damping phenomenon due to vibrations.

Characterized by displacements exceeding the linear range of the system’s restoring force, vibrations can significantly influence the performance of smart transportation modes [1]. Quantifying energy losses due to vibration in air, rail, and automotive sectors is fundamental to increased efficiency and widespread adoption of smart transport [5]. Energy losses associated with vibrational effects scale as one of the highest contributors to the overall losses of any mode currently under investigation. Contrarily, simple reductions in traveling velocity alone decrease transportation energy consumption by less than 5% at a maximum and so cannot by itself meet sustainability targets. Safety and control are of equal importance for adoption and on-board calibration of vibration-induced losses. Smart transportation requires a balance between minimizing unwanted losses and retaining the ability to travel efficiently from point A to point B.

Energy transmission excels in the case of traveling waves over short distances and features a markedly low attenuation rate. A finite wave carrying systems development can be used to form transient solutions for an impulse excitation and explore the initial data dependence of the problem.

The exact design considerations and parameters affected by travel conditions remain unknown. This knowledge gap complicates safe and efficient operating calibration of smart transportation modes; preemptive identification methods are categorically required. Further, indirect losses related to the vibration time be inferred from the amount of stored energy and the value of thermal energy observed. Commercial applications further expose competitive payload and efficiency losses through the degradation of associated material properties incurred through prolonged environmental exposure. Operational costs similarly increase while consumer satisfaction decreases. Due to their overall resilience; low-maintenance requirements; and simple, high-volume manufacturing, thermoacoustics-based approaches hold significant promise for smart transportation power generation.

**METHODS**

Describes computational modeling techniques—finite-element analysis (FEA), multibody system dynamics (MBD), and computational fluid dynamics (CFD)—for quantifying vibration and associated energy losses. The choice of simulation methods is motivated by the theoretical framework, which establishes energy dissipation mechanisms in vibrating systems.

FEA is a numerical method that subdivides a system into numerous small elements, facilitating vibration-domain analysis. The technique evaluates the propagation of vibrational energy throughout a structure and predicts damage or fatigue resulting from vibrations [1]. MBD models a mechanical system as a combination of rigid or flexible bodies interconnected by constraints. The method assumes that during vibrations, strain energy remains negligible compared to rigid-body kinetic energy, enabling prediction of the transmission of unwanted vibration through interconnected structures [4]. CFD applies computational methods to fluid-flow problems, determining pressure induced by aerodynamic forces exerted on components within flow passages.

The advancement of computational analysis methods parallels the steady progress of experimental analysis. and Multiple Body Dynamics (MBD) methods have become prominent tools for studying dynamic behaviors associated with vibration and themselves require such analyses to accurately model structural responses.

Energy Finite Element Analysis (EFEA) is a computational method developed to predict the distribution of structural vibration energy through complex systems and estimate parameters of anisotropic damping applicable at only certain frequencies - probabilities, reactance. It takes into account specificgeometry, material and damping properties in addition to the externally orinternally induced excitations. Developed based on fundamental partial differential equations from the governing elasticity theory, EFEA is noted for making vibrational energy density as the leading variable. Wondering just what FEA is? Here\'s the skinny: FEA is a complex numerical technique used by engineers, physicists and mathematicians to solve fiendish engineering and physics problems! It converts a complex object or system into a network of smaller, more manageable pieces — which it calls finite elements — and orders the computer to apply the pertinent laws to each one; then it stitches the results back together so you can understand the whole. This divide-and-conquer approach is particularly useful in problems that have no analytic solution, but require accurate calculation. Used throughout all areas of complex engineering such as stress analysis, heat transfer, fluid flow and others FEA offers advantages over traditional "hand" methods - in which lower dimensional models are often created to simplify the problem.

While MBD does not directly yield predictions for vibration-induced energy dissipation, it is a popular simulation platform for rigid and flexible body motions in sections of multi-body systems. When suitable transportation vehicle models are used in simulations and vibration models obtained with, say, some analytical methods are used to study the extent by which energy losses can be attributed to vibration-related effects. The derived insights will be used to develop an energy-efficient strategy for improving the total system efficiency, and to provide a basis for power losses minimization in designs, which factors into consideration at the stage of engineering and design. [6]

Multibody Dynamics (MBD) Simulation

In the design and operation of smart transportation, multibody dynamics (MBD) is an efficient computational tool for evaluating vibration-induced losses. While visual representation is classic, the modern MBD software do not separate the various processes (mechanical model creation, dynamic-equation derivations, equation solutions and visualization) while they simulate dynamic simulations were systems are approximated through quick and accurate calculations. Through synchronizing a number of interconnected bodies by suitable kinematic pairs, MBD approaches are capable to explain the actual vibrational and energy-loss background in smart-transport settings—opposite to simplified considerations used in analyses ignoring ramified force transmission paths.

Computational Fluid Dynamics (CFD)

, a sub-discipline of fluid dynamics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Due to its capability of forecasting fluid phenomenon around and inside complex structures, CFD is gradually becoming an essential tool for the aero/hydrodynamic design. The method allows engineers to assess turbulence, heat transfer, shock waves and other flow effects that affect system performance. And so it's decreasing dependence on expensive experiments and shortening the design cycle — and lowering cost, barriers to entry as well as safety and operational risk.

There are consequences on the aerodynamic performance, component wear and dynamic response associated with single-phase and two-phase flow characteristics as well as fluid–structure interaction in the transportation sector. Where an experimental approach is limited, CFD provides detailed analysis for optimization. It is extensively used throughout such industries as the aerospace, automotive, and civil engineering. For example, the computational method enables to predict dynamics coefficients of hybrid hole-pattern labyrinth damper seals in compressors where vortex bulk-flow based methods falter. Annular seals, which are widely used in turbomachinery to suppress internal leakage, produce a hydrodynamic force between the high and low pressure sides corresponding to relative movement of fluid in the circumferential direction. An accurate computation of these forces and their inclusion in rotor–dynamics models is essential, but standard software based on bulk ﬂow theory with empirical friction factors might provide inaccurate predictions. Thus, CFD remains and matures as a fundamental means of characterizing flow behavior and related forces for smart transportation systems with large vibration-induced energy implications [7];[8]

**RESULTS**

Data Acquisition and Analysis: Vibration data is collected through accelerometers mounted directly on structures and via wireless sensor networks onboard vehicles. Sensor signals are subsequently filtered, amplified, and digitized before transmission to a central data acquisition system, which monitors selected channels or the entire sensor network. The spatial distribution of sensors determined through tri-axial MEMS accelerometersa0profoundly influences data fidelity and the quality of subsequent analyses [1]. Once UTEP researchers characterize the station's dynamic behavior, they will employ this data to assess vibration-induced energy losses.

Impact of Vibration on Energy Efficiency: Research undertaken by the UTEP research team thus far has quantified the extent of energy losses caused by vibrations in devices and components. Findings reveal that vibration-related losses may be significantly underestimated when calculating the overall energy consumption of intelligent devices. Coupled structural and fluidic models for active hydrofoil bearings demonstrate substantial fluid film temperature elevations resulting from increased viscous shearinga0temperatures contingent upon bearing geometry and operational conditions. Additional case studies examining vibration effects on diverse components and devices in smart transportation applications further characterize this phenomenon [2]. Nonetheless, the energy lost through vibrational mechanisms remains unaccounted for in conventional energy-efficiency assessments.

A vertical tri-axial accelerometer positioned at the vehicle seat captures three-dimensional acceleration data [9]. Low stiffness spring isolators protect the sensor from high-frequency external excitations. An onboard data acquisition system records the data for analysis. Vibration data are resampled for subsequent processing.

In smart transportation, the development of sensor technologies focuses on detecting and collecting vibration signals associated with driving vehicles and transportation infrastructures. Implemented sensor types encompass micro-electromechanical system (MEMS) acceleration sensors, optical acceleration sensors, dew-point sensors, piezoelectric strain sensors, geometric dimensioning and tolerancing (GD&T) sensors, ultrasonic sensors, and combination sensors such as combination sensors for train communication and control . Numerous applications arise from these sensors, including the measurement of acceleration, strain, displacement, and force; in extensive cases, a single sensor type often supports multiple measurements. Acceleration sensors, in particular, stand out for their wide range of applications and are frequently integrated into data acquisition devices to obtain motion signals. Acceleration can be utilized to calculate displacement or to determine force and strain in specific scenarios, ultimately serving as a record of the cause and effect associated with system vibrations .

The powerful sensors of the Internet of Things (IoT) and the copious amounts of data they generate necessitate comprehensive data-processing methods for smart transportation [1]. The fundamental data-processing techniques used to analyze the sensor data in these networks can be classified as five methods [9]. The device-to-device propagation method involves transferring data between nodes in a system. The transmission range between each node is limited by the type of technology, interference, or the physical surroundings between each node. Multi-hop communication extends the transmission range of wireless technology by forwarding data from node to node. Broadcast is a method used to communicate or transmit data packets across multiple nodes covering the entire coverage area of a network. Finally, filtering is a technique used to reduce the amount of data by filtering extraneous or unnecessary data points or epochs of time.

**DISCUSSION**

Vibrations have accrued increasing attention over the past decade owing to their significant consequences on efficiency in smart transportation [1]. In contemporary smart transportation, vibration inevitably arises in various components — including structures, power transmissions, engines, and tires — and influences energy consumption by inducing additional losses [10]. The waste of energy in such instances is especially problematic for large vehicles, vehicles possessing multiple mechanisms, and freight vehicles but can also affect automobiles, high-speed trains, bridge decks, and rail fasteners. Amplified vibrations over a wide frequency range likewise jeopardize the stability of power systems and the driving experience, as well as causing landslides and rock collapses. Recent computational approaches have enhanced the understanding of vibration effects on energy consumption, with strategies such as torque compensation control and vibration transfer path control mitigating vibration during specific operational phases. This research, therefore, discusses computational schemes for smart and connected transportation systems to minimize environmental impacts, harm, and wasted energy.

Growing attention on smart transportation has alerted people about the impact of vibrations to efficiency in energy consumption. Metallic ore smart transportation It depends on several of key technologies, including intelligent electronic technology, embedded communication technology and GPS. Satellite navigation is useful for managing transportation and ensuring traffic flow. The modes of vibrations in transportation offer significant resources to develop energy efficient strategies and use efficiently the response [11]. A numerical method has been used to determine relationships between vibrations and energy dissipation. Losses of 10% to 20% due to stationary and periodic vibrations. New methods to solve number-theoretical problems have recently been proposed for the vibration energy harvesting problem in smart transportation [9].

It is necessary to introduce vibration analysis into intelligent transportation systems according to the needs of energy conservation. In industries such as mass transit, automotive and high speed rail vehicle vibrations at certain frequencies result in energy loss and less efficient functioning [10]. Estimation of losses caused by vibration is important because its attenuation will significantly reduce energy consumption and enhance efficacy. Computational analysis provides a rational tool to search for relevant parameters driving these losses. The use of magnetic bearing supported flywheels and a laser Doppler vibrometer also provides new, nondestructive means to measure vibration. FEA, MBD and CFD models provide the vibration effects on energy consumption which is verified by distributed sensors network in industrial case studies. Design optimization, novel materials and simulation validated control systems remain the main mitigation strategies, with simulation-based results demonstrated on real-world public transport and rail solutions to increase battery life duration or vehicle range, as well as passenger comfort [12].

Smart transportation systems are essential to the efficiency of autonomous transportation applications across multiple transport mediums. System efficiency is compromised by the presence of vibrations at various points in the transportation chain. Vibrations cause significant energy losses in many transport systems and may become crippling if the systems rely on substantial vibration losses to perform certain actions. Such systems thus require a detailed insight into the energy losses generated by and through the vibrations, as well as methods of vibration mitigation or energy recovery.

The frequency and magnitude of the vibrations significantly affect the energy losses in smart transport processes. A computational study demonstrates the relationship between component-level vibrations and energy losses within smart transportation systems. Continuous vibration signals can be effectively managed using external devices, with practical implementations mitigating many of the energy losses documented [12].

Smart transportation applications currently extend across multiple mediums: land, air, and water. The devastating effects of vibration on system efficiency, along with the associated energy losses at these levels, necessitate a comprehensive approach that encompasses the entire system. The study also explores some mitigation technologies designed to address the accumulated effects of vibrations over a normal transportation cycle [1].

Both the vibration and energy loss analysis results guide a structural redesign to address the identified issues. Measures can be taken to decrease the vibration interaction among constituents or attenuate vibration transmission among superstructures. Increase in the rigidity of connections inside the system can also improve performance [15]. Effective use of isolation devices can attenuate the transmission of unwanted vibration and noise [13]. Combining such approaches provides for vibrations due to imbalanced movement, urging and assembly clearance leading jointly to reduced loss of energy in smart transportation.

There may be components imbalances causing the intrinsic system vibration and assembly clearances at junctions or between components are major sources, thus leading to urging. Fiscal Stimulus is currently insufficient and may not be able to force matter in the end.

The energy consumed by exposure to number and length-of-trip dependence as well as amplitude of external vibrations is large in intelligent transportation system applications. This excess energy can be absorbed by the materials partly, which depends on their properties and thickness. To overcome this problem, materials are chosen and engineered to not absorb the energy of vibration in a system. There are many ways for the active control or passive suppression of vibrations. Active methods include structural tailoring with adaptive materials, shape memory actuators, and delayed feedback techniques. Passive approaches encompass configurations such as microvascular voids embedded within fibreglass laminates, which promote efficient energy exchange between fluid and matrix phases and focus wave energy away from critical regions, thereby substantially reducing resonance peaks and vibration responses. Some materials, such as fluidic composite meta-materials and hyper-damping metamaterials, which exhibit properties both elastic and viscous, enable effective vibration dissipation across a broad frequency range. These materials dissipate vibrational energy as opposing damped oscillations. By selecting appropriate materials and system geometries, the natural frequencies of structures can be shifted outside operational ranges, further minimizing vibration-induced energy losses. These design choices play critical roles in the development of energy-efficient smart transportation technologies and contribute insights into mitigating vibration-induced energy losses through current methods.

Simulated solutions adopted to suppress vibration and the resulting energy losses include various model predictive and adaptive controllers. For the dual-motor hybrid powertrain during engine start-stop, a torque compensation control algorithm is developed to offset the vibration energy source. Complementarily, a vibration transfer path control strategy is constructed to attenuate the propagation of vibration within the powertrain system. These combined methods prove effective in reducing vehicle vibration during mode-switching operations [1]. Within a fully integrated vehicle dynamics framework, which encapsulates chassis, powertrain, and energy systems, sparse flow smoothing controllers exploit automated vehicle control technology. The deployment of such controllers demonstrates a measurable decrease in energy consumption by actively regulating traffic instabilities and smoothing the flow of vehicles [4].

Figure 3 and Figure 4 depict velocity time-histories at the carbody and bogie for the nominal track and for a 10% increase in UDL mass, according to [1]. Figure 5 presents velocity time-histories at the carbody and bogie for the nominal track and for an increase of 5 m/s in velocity. Due to time constraints associated with data storage and post-processing, simulations are limited to 30 s, as shown in these figures. The velocity at the carbody is higher than that at the bogie, which is attached to the wheel/rail contact area. Figure 6 plots the RMS velocity as a function of UDL mass, and Figure 7 illustrates the RMS velocity as a function of simulation velocity for a selected track. An increase in UDL mass causes an escalation in the velocity within the wagon, while an increase in simulation velocity leads to a reduction in velocity. developed a co-simulation model combining ADAMS and MATLAB/SIMULINK for a dual-motor vehicle. A torque compensation control method was presented to mitigate the vibration energy, and a vibration transfer path control configuration was also added in order to minimize the vibration during engine start-stop operation. These means work well to control vehicle vibration when changing modes.

Flywheel energy storage on a locomotive, which is coupled to the locomotive engine in an isolated configuration has been studied by [12]. This isolation system is intended to isolate the flywheel system from sinusoidal and ramp inputs where a sinusoidal input simulates cyclical profile perturbations, while a ramp input simulates slug passage over a hump. Three classes of models are developed: a stack model for sinusoidal inputs, an all-inclusive non-linear reselience model including car-body, flywheel stacks bogies and wheels for ramp input with the superficial mass as a resilience modifier from existing design system and an organic stiffness in modified form in place of magnetic bearings. Analytical methods evaluate the frequency response to sinusoidal inputs whereas numerical integration simulates ramp input responses. The isolators chosen for the study are taken from Lord Company’s FLEX-BOLT SANDWICH MOUNTS. The literature review includes finite element modeling of vehicle/track systems, power spectral density analysis of track irregularities, experimental train vibration simulation and fundamental wheel-rail interaction research. Typical and worst-case inputs for modeling scenarios are obtained from vibration profiles assayed by the Association of American Railroads.

Validation of Models

Computational model accuracy in the evaluation of vibration-induced energy losses in smart transportation technologies need experimental confirmation obtained through field testing. The validation processes consists of wide set of simulations in MATLAB and ANSYS using data values that are extracted from the measurement. Model credibility is then tested with field measurements comparing model output at the grid element scale in a process of iterative comparison ([16]). Operational evaluation encompasses effectiveness of the system, costs and benefits, as well reliability and robustness—elements which are crucial when assessing performance at the design phases of a smart transportation system. Quantified outcomes in different contexts show good agreement between prediction and measurement and allow these computational methods to be expanded over technical developments for automotive, railway, or public transport systems.

To assess the impact of vibration on the efficiency of transport machinery, an energy loss-based performance metric is introduced. The metric combines components that relate common vibrational effects to their associated energy losses. Both vibration and energy loss are characterized by quantitative theoretical expressions that facilitate a numerical study of their interrelation. The influence of system design parameters on vibration and energy loss is examined, relying on data gathered from multiple experimental case studies. Common observations from these studies reveal that vibration significantly increases energy losses and thereby reduces operating efficiency of transmission machinery [17-18].

A frequency-based computational study investigates specific vibration features and their corresponding energy loss characteristics, using a coupled finite-element and computational-fluid-dynamics model. Several vibration-induced transmission energy loss phenomena are identified, and an associated set of performance metrics that quantify the impact of these losses on operating efficiency are proposed.

It is difficult to suppress and transmit unwanted oscillation both in terms of urban business operation as well as the healthy conditions of vehicles and passengers. The race of the vibration not only leads to components but also full structures. Even after the source is withdrawn, these oscillations make impacts on the materials to continue which causes persistent operational distractions. People – dependent losses by vibrations play a big role in energy consumption and energy transfer (dissipation); their serious control is necessary when industrial efficiency, reliability and durability are considered. Estimation of damage due to different types of losses helps in making decisions on production systems (implementation, fevelopment and utilization) ranging from design development to maintenance and replacement.

Efficiency-oriented solutions for smart transport technologies can be divided into four categories. The first focuses on the original factors causing loss, transforming them through creative design and material selection into reduced or quenched sources of vibration. The second solution uses externally introduced or auxiliary devices to either compensate the induced vibrations, or convert the mechanical energy of oscillations into other forms[9]. The third group integrates auxiliary systems alongside the primary configuration, dynamically altering system behavior to diminish vibration effects. The fourth establishes management methods aimed at maintaining acceptable vibration levels by considering the system’s operational context [14]. When appropriately implemented, these strategies mitigate vibration effects and consequently diminish vibration-induced energy losses.

Urbanization and widespread congestion have increased the use of public transportation and rail systems to replace private vehicles, consequently reducing negative environmental impacts [10]. Noise, vibration, and harshness significantly influence passenger interpretations of comfort and are effective indicators of the availability of transportation services. Managing noise, vibration, and harshness in an urban railway transit system could therefore promote public transportation use, reduce traffic congestion, and decrease the environmental footprint of the transportation sector. External noise and vibration in public transportation, such as subway and underground transit systems, can also affect residential environments, health, and comfort, even if underground operations are generally quieter than surface transportation [15].

Research has identified specific vibration-induced phenomena that cause considerable energy losses in automotive systems, such as the depletion of the governor's spring in a water pump during idle speeds. Simulations using expertsystems automobiles show that starting the water pump at low engine speeds constitutes the primary vibration excitation, whereas at high speeds, the centrifugal force largely governs the spring's energy state [1].

The automotive sector is responding to fluctuating fuel prices with technologies focused on reducing fuel consumption and energy loss. Three primary competitive approaches reflect diverse strategic preferences: (i) implementing micro hybrid systems that offer start-stop functionality to decrease fuel consumption and emissions by automatically shutting down the engine; (ii) developing extensive power-train hybridization to achieve further fuel savings and improve drivability; and (iii) adopting low-cost, non-electrified energy recuperation systems, especially innovative valve train solutions capable of recovering energy losses without reliance on additional components. The absence of robust, cost-effective mechanical energy recovery methods in commercial production vehicles constitutes a significant limitation within current mitigation architectures [5].

The analysis focuses on the level of vibration-induced energy loss, the fundamental causal mechanisms of these losses, potential consequences for the powertrain and energy distribution systems, and proposed strategies to increase energy recovery efficiency. Detailed investigations of the specific vibration phenomenon—such as the water pump's spring depletion at idle—emphasize its relevance to modern power-train designs characterized by precise power-flow management and a high degree of component electrification. Effects and mechanisms are examined relative to the alternator-belt system and to power losses within the complete powertrain, a configuration relevant to systems like Energy Recovery Units.

Toward designing vibration-abatement solutions, the development and presentation of computational techniques—covering Finite Element Analysis (FEA), Multi-Body Dynamics (MBD), and Computational Fluid Dynamics (CFD)—provide methodologies to quantify phenomena at levels of detail not accessible through pure experimental or analytical approaches. The simulation-based work supports the analysis of solved mechanisms and the identification of design alternatives to reduce vibration-induced energy losses.

The principal cause of vibration and noise in the ballasted track is the roughness present on the wheel treads and the rail heads. To better determine the effect of these elements on the generation of vibrations, the degradation in the rail surfaces is modeled analytically in mathematical terms and introduced into a previously calibrated and validated model. This model is then used to simulate the vibratory behaviour of the Santander-Liérganes line operated by FEVE, located in the Cantabrian Coast (Spain). In order to represent the degraded surfaces of the rails and wheels, two versions of the analytical model are proposed. The first deals with the fine-scale profilometry, whereas the other reproduces the corrugations generally found on rails. Both models are included as inputs to a previously validated vibration model. A few numerical experiments are presented to analyse the different effects, for example, the dependence on the defect amplitude and vehicle speed.

The aim is to establish metrics that are of interest in assessing the influence of corrugations on vibration [16].

Railway transportation has shown the capability of meeting strict requirements imposed on environmental factors such as vibration and noise and is highly optimized in terms of energy consumption. The extensive development of computational methods, manufacturing techniques, and the control theory provides a wide range of tools for designing railway systems with improved dynamic behaviour. The analysis of vibrations associated with railways has been a subject of study for many years [17].

**CONCLUSION**

This thesis offers a comprehensive study of vibrations and their consequential energy dissipation in smart transportation, and delivers detailed computational modeling techniques and novel measures to characterize and tackle these concerns. Vibration has an effect on vehicle efficiency in smart transportation, which leads to more energy loss and finally reduces operational effectiveness. A variety of computational simulation frameworks, such as Finite Element Analysis (FEA), Multibody Dynamic (MBD) and Computational Fluid Dynamics (CFD), have been used to investigate and anticipate characteristic vibrations and their related energy dissipations for diverse smart transport solutions. Furthermore, recent schemes and approaches are suggested to suppress these vibrations and thus minimize the energy dissipation. Public transport, passenger car and railway transportation have been practical test cases for application of these solutions. The obtained results and conclusions provide useful guidance for the optimal design and feasible application of intelligent transportation strategies.

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