ETALON

D 4.2 On-board Energy Harvester, Power management and Energy Storage Solution, design and predicted performance report for adapted or developed solution

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EXECUTIVE SUMMARY

This report describes adaptation of an existing design of vibration energy harvester product for bogie condition monitoring, and a proposed adaptation of displacement energy harvester concepts for rail. Engineering constraints driven by the application and environment are discussed. Energy output from the proposed mounting location, and the reasons for selecting the mounting location are shown. Finally, alternate complete solutions including energy storage and power management strategies appropriate to the harvester are described.

Context:

S2R-OC-IP2-02-2017

Energy harvesting methodologies for trackside and on-board signalling and communication devices. Adaptation of already existing technologies for developing a purely on-board Train Integrity.

Task 4.2 - **The identification of solutions and the development or adaptation of devices for on-board energy harvesting solutions including energy storage and distribution**

(Task Leader: PER, Task Contributor: ARD, BUT, UNEW) Starting at month 3 – Ending at month 12.

Taking as the starting point the functional requirements developed in WP2, the most appropriate energy harvester systems will be identified for adaptation or development to deliver reliable power for OTI and other applications. The output of this will be a report detailing the engineering constraints for the energy harvester, and explaining the rationale for the selection made.

D4.2 - On-board Energy Harvester, Power management and Energy Storage solution, design and predicted performance report for adapted or developed solution (M12).

This report includes a justification for the one or more technologies selected from D4.1 and an analysis of the development or adaptation for the demonstrator, showing compatibility with SIL4, existing OTI solutions, requirements established by D2.3 and interoperability with other rail systems (IP4Laboratory demonstrators of on-board energy harvester and OTI development platform will be produced for integration and testing in WP5.

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LIST OF PARTICIPANTS

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1. INTRODUCTION

On-board Train Integrity Power is to be generated from energy harvester technology that is adapted from already existing technologies. This report contains a description of the adaptation of an existing vibration energy harvester technology that is widely deployed in passenger trains and locomotives, and the development of existing linear displacement technology that has seen some testing in automotive applications.

This document covers:

- The fundamental Requirements for Energy Harvesting
- SIL-4 principles and how they affect Energy Requirements
- Train Integrity Power Balance
- Energy Harvester Types and Mounting Options
- Energy Output Calculation and the Energy Storage Options
- Discussion about the results from other work packages and complementary projects

1.1 LIST OF ACRONYMS

EH	Energy Harvester
EHD	Energy Harvester Device
ETCS	European Train Control System
HLC	Hybrid Layer Capacitors
OTI	On-board Train Integrity
PV	Photo-Voltaic
VEH	Vibration Energy Harvester
UIC	UIC - Union Internationale des Chemins de Fer

Table 1 – List of Acronyms

1.1 Relevant Requirements

The requirements used by this document should respect the ones previously analysed in WP2, WP3 and in the complementary project X2RAIL-2. In the next sections are displayed the relevant requirements used to develop the energy harvesting solution.

1.1.1 Summary of requirements from WP2

This section shows the list of system requirements taken from the deliverable D2.2 “System Requirements Specification” that are directly applicable to Energy Harvesting.

Code for this component: EH_OTI (Energy Harvesting On-board Train Integrity).

SR_EH_OTI_1: For a given operational cycle of the train integrity operation, the total energy output of the energy harvester must be greater than the energy requirements for reliable operation of the OTI.

SR_EH_OTI_2: For a given operational cycle the energy storage capacity provided for the energy harvester must be greater than the total energy requirement for reliable operation of the OTI over the maximum time when energy harvester output is zero (train is stationary or no daylight for vibration or solar PV respectively).

SR_EH_OTI_3: The maximum charge rate of the energy storage device must be greater than the maximum peak output of the energy harvester.

SR_EH_OTI_4: The energy storage device must have appropriate protection devices to prevent under/over voltage and current conditions.

For example:

- Capacitors/super capacitors:	Over voltage protection
- Hybrid Layer Capacitors (HLC) / rechargeable batteries:	Over/under voltage protection (under voltage protection via a primary battery), over current protection (excess charge current may cause damage).

SR_EH_OTI_5: Design life of the energy storage and harvester shall both be matched to the design life of the vehicle.

SR_EH_OTI_6: Lifetime cost/benefit assessment of the system will include any maintenance and subjective degradation mechanisms:

- Vibration energy harvester – extreme vibration robustness (no maintenance)
- Storage capacitor – capacity degradation over time, susceptibility to vibration
- Solar PV – contamination, seasonal and geographical variations
- Batteries/HLC – capacity loss over time, degradation with temperature, susceptibility to vibration

SR_EH_OTI_7: Reliability and safety assessment of energy harvester performance is permitted to include improved performance through multiple (redundant) installations.

To comply with this specification, the energy harvester must be designed for a service life of either 20 years or the remaining service life of the train (if greater). The system must be designed such that over a given operational cycle, the average energy demand is less than the average energy produced. The length of the operational cycle is determined by the amount of energy stored and by the level of activity required by the system when energy harvesting is not possible. For vibration energy harvesters, this is when the train is stationary, which could be a few days. For solar PV harvesters this could be overnight, or the winter in the north.

Environmental considerations: EN50155 is the harmonised standard covering all requirements for on train electronics. These are covered extensively in D2.2.

1.1.2 Summary of requirements from WP3

This section shows the list of communication requirements taken from the deliverable D3.2 "On-Train Communication Systems and RF Components Report" that are directly applicable to Energy Harvesting.

Distance Sensor

1. SR_DS_1: The DS module shall be capable of measure a distance up to 15 meters (with a maximum error +/- 5 meters) to ensure that integrity is actually lost and not that the module is unable of measuring the distance.
2. SR_DS_2: The DS module must present one or more interfaces for exposing the APIs for the Microcontroller unit.
3. SR_DS_3: The DS module shall be able of performing a measurement under 1 second, in order to not introduce a delay that will confirm integrity lost due to timeout.

Microcontroller

1. SR_MU_1: The Microcontroller unit must present one or more interfaces suitable for communicating with the other modules.
2. SR_MU_2: The Microcontroller unit shall be capable of managing an ad-hoc communication protocol stack for a WSN
3. SR_MU_3: The Microcontroller unit shall be compliant to very low power consumption computing and capable of being powered by an EH solution.

Communication Module

2. SR_COM_1: The Communication module must present one or more interfaces suitable for communicating with the Microcontroller unit.
3. SR_COM_2: The Communication module must be compliant to the Sub-GHz 868 MHz communication standards of frequency, band and power.
4. SR_COM_3: The Communication module shall be capable of enhanced features for power consumption and communication reliability adapted to a WSN.

WP3 includes a discussion of the operating cycles of the train integrity system, defining the level of activity (power demand) required by the train integrity system and the corresponding times when energy is harvested. The OTI has two components necessary for train integrity; a vehicle proximity system, for detecting the presence of the next vehicle along, and networking communications, which serves as a secondary detection of the rest of the train, and communicates vehicle proximity data. In order to facilitate prompt start-up of OTI when the train is assembled and starting, or even after a short stop during a journey, both vehicle proximity and network communications need to be maintained, although the update rate may be reduced to extend the time available from stored energy. It is expected that the time available will be different for each node, therefore update rates and energy storage management must be somewhat managed by the OTI device, with some supervision from the network manager. Significant redundancy provided by OTI devices on each wheel (or single solar PV on each wagon) and the communications range extending over several wagons enables better sharing of the communications and update load. From the energy harvesting perspective, increased redundancy and overlap of communications means that more energy harvesters can be applied to the same task, improving reliability and response time.

1.1.3 Summary of requirements from X2Rail-2

In this section is shown the list of Power Requirements taken from X2RAIl-2 Complementary Project – shared document "TIN_OTI-10 Overview of the on board Energy Requirement Specification that are directly applicable to Energy Harvesting".

1. REQ_7.1. EHD shall provide power supply for SIL4 equipment according to Cenelec 50155.

2. REQ_7.4.2. EHD shall provide power supply both in case of train at stand still and in case of train in running phase.

3. REQ_7.4.3. EHD shall provide power supply with a minimum power of sensitisation of:
   - 2.025 W at peak power consumption.
   - 1.3 W during continuous power consumption.

4. REQ_7.4.4. EHD shall provide a minimum power supply of 5V for small wireless nodes. This value is not CENELEC 50155 certified but it may not block the SIL4 certification. In order to be EN50155 compliant a voltage level of 24V as minimum nominal voltage. The

minimum voltage provided by the EHD must be greater or equal than 16.8V and the maximum voltage must be smaller or equal than 30V.

5. REQ_7.4.5. EHD shall provide power supply with a minimum current level of 84.4 mA.

6. REQ_7.4.6. EHD shall include a storage to guarantee power supply availability also in case of vehicle at standstill for TBD months for the Product Class 2-B.

   Note: Maximum number of months depends on specific railway requests from few weeks to 1 year.

7. REQ_7.4.7. EHD shall provide efficiency status.

8. REQ_7.4.10. EHD shall provide energy level of storage device.

According to *X2R2-WP4_TIN-OTI-10-Overview of the on board Energy Requirement Specification,* an outline for a conventional approach to power supply design is described, calling for an output voltage of 24V nominal and power delivery over 2W. This assessment seems to be based on some assumptions that do not necessarily have to hold; that the train integrity device will be external and independent of the power supply, and that no low power strategies will be applied in the design of the on-train integrity device. Energy storage requirements are not well defined, but implied at many 10s of Watt hours. Based on currently available technology (a requirement placed by the call text) this implies a substantial solar cell and significant rechargeable battery energy storage, which may be too large for fitment to a freight wagon body (significant size implies fitment above the suspension).

From the document X2R2-TSK4.3-T-ANS-004001_-_X2Rail-2_WP4_Technical Note Preliminary communication network specification the following approach is also stated:

Relevant decision driver for product classes definition is also the “migration strategy” for existing trains. Final aim for OTI functionality implementation is to remove expensive train integrity trackside infrastructures (e.g. track circuits, axle counters). However this removal is possible after equipping all train with OTI functionality. Therefore a long period and significant on-board investments could be required before removing trackside infrastructure. To facilitate the migration to OTI equipped vehicles two specific solutions have been identified during the analysis: (i) designing OTI device applicable also to non ETCS applications and (ii) supporting optional diagnostic functionalities (e.g. wagon diagnosis, cargo monitoring).
Therefore compatibility with non ETCS systems and support for wagons and cargo monitoring ensure an higher attractiveness for operators and infrastructure managers.

For reliable wheel and bearing condition monitoring, vibration sensing equipment mounted on the bogie or axlebox is preferred, although the shock and vibration limits the size of the device to a much smaller power output than the 2W stated above.

Cargo condition monitoring and tracking can be implemented using vehicle body mounted solar powered devices (e.g. www.nexiot.ch/globehopper) and a train integrity function could be added, although vehicle proximity detection would be difficult from the side of the vehicle where most power is available, unless proximity is detected just by radio signal strength to the rest of the vehicle. GPS positioning at the rate required by ETCS would not be feasible at all locations across

Europe (solar power is low in Northern Latitudes in the winter). A significant number of freight wagons in Europe have already been fitted with solar powered tracking devices – it may be possible to add a train integrity communication function to these. It should be noted that X2R2 X2R2-TSK4.3-T-ANS-003-01_-_X2Rail-2_ WP4 Technical Note Overview of the Functional Requirement Specification in the discussion of product class ID for OTI discusses three components in *Section 6 Product Classes and Scenarios,* an end of train OTI device, wireless network down the train (no intermediate integrity detection) and an OTI master at the head of the train. This could be implemented with vehicle body mounted communication devices (sole purpose communication between the head and tail) and an end of train integrity device. The latter could be implemented with an optical motion detector (www.gobotix.co.uk/) incorporated into the tail light.

X2Rail2 requirements also specify minimum maintenance training and intervention from personnel, allowing local manual intervention for configuration of an end of train device, but intermediate components in the wireless network must auto-configure network topology. This is reasonable, since tail lights are already fitted to freight trains – adding some additional configuration is not a significant burden. Requiring individual configuration of devices on all vehicles could add a significant time delay to train departure, not least because of the distance travelled.

From these requirements and outlines in X2Rail-2 requirements, the choice of harvester is driven by the additional functions that could be delivered by the train integrity harvester. Vehicle body mounted devices (solar PV) could be used to add cargo condition and tracking functions. Bogie mounted devices can add wheel and bearing monitoring with potential future axle monitoring functions. Wagon owners may wish to employ a variety of additional monitoring, therefore it would make sense to implement compatible communication systems on OTI devices of both types.

1.2 Train Integrity Fundamental Requirements affecting Energy Harvesting

If the only function to be performed by the sensor nodes on the train was wagon condition monitoring (wheels, tracking or cargo condition), then it would not be necessary to maintain communication to the (locomotive mounted) network manager when the train is stationary. The network will automatically form itself into the correct vehicles in the train as soon as it has left the yard and is a safe distance from any other traffic. Sensors on wagons can then lock themselves into the network until the train is broken up. Vibration energy harvester (or displacement) devices, since they harvest energy whenever the train is in motion, would, for this application, not require a large energy store. Some short term temperature monitoring might be useful when the train stops, but this would not be a significant demand. Solar PV systems harvest independently of train motion so would still need enough energy stored to run for several months.

The addition of train integrity functions has a larger effect on energy storage requirements for vibration or displacement harvesters, since this represents a significant increase in “out of hours” activity. These devices are bogie mounted, and any significant increase in energy storage capacity must be balanced against the increase in physical size (volume and mass) necessary to contain the assembly. A good understanding of the functions necessary to establish train integrity before the train starts, and to maintain it when the train pauses is embodied in a power balance model, where the various strategies available for reliable and responsive train integrity function can be tested.

1.2.1 SIL-4 and How It Affects Energy Requirements

A system that has been developed to meet SIL-4 requirements must be shown to cause less than one failure in every 10^9 operational hours. This is assumed to be hours of operation per train, and describes the rate for a false positive detection of train integrity (this is the safety critical failure mode). For a single energy harvester, achieving this level of reliability presents a problem. Many safety critical systems achieve high reliability through internal redundancy of electronic systems, and multiple software methods to eliminate systematic coding errors. Other systems use multiple redundant copies of the hardware, with an independent voting system to discard results from one of the units if its output differs from the other two. These approaches, taken at a simple level, all imply a higher energy consumption per energy harvester. Additionally, energy harvesters are intrinsically variable and unreliable devices (energy availability subject to train movement). A unit that is designed to go into a highly quiescent state when it runs low on energy cannot be relied on to perform at a 100% activity level at all times. By considering the train as a single system, however, we can include multiple sensors and energy harvesters to be acting across the same and consecutive wagon couplings. Using this approach, it is possible to design system level features that will cause the system to fail safe, therefore delivering demonstrable SIL-4 performance. The occurrence of false negatives, which are not safety critical, must be As Low As Reasonably Achievable (ALARA), in order for the system to be operationally acceptable (the cost savings from occupying less track must exceed the cost of operating the system). To achieve this, the advantages of distributed sensing and communications devices with flexible communications and ample energy storage can be exploited.

1.3 Average Power and Storage Requirements for Train Operational Phases

Table 2 - Train Integrity State Classified by Power Balance

	DORMANT	IDLE	SHUNTING	STATIONARY	SLOW MOVING	MEDIUM SPEED	NORMAL SPEED
TRAIN INTEGRITY STATE	Not loaded, not in a consist	Loaded, not in a consist	Not in consist, intermittent movement, in a yard	In a consist, not moving	25km/h	50km/h	80km/h
Confirmed	Off	Off	N/A - Listen only	Full function low TI check freq. (R5)	Full function low/med. TI check freq. (R3)	Full function med. TI check freq. (R2)	Full function (high/max. TI check freq. R1)
Integrity lost	Off	Off	N/A - Listen only	Full function	Full function	Full function	Full function
Reforming consist	Off	Off	Listen only	N/A - Full function	Full function	Full function	Full function
Not active	Off	Off	Listen only	N/A	Full function	Full function	Full function
Topology discovery	Off	Off	Full function on TD request	N/A - Full function	Full function	Full function	Full function

Referring to the table above of train states, the following energy states can be defined (capacitors not included since energy storage will not be sufficient, NiMH is rejected for short life of the technology). Listen only communication is estimated for 1 second of listening every 10 seconds (10% on time, opportunity to detect a network master transmission to collect sensors), 30mW consumption when active. Once the network is established, maintaining communication can be more efficient, since the timing of anticipated communication slots is established and less time is spent waiting/checking for a network management communication.

Table 3 - Train Integrity Power Balance

OTI /mW	Comms + microprocessor etc /mW	Generation using 1kg harvester /mW	Storage (charge/ discharge) /mW	Balance (positive or discharge time in hours (days)) – energy storage type		
				Super capacitor, 1F = 9.6J	HLC (Tadiran) 3.7V, 155mAh = 2064J	Rechargeable lithium 2.7V, 2500mAh = 33300J
0	0.05	0	-0.05	53 (2.2)	11470 (478)	185000 (7708)
0	3	~0	-3	0.9 (0)	191 (8)	3083 (128)
0.06	1	0	-1.06	2.5 (0.1)	541 (20)	8726 (321)
0.17	2	3	>1	2.5 (0.1)	541 (20)	8726 (321)
0.5	3	6	2.5	1.1 (0)	229 (9.6)	3700 (154)
1.3	3	10	5.5	0.5 (0)	104 (4.3)	1680 (70)

Figures previously provided for an inductive, inertial energy harvester on the axle box of a rail vehicle:

Table 4 - Example Power Output from a Vibration Energy Harvester (previously shared in X2Rail-2 COLA).

Installation Mass	Speed (km/h)	Power output/mW
>2.5kg (bracket included)	145	90
	80	30
>1kg (bracket included)	145	30
	80	10
Power required for minimum sensor functions ~3mW average.		

By way of example, it can be seen from tables 1 and 2 that the worst case combination of activities would be some shunting and slow movement, with the maximum discharge and minimum recharge, where a supercapacitor could be discharged in less than an hour, and it could take 2.5 hours to recharge. If this extended length of time of slow movement is likely, it may indicate that a larger (more expensive) energy store should be used, such as an HLC in order to maintain functionality.

Considering power leakage when the vehicle is stationary, the vehicle only needs to be moving slowly for 5% of the time (over an interval determined by the energy storage size) to prevent net discharge of the energy store. If a cycle of vehicle activity is significantly longer than a few days (or weeks) during which it might be stationary, then move for a few hours, energy storage larger than a 1F supercapacitor will be required, to maintain train integrity when the train is parked. Use of an HLC provides >>100days of operational OTI maintenance, providing ample margin for low levels of activity.

2. ENERGY HARVESTER TYPES AND MOUNTING OPTIONS

Energy harvesting around a train should be easy – there is access to sun, wind, vibration, displacement and temperature gradients from components and locations above and below the suspension. The environment, however, eliminates many of these options; brake dust, oil and dirt from ballast and pollution cause contamination of surfaces leading to additional maintenance operations for solar PV panels and wind turbines (although solar powered tracker devices are used in freight) and a reduction in efficiency for thermal harvesters (freight wagons lack a reliable source of heat). The high vibration encountered (shocks greater than 100g, vibration up to 10g RMS) imposes severe constraints on the mass of displacement and vibration energy harvesters, although these can be addressed by suitable mounting design and optimising the device mass to match energy requirements. Mechanical harvesters have the advantage of an internal mechanism, protected from contamination and independent of seasonal or diurnal variations in energy source. They also harvest energy at a rate that depends on the train activity, which helps to match energy storage demand and supply (i.e., when the train is stationary, less energy is required).

The call text for this project asks for adaptation of already existing technologies for developing a purely on-board Train Integrity. Described below are adaptation of a vibration energy harvester that is already used in vehicle condition monitoring, and a displacement energy harvester that has been developed by a number of academic institutions for both rail and automotive applications.

2.1 Suspension-based Harvesters

Various design concepts and structures of regenerative suspensions have been proposed and investigated for the recovery of the energy from motion and vibration induced by road/track disturbances. Generally, the regenerative shock absorbers can be classified into three categories: hybrid, electromagnetic, and piezoelectric. Some typical designs have been identified and reviewed. The specific configurations of these systems and the estimated/tested energy output of each selected design is introduced individually in the following subsections.

2.1.1 Design #1 - hybrid shock absorber

A hybrid shock absorber system was designed by R. Wang et al. [1, 2] at University of Huddersfield, which converts vibration motion into rotary motion through the adjustment of hydraulic flow. A schematic of the designed regenerative shock absorber is shown in Figure 1; it mainly consists of a double-acting hydraulic cylinder, a hydraulic rectifier in the form of four check valves, a hydraulic accumulator, a hydraulic motor, a permanent magnetic generator, pipelines, and an oil tank. The hydraulic circuit is configured such that one way flow and energy regeneration can be achieved during both compression and expansion stroke. In the current test rig conceptual design, the end of the shock absorber is fixed to a stationary frame, and the piston rod is connected to a hydraulic actuator which provides oscillatory excitations to simulate travel over uneven roads.

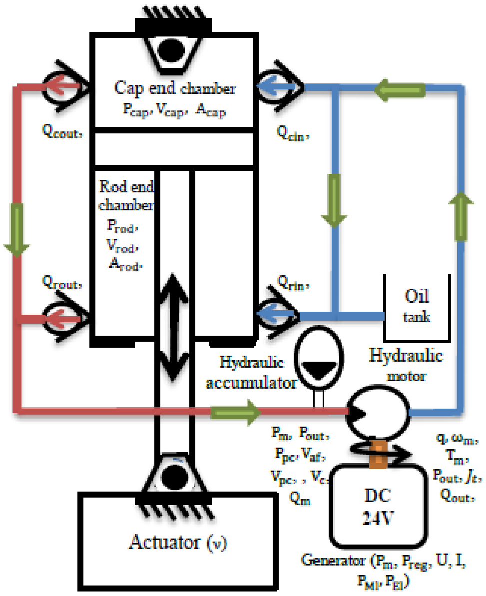


Figure 1 - Hybrid shock absorber system designed at University of Huddersfield [1]

Figure 2 shows the prototype and test bench of the designed hybrid shock absorber system. The hydraulic pressures within the test system were analysed using two pressure transducers mounted upstream of the accumulator port and the upstream of the hydraulic motor inlet. The shaft speed was measured with a U-shape micro photo sensor. An electronic load bank was adopted to vary the load and a voltage transducer measured the electrical output for analysis of power regeneration and conversion efficiency. A single sinusoidal wave was used to simulate the fundamental frequency of a road surface as the system input for both numerical modelling and testing. During the experimentation, one corner of a four-post servo-hydraulic ride simulator with a digital control was employed as the source of vibration to excite the shock absorber system. An average power of 118.2W and 201.7W with the total energy conversion efficiency of 26.86% and 18.49% were reported based on experiments under sinusoidal inputs with 0.07854m/s and 0.1256m/s respectively [2].

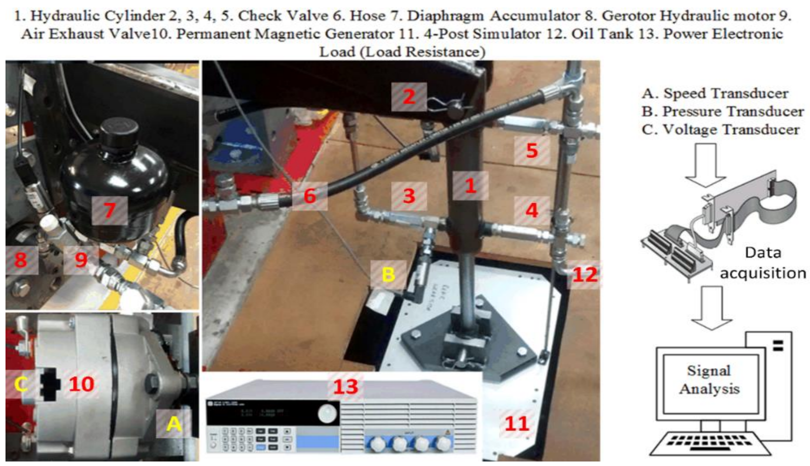
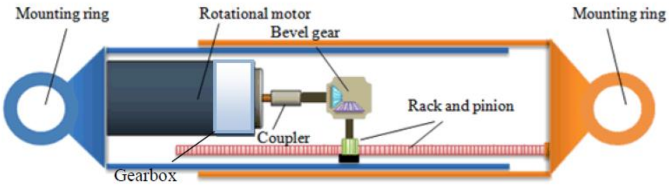


Figure 2 - Hybrid shock absorber prototype designed at University of Huddersfield [2]

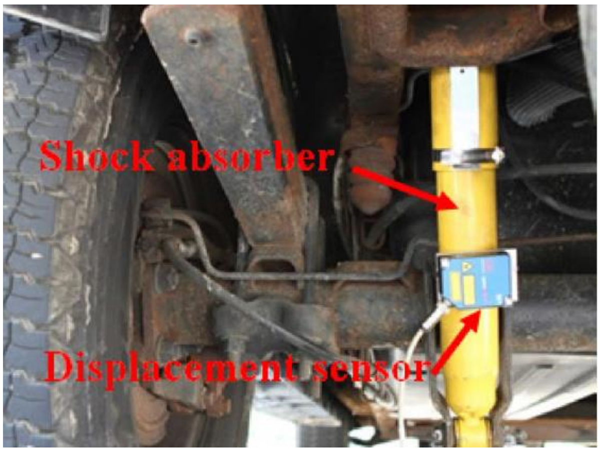
2.1.2 Design #2 - Electromagnetic shock absorber

A retrofit regenerative shock absorber was proposed by ZUO el al at State University of New York based on a permanent magnet rotary generator and a rack–pinion mechanism for the purposes of energy harvesting and vibration damping [3, 4]. It mainly consists of two cylindrical casings, on which two mounting rings were placed to mount the device to the vehicle chassis and the wheel. A rack and pinion mechanism was adopted to transform the linear vibration motion of the vehicle suspension to rotary motion of a pinion gear. The rotary motion is transmitted to a gearbox, which is used to increase the rotational speed of an electromagnetic motor which is connected as a generator to harvest electricity from the suspension vibration.



(a) Conceptual design

(b) Prototype



(c) Experiment setup for suspension vibration tests

Figure 3 - Retrofit regenerative shock absorber developed at State University of New York [3]

Road tests were undertaken using a Chevrolet Surburban SUV (2002 model), which were conducted on the campus road of Stony Brook University, Stony Brook, NY, at different speeds, including 48 and 32 km/h. It is shown that the peak voltages were over 40 V. Correspondingly, the peak powers are 67.5–58.2 W. The average power values are 4.8 and 3.3W, respectively, at 48 and 32 km/h (30 and 20 mi/h), if four shock absorbers were fitted, one to each wheel, 19.2 and 13.2 W can be harvested at 48 and 32 km/h (if the suspension and vibration characteristics of each wheel are similar). The estimated energy that the suspension system is expected to dissipate on a local road at 48km/h was 54.1W. The results from the road tests are encouraging, although detailed conclusions about the harvesting efficiency cannot be drawn from these tests since the suspension vibration highly depends on the road conditions [3].

2.1.3 Design #3 - Hybrid electromagnetic shock absorber

Researchers at Vishwakarma Institute of Technology India developed a hybrid electromagnetic shock absorber system for energy harvesting in the suspension of a vehicle [5]. It was reported as a novel technique to use fluid link for velocity amplification in an electromagnetic shock absorber. The conceptual design of the system is shown in the figure below. It comprises of fluid damper, amplifying cylinder, and linear generator. Fluid damper and amplification cylinder are connected to the un-sprung mass. Magnet and spacer assembly of the linear generator is carried by the sprung mass, whereas the armature copper coils move with the amplification cylinder piston. The fluid cylinder and amplification cylinder are connected by fluid pipelines. The fluid damper is designed to work as a reciprocating pump within a stroke length “$l1$” (as shown in the conceptual figure). During this stroke length, annular clearance in the damper cylinder does not offer any damping. However, damping is achieved due to fluid friction as the oil flows from fluid damper to the amplifying cylinder through connecting pipelines. For further displacement of the fluid damper piston, increased cylinder diameter ensures damping by throttling oil through annular clearance between the piston and cylinder.

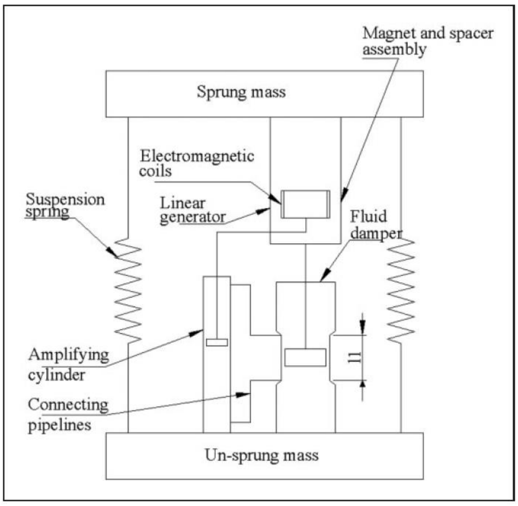


Figure 4 - Conceptual illustration of the hybrid electromagnetic shock absorber [5]

The hybrid electromagnetic shock absorber prototype is shown in the figure below. Experimentation was conducted in a two degree of freedom test setup, which could simulate quarter car model and comprised of the lower mass, un-sprung mass and sprung mass.

Experimentation has been performed on the prototype with vertical excitation velocities of 0.1–0.7 m/s and peak voltage of 0.60–24.2V was recorded. Comprehensive evaluation was discussed including the effect of electromagnetic force fraction on comfort and handling of the vehicle. The design of the real size version for implementation in a McPherson strut suspension was presented. Simulation results indicated that average power up to 50.56W can be recovered from a single shock absorber for the normal driving conditions [5].

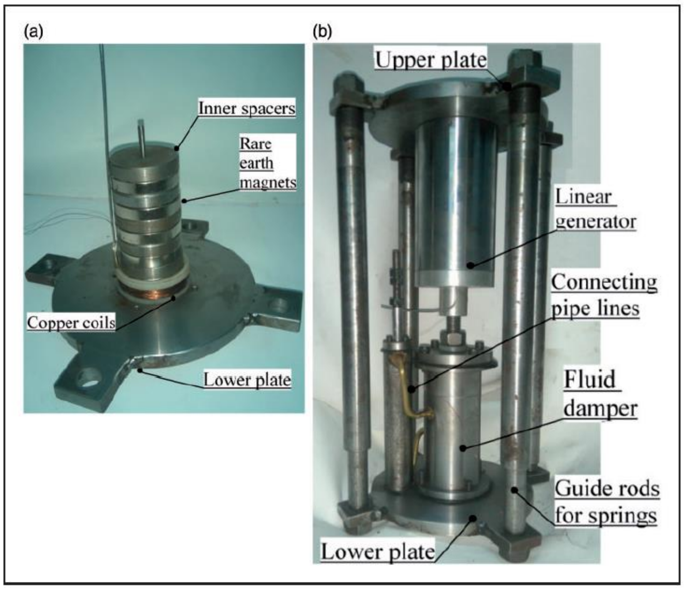


Figure 5 - Hybrid electromagnetic shock absorber prototype [5]

a) Linear generator subassembly; b) Prototype assembly

2.1.4 Design #4 - Electromagnetic shock absorber

Lei Zuo, et al designed a new type of mechanical-motion-rectifier-based energy-harvesting shock absorber using a ball-screw mechanism and two one-way clutches to replace the conventional oil dampers in vehicle suspensions [6]. The designed energy-harvesting shock absorber was able to work as a controllable shock absorber as well as an energy harvester. As shown in the figure below, it consists of three main parts: the ball screw, the enclosed mechanical motion rectifier (MMR) gearbox and the generator. The ball screw and nut were employed in back-driven mode, and the nut could move along the linear guide in the ball-screw case. Two eyelet connectors of the proposed shock absorber connected to the vehicle body and the wheel axle respectively.

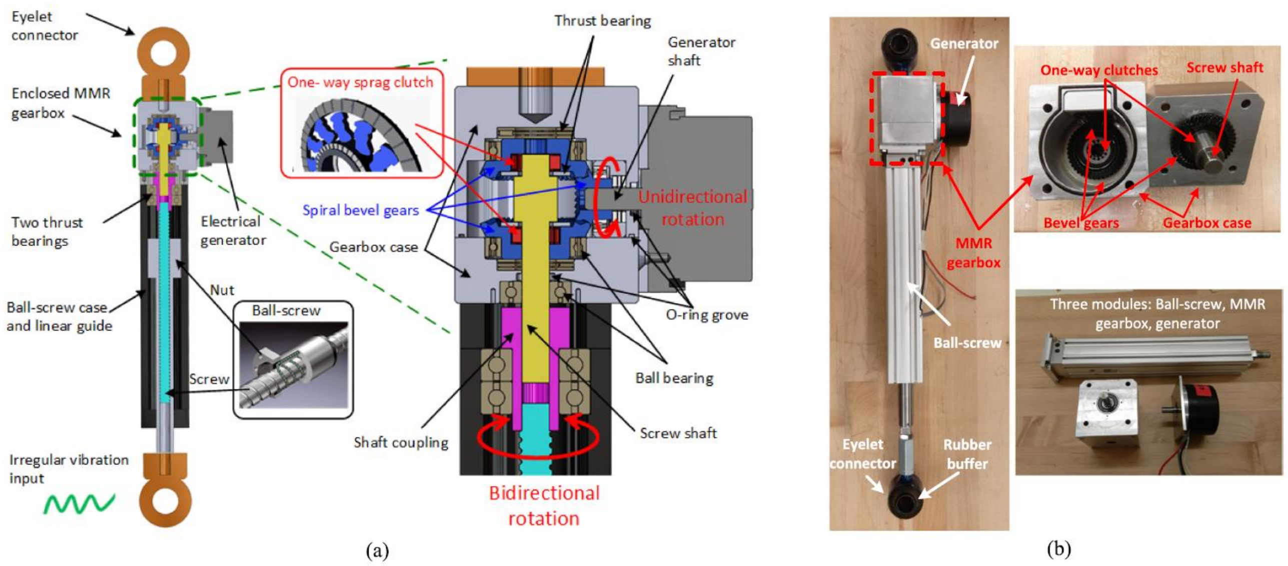


Figure 6 - MMR-based energy-harvesting shock absorber using a ball-screw mechanism [6]

Design drawing. b) Built prototype

The shock absorber prototype was tested on an Instron testing machine, which is shown in the Figure 7. A series of sinusoidal inputs, with frequencies ranging from 1 to 10 Hz and amplitudes ranging from ±0.5 to ±5 mm, were used to excite the shock absorber prototype during the tests. It was found that the equivalent damping increases from 4425 to 15 420 Ns/m as the electrical load changes from open loop to 3 Ω under harmonic excitations. The highest mechanical efficiency of 70.1% and the corresponding 51.9% energy harvesting efficiency were reported under 4 Hz harmonic vibration input with 3 Ω external electrical loads. Further field tests were carried out to validate the feasibility of the proposed energy-harvesting shock absorber, which is shown in Figure 7(b). It was reported that when the modified vehicle was driven on a paved road at 40 mph, the proposed energy-harvesting shock absorber was able to reduce the root-mean-square value of chassis acceleration by 11.12% over the oil shock absorber and simultaneously harvest an average power of 13.3W for a representative period of 8 s [6].

a)Experimental setup b)Field test setup

Figure 7 - MMR-based energy-harvesting shock absorber tests [6]

2.1.5 Design #5 - Piezoelectric Harvester on a car damper

B. Lafarge et al at University of Valenciennes and Hainaut-Cambresis France proposed a piezoelectric harvester on a car damper, which aimed at harvesting low power levels to supply wireless sensors embedded inside automotive suspension [7]. As shown in Figure 8, the proposed system uses piezoelectric element to convert ambient vibrations. The innovative bond graph model developed by the authors gave an estimation of power harvesting of around 0.5W, which was considered promising since around 100mW is sufficient to use new miniaturised microcontroller generation. The simulation results were presented only for two locations but could be easily extended for all locations. The numbers of piezoelectric devices could be extended to increase the capacity of energy harvesting.

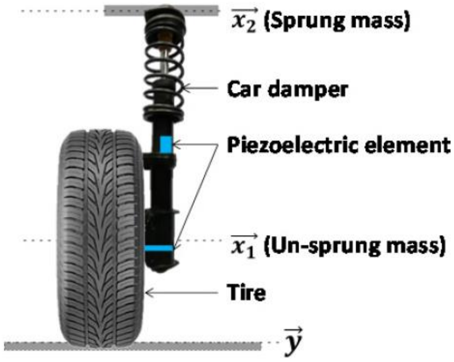


Figure 8 - Piezoelectric harvester design on a car damper [7]

2.1.6 Design #6 - Electromagnetic shock absorber

Gupta et al at Northern Illinois University proposed an electromagnetic (EM) shock absorber. The shock absorber consists of three assemblies: the permanent magnet assembly, the coil assembly, and the case assembly [8]. Voltage is induced in the shock absorber windings when the coil assembly moves relative to the magnet assemblies. The coil assembly consists of an inner coil surrounded concentrically by a larger diameter outer coil. Each coil consists of four continuously wound layers of #25 magnet wire with approximately 800 turns. The case assembly aligns and enables the piston-like motion between the coil and magnet assemblies. The designed EM shock absorber was tested on a 300 lb electrodynamic shaker, which is shown in Figure 9. The base of the shock absorber was supported from a stand and the moving rod was attached to a stinger through an impedance head. The shaker was run using sine dwell at certain frequencies. One end of the inner coil and one end of the outer coil were connected such that combined voltage can be measured. The other ends were connected with various resistances (0.1 Ω, 30 Ω, 50 Ω or open circuit).

Figure 9 - Experimental setup [8]

The EM shock absorber was excited at two different accelerations 0.5g and 1 g at frequencies ranging from 10 Hz to 100 Hz. The EM shock absorber was tested at 1 g level with a 33-ohm external resistance (close to optimum resistance) and results are shown in Table 1. The fabricated electromagnetic shock absorber was reported to perform as expected, while a larger magnetic field was suggested if more power needs to be generated.

Table 5 - Results for 33ohm external resistance

Frequency in Hz	Velocity in mm/sec	Displacement in mm	Voltage across 33 ohm in volt	Power Generated in watts
10	110.38	1.757	3.082	0.2878
11	100.35	1.452	2.276	0.1570
12	91.99	1.22	2.09	0.1324
15	73.59	0.781	1.47	0.0655
20	55.19	0.439	1.333	0.0538
30	36.79	0.195	0.883	0.0236
40	27.60	0.11	0.673	0.0137
50	22.08	0.07	0.553	0.0093
60	18.40	0.049	0.475	0.0068
70	15.77	0.036	0.417	0.0053
80	13.80	0.027	0.372	0.0042
90	12.26	0.022	0.34	0.0035
100	11.04	0.018	0.31	0.0029

2.2 Novel Concept of On-train Linear Generator

In this subsection the concept design of a new on-train energy harvester based on an electromagnetic linear generator is described, and the energy output estimated. The concept involves installing a linear generator in parallel with the primary suspension springs that is with one end attached to the axlebox and the other to the bogie frame, so that the primary suspension displacements when the train is running induce a relative displacement between the components of the linear generator. The stator and coils of the generator being attached to the bogie frame with the magnet within the coils free to move along the axis of the coils and attached to the axlebox so that displacement of the suspension causes relative displacement between the magnet and coils inducing current in the coils. The power output of the concept design has been estimated by calculating the energy output of the linear generator design when subjected to the same displacements as calculated for an example vehicle when running using vehicle dynamics.

2.2.1 Linear generator concept design

Figure 10 illustrates the concept showing a linear generator device installed across the primary suspension of a freight wagon bogie, extending and contracting along its long axis with the movements of the suspension in a similar manner to the installation of a damper, other arrangements of the linear generator (for example within the spring or on the end of the bogie instead of the side) are also possibilities.

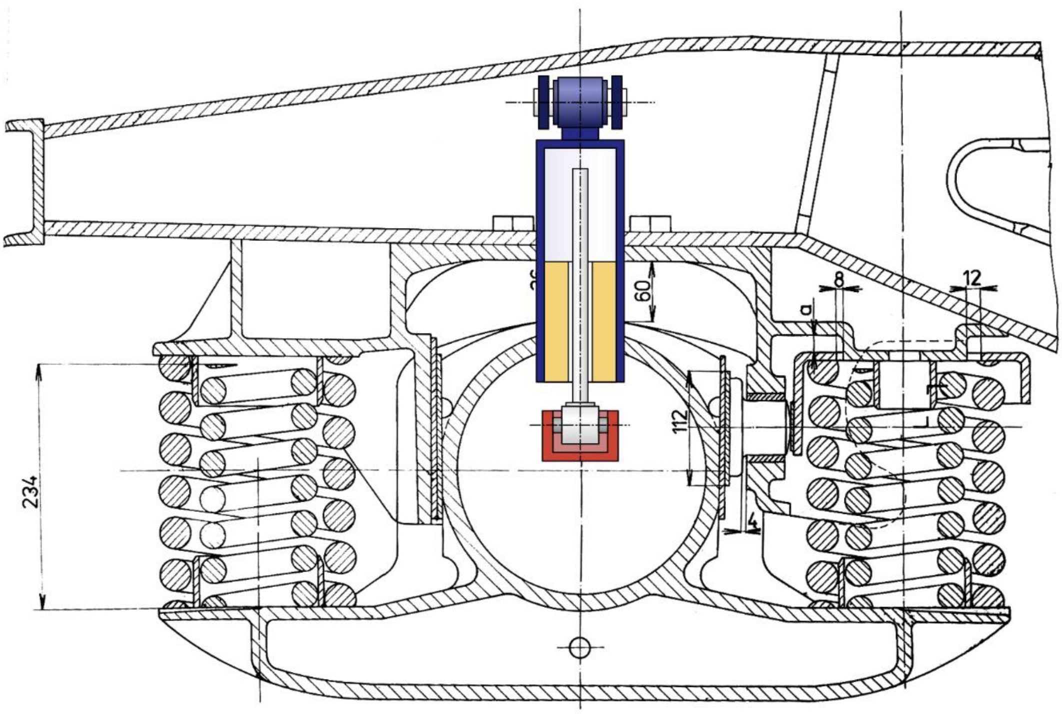
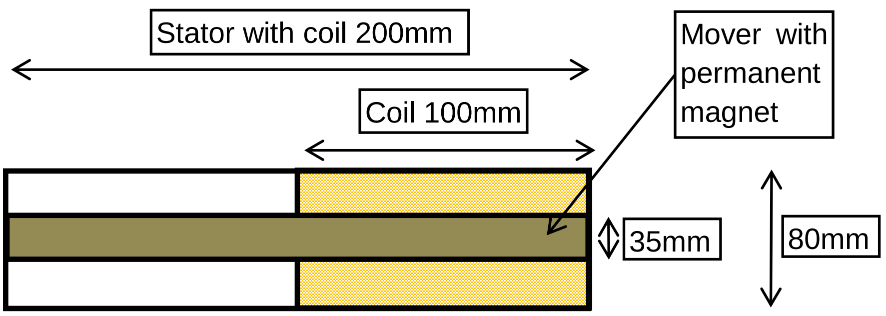
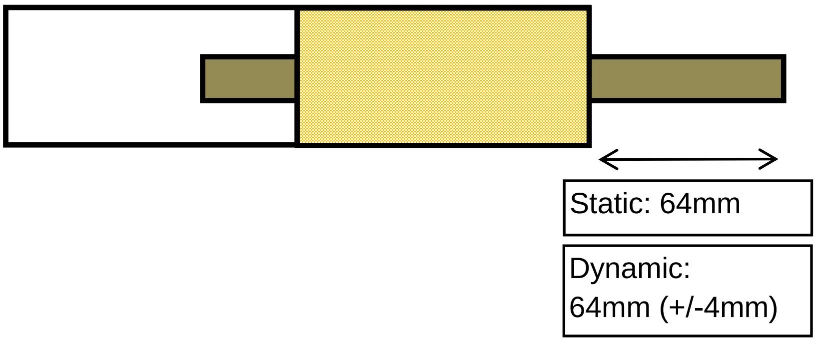


Figure 10 - Illustration of concept design of linear generator energy harvester installed across the primary suspension of a rail vehicle, between the axlebox and bogie frame.

The difference between the maximum extension and compression of the linear generator, i.e., the stroke, must be slightly greater than the extreme limits of suspension travel so that the device does not reach its limits of travel under these conditions. The limits of suspension travel are determined by the extension when the wagon/bogie is lifted with the wheels retained (if the wheel/axlebox retaining component is removed, so should the linear generator) or compressed to the physical limit of axlebox travel. For a Y25 bogie the limits of axlebox travel are 96mm, therefore the concept design explored here has a maximum stroke of 100mm, the design could be varied for different geometries, it will not travel the full stroke in normal operation, the large stroke is to take into account the extreme limits of suspension travel. In operation, harvesting energy whilst the train is running, the relative displacement of the linear generators will be a few millimetres either side of the static position for the current load state of the vehicle. The concept design for the length of the energy harvester device between the centres of the mounting holes at each end is 350mm at full extension and 250mm at full compression, and it is 100mm in diameter, this includes the housing and mounting points for the device. Within the housing of the device the dimensions of the linear generator components are shown in Table 6 along with representations of the arrangement of the linear generator at three different states, fully compressed, fully extended and at the extension in the static case for an example unloaded vehicle. Also shown on the example unloaded vehicle are the range of displacements calculated for the vehicle when running.

Table 6 - The different states of the linear generator duty cycle (dimensions and illustration of components' positions)

Duty cycle of the linear generator	State and components details
	Fully compressed state: Length 200mm
	Fully extended state: Length 300mm

	Static state when wagon empty: 64mm of extension (of full 100mm possible), 36mm of compression. Dynamic movement about this state, extension approximately 64mm +4mm and -4mm. Case modelled by vehicle dynamics.

2.2.2 Estimation of the linear generator power output

The estimation of the linear generator power output when the train is running was carried out in three phases. In the first phase the equations which describe the electrical power output of the linear generator, based on the physical characteristics of the generator and the relative motion of the components were expressed. In the second phase a vehicle dynamics model of a representative freight vehicle was used to calculate the suspension displacements and velocities for a wagon running along the track. In the third phase a linear generator system model was built in Matlab/SIMULINK in which the characteristics of the linear generator and the suspension displacement/velocity output from the vehicle dynamics model were entered into the equations which calculate the power output.

The following equations show how the electrical power output of the linear generator was calculated. The voltage across the generator, ε can be written as:

$$\varepsilon = Ri + L\frac{di}{dt} + C\int idt \qquad \text{(Equation 1)}$$

Where R is the resistance of the circuit; i is the current; L is the inductance of the circuit and C is the capacitance.

Assuming the load circuit is purely resistive ($C = 0,\ L = 0$), Faraday's electromagnetic induction laws give the back electromotive voltage ε as:

$$\varepsilon = N\frac{d\phi}{dt} = k_v\frac{dx}{dt} \qquad \text{(Equation 2)}$$

Where ϕ is the magnetic flux; N is the number of turns of the coil for the stator; k_v is the electromagnetic constant, which is determined by the design parameter of the permanent magnet mover; x is the displacement.

Then the electric power output of the linear electric generator is:

$$P_e = \frac{\varepsilon^2}{R_s + R_l} \qquad \text{(Equation 3)}$$

Where R_s is the internal resistance of the linear electric generator; R_l is the resistance of the external load.

The objective of the vehicle dynamics simulation was to obtain an output of vertical primary suspension displacements (variation in relative position between the axlebox and bogie frame) which represented a typical freight vehicle running along the track. The simulation was carried out using a commercial simulation package; the simulation represented an unloaded freight wagon with Y25 bogies running on a straight track at 80km/h. The initial results from the simulation output, which included the effects of the model transitioning from the initial static values to dynamic values based on the interaction of the vehicle with the track, were excluded. The variations in the nominally straight track alignment used in the simulation met the criteria to be classed as being of “good” track quality according to the UIC, therefore the simulation represented a freight vehicle running on well-maintained track. The speed selected for the simulation represents a speed near the higher end of the operational range of freight vehicles, and therefore the amplitudes and frequency of the suspension displacements would be near the higher end of the range that a freight vehicle would experience. This means that the amplitude and velocity of the displacements experienced by the linear generator, and therefore the power output, would be near the higher end of the range. Discrete disturbances in the track, such as at switches and crossings, or poor quality sections might increase the displacements and therefore the power output briefly, however the case modelled was chosen to represent the general case. That is the displacements and power output that could be expected from the linear generator concept design fitted to an unloaded freight wagon running for sustained periods of running on good quality track at a reasonable speed (80km/h). Figure 11 shows a sample of the relative suspension displacement and velocity results from the vehicle dynamics model which were applied to the linear generator system model.

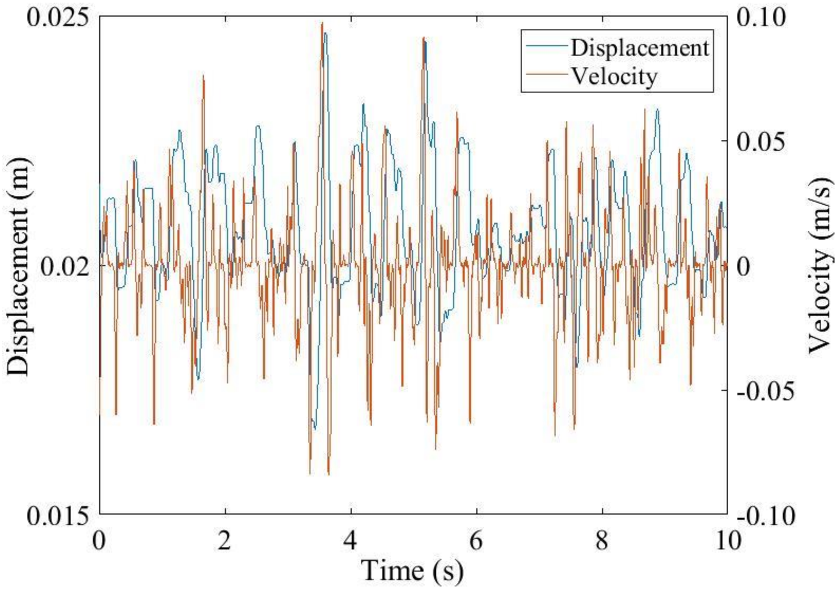


Figure 11 - Sample of suspension relative displacement and velocity (dynamics simulation result)

The linear generator system model used to estimate the power output of the linear generator concept design was developed in Matlab/SIMULINK, it mainly consisted of three parts:

- A parameter file to initialise parameters for the linear generator (the values of the parameters used being those of the concept design);
- Blocks to import the results of the suspension dynamics model, including displacement and velocity;
- A linear generator sub-system to simulate the power output of the linear generator.

A schematic representation of the linear generator system model is shown below.

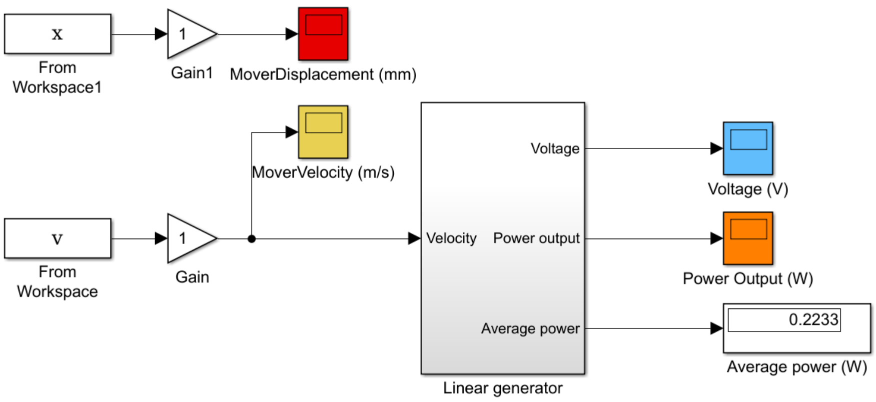


Figure 12 - Schematic representation of the Matlab/SIMULINK linear generator system model used to estimate the power output

The results of the linear generator system model for the inputs described are shown in Figure 13, with a summary of the results in Table 7. They represent the expected output from the concept design linear generator fitted to a Y25 bogie on an unloaded freight vehicle travelling at 80km/h on good track. The peak voltage is around 2.0V, and the peak power output could reach 4.0W, the average power output is 0.2W, which is the predicted sustained output for the conditions modelled. At lower speeds the power output would be expected to be less, and on poorer quality track (which would increase the excitement of the suspension) the power output would be expected to be higher, however in practice the speed at which a freight train would be travelling on poorer quality track might be lower.

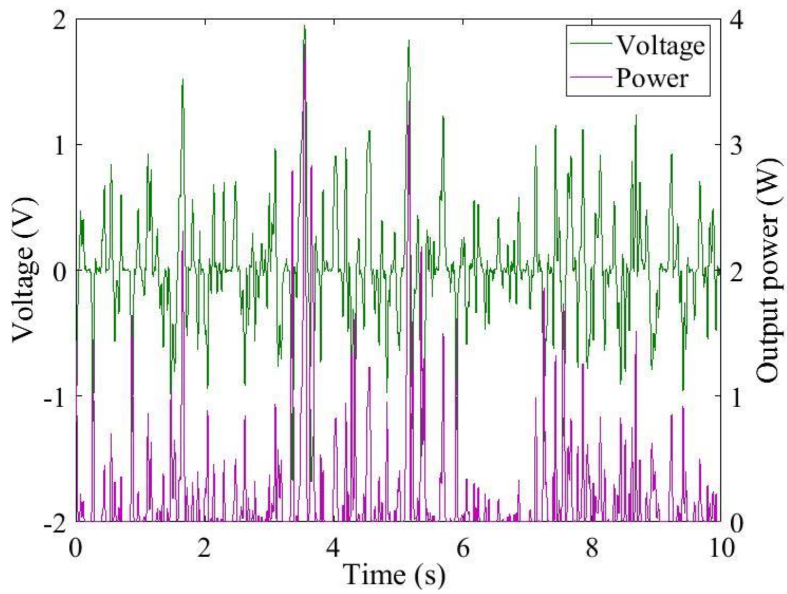


Figure 13 - Estimated voltage and power output for the on-train linear generator concept

Table 7 - Summary of results of linear generator system model for on-train linear generator concept design

Parameter	Value
Vibration amplitude	8 mm
Peak voltage	2.0 V
Peak power output	4.0 W
Average power output	0.2 W

2.2.3 Summary and analysis of linear generator concept design

The average power output of the linear generator concept design was predicted to be 0.2W for the conditions modelled. This is a useful amount of power in terms of powering low power consumption electronics. In the case modelled the vehicle was travelling at 80km/h on good quality track:

- At lower speeds the power output would be expected to be less.
- On poorer quality track (which would increase the excitement of the suspension) the power output would be expected to be higher; however, in practice the speed at which a freight train would be travelling on poorer quality track might be lower.
- When the vehicle is stationary there would be no power generation

The preceding points mean that the on-train linear generator energy harvester concept design would have to be connected to an energy storage module in order to provide continuous power to the connected devices. Also the average power output predicted was calculated for conditions which were generally favourable to energy harvesting for this concept (particularly the speed), therefore the average power output over an operating cycle of days, where the vehicle would spend time moving slower and stationary, would be much lower. Therefore, for the linear generator concept design and connected suitable (in terms of capacity) energy storage module to provide a reliable energy supply to a connected device, the average power consumption of that device over the same cycle would need to be much less than 0.2W.

Considerations relating to the viability of the on-train linear generator energy harvester concept design, other than power output, are the installation requirements and constraints, reliability, maintainability, cost, and other factors affecting life cycle costs of the device. Some of these include:

- The device would require special mounting points fitted to the bogie frame and the axlebox (or other suspension component rigidly connected to the axlebox), these would require modification of the vehicle, and the modifications would have to pass safety checks.

- The linear generator and the required housing and attachment points have mechanical elements which must be reliable, with a long service life and minimal maintenance requirements for the device to be cost effective.
- The concept design is at the very initial stages of development, whilst linear generators in general have been proven in other applications, in this application the concept and implementation have not been proven. Therefore, there is no field data to validate the predicted power output of the on-train linear generator energy harvester concept design.
    - This means that developing the concept further, carrying out further simulation and validation testing work within ETALON would expose the project to the risk that the device might not be capable of developing the predicted, or sufficient power output for the application. Also the integration of the device with a vehicle or vehicles for testing and validation, including satisfying relevant safety regulations, might be more work than is possible within the scope and resources of the project.
- Since the linear generator concept design is actuated by displacements in the vehicle suspension system, extensive vehicle dynamics simulation and possible verification testing would have to be carried out in order to establish the effect of the reaction forces of the linear generator on vehicle dynamics. It is possible that the damping effect of the linear generator might have a beneficial effect on vehicle dynamics, however it is not intended that the device would add a large resistance to suspension travel, the main requirement would be to establish whether the vehicle dynamics would be within safety limits regardless of the electrical load on the generator.

2.3 Solar PV Tracking Device

There are several solar powered tracking devices available, of which the Nexiot Globehopper (below) is one example. These are equipped with large rechargeable batteries, mobile data communications and GPS devices and are designed for independent operation from individual wagons. Adaptation of these devices would require addition of a rapid update rate (every 5 seconds) local wireless network to pass train integrity messages on from the end of the train to the locomotive. The challenge for these devices would be to ensure continued functioning over the winter in northern Europe, when low temperatures also impede efficiency of rechargeable batteries.

Figure 14 - Nexiot Solar Powered Tracking Device

http://nexiot.ch/globehopper

2.4 VIBRATION ENERGY HARVESTER USING SUSPENDED INERTIAL MASS AND ELECTROMAGNETIC GENERATION

The Perpetuum VEH exploits electromagnetic induction to convert vibration to electric potential. The device can be fixed directly to the bogie or axle box. Vibration of the fixture moves a coil through a magnetic field, which is held in place inertially by a resonant, sprung mass. Efficiencies above 80% are possible, with adequate power supply design. There is a direct relationship between energy harvested and the mass of the harvester, leading to a compromise between harvesting more power and safely fixing the device to a vehicle component that can experience shocks over 150G and persistent vibration around 10Grms. This can lead to very substantial bracket designs (one example shown below), which must also be easy to fit and minimise impact on normal wheelset maintenance functions.

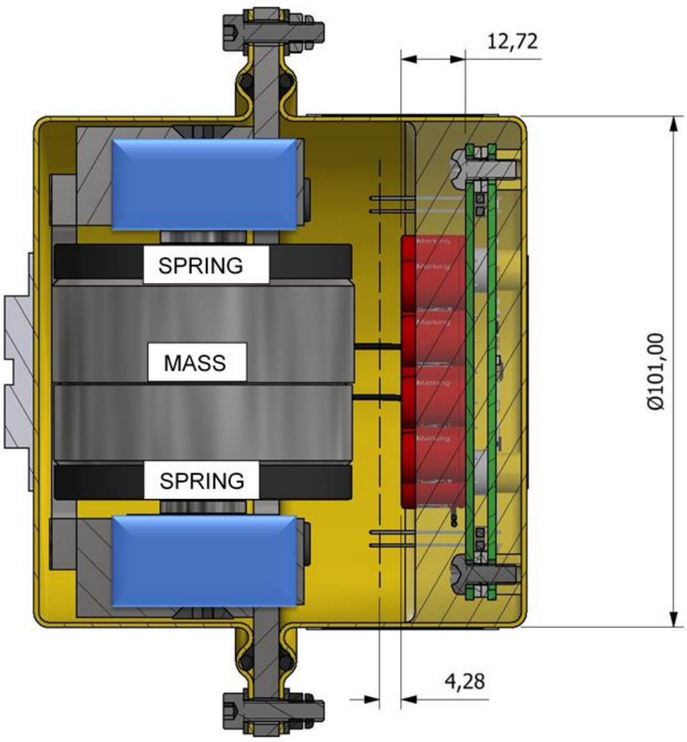


Figure 15 - VEH Example

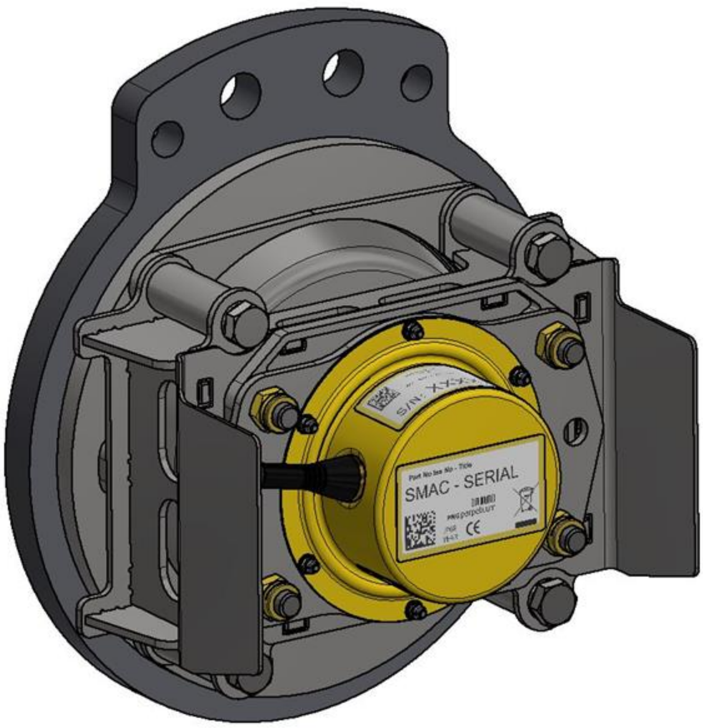


Figure 16 - Axle End Bracket Example - Note the impact protectors

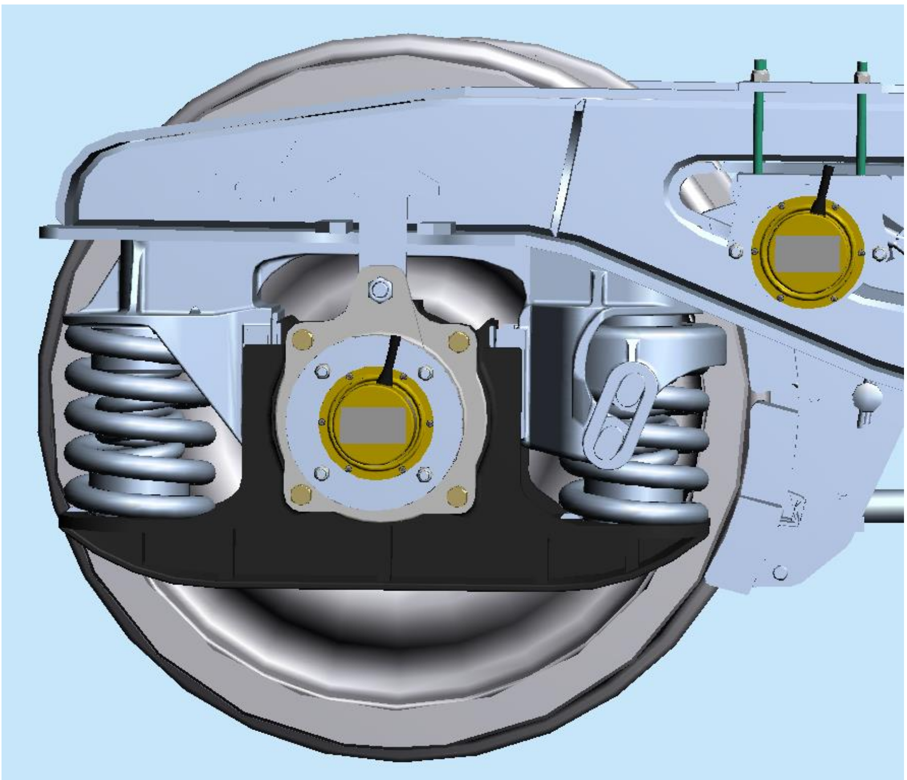


Figure 17 - Possible Mounting Options on the Axle Box and Bogie

Note that the bogie frame is considered a possible candidate for installation. Although this is not the optimal location for energy harvesting or sensitive detection of bearing faults, it should be possible to install the WSN in a location that does not interfere with wheelset maintenance operations. The rail freight industry is very cost sensitive, and an increase in service requirements adds to the economic barriers that need to be overcome for widespread installation of the system.

It is also noted, however, that vibration damping is only present between the bogie and wagon body, not at primary suspension, and although the vibration spectrum is shifted, overall energy available is very similar to the axle box.

3. ENERGY OUTPUT CALCULATIONS

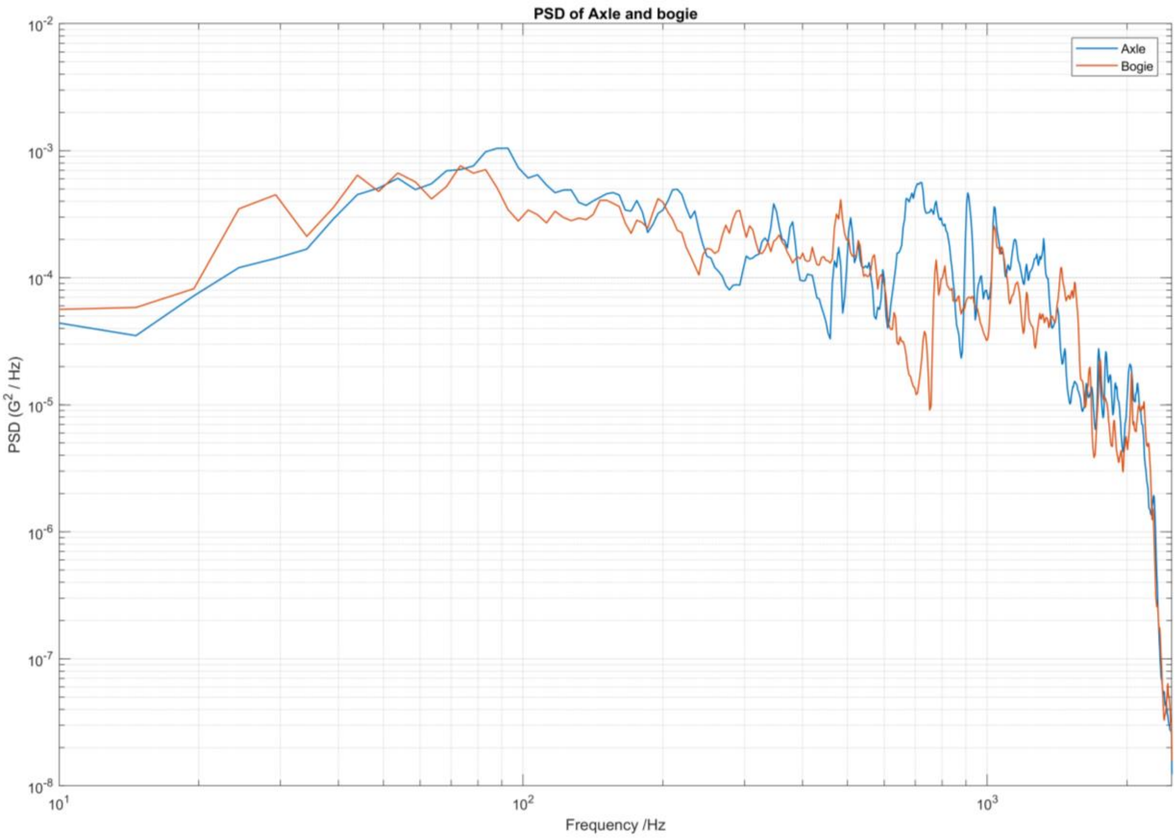


Figure 18 - ESZÜG (2016): Energieautarke Sensorsysteme zur Zustandsüberwachung am Güterwagen, Research project funded by Federal Ministry of Education and Research, 2016 (Dachuan Shi, TUB). PSD of Vibration Energy on a Y25 Freight Bogie.

When looking at the output of vibration energy harvesters, the most convenient and generally accurate method is to look at the energy density around the resonant frequency of the harvester mass. The response of the harvester is established by driving it at known vibration levels on a shaker. Vibration of the target is established by direct measurement with a datalogger of appropriate response, or by simulation. In Figure 18 (above, data measured by datalogger), it can be seen that at 60-70Hz, there is >>10^{-4} G^2/Hz of broadband vibration, which is sufficient to generate milliwatts of power.

Figure 19 is a plot of simulator output, showing similar levels (from the perspective of the VEH).

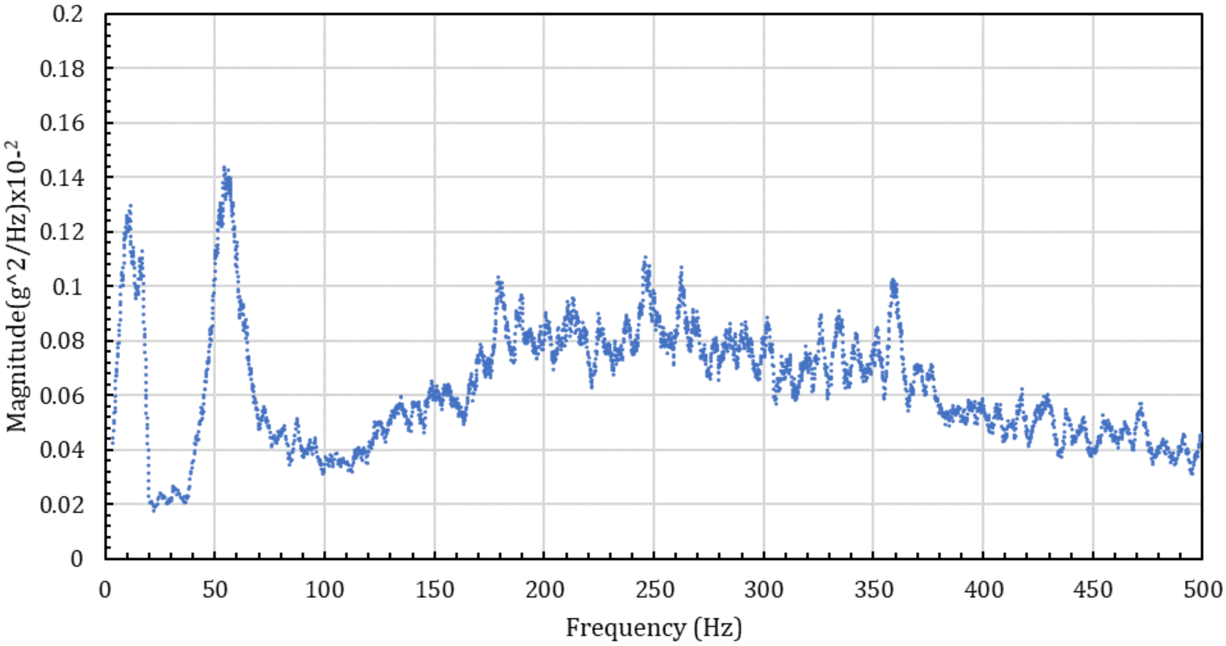


Figure 19 - PSD of vibration on the axlebox of a freight wagon (simulated, courtesy UNEW)

Table 8 - Table of VEH Outputs

Vibration Energy Harvester Summary Output Table for an installation size of 1kg		
Energy output from simulation data		Adjusted for runtime per day of 20% (Wh/day)
Location	Vertical (mW)	Vertical (Wh/day)
Axle box	23	0.12
Energy output from measured data (vertical vibration only)		
Location	Vertical (mW)	Wh/day
Axlebox	30	0.8
Bogie	30	0.8

3.1 Larger Harvesters For Slave OTI Additional Functions

Energy output from vibration energy harvesters depends on the inertial mass on the harvester. For powering an OTI slave module, a 5kg installation mass for a VEH on the bogie frame (this would be too much for an axle box mounted device) should have a peak output (at operational speeds) of approximately 200mW, which would be sufficient to power additional inertial and positional diagnostic functions in an OTI slave (although it could be argued that the already battery powered tail light would be a more secure location for these functions). Field testing on a freight bogie in WP5 will establish the actual possible limits of harvester power in the freight environment. Solar powered devices may also be suitable for this role.

4. ENERGY STORAGE OPTIONS

The choice of energy storage component is driven by a number of competing priorities and compromises. From the table below, it can be seen that there is no ideal energy storage device. For example, capacitors are low cost, low leakage and have a long lifetime but don't store very much energy. The highest energy density devices (rechargeable lithium batteries) are high cost, can have significant leakage and a poor lifetime.

Selection of an appropriate energy storage device must therefore take into account the maximum amount of energy that will be required to cover the intervals of low energy harvesting, the maximum charge and discharge rate, in-service lifetime (this may be strongly duty cycle and temperature dependent), cost and size (larger devices are more difficult to protect in high vibration environments). Table 9 - Comparison of Energy Storage Types below provides a subjective comparison of a selection of available devices.

Table 9 - Comparison of Energy Storage Types

Type	Energy density	Degradation mechanism	Charge/ Discharge capacity	Cost	Leakage	Duty cycle (full charge/discharge cycles)
Capacitor	Very Low	Electrolytic (drying)	High	Low	Low	High
Supercapacitor	Low	Electrolyte loss	High	High	High	Medium
Hybrid layer capacitor (HLC)	Medium	Electrode loss (20yrs)	Low	Very high	Very low	Medium
Lithium rechargeable	Very high	Charge/ discharge cycles	Medium	High	High	Low
NiMH rechargeable	High	Charge/discharge cycles	High	Low	Low	Low

Table 10 - Energy Storage Solutions – Energy Stored

Capacitors/J *Electrolytics, 16-10V discharge range, 20mF*	Super-capacitors/J *4.5 - 1V discharge range, 1F*	HLC (Tadiran)/J *3.7V, 155mAh*	Rechargeable lithium/J *3.7V, 2500mAh*	Rechargeable NiMH (AA)/J *1.2V, 2500mAh*
1.56	9.625	2064.6	33300	10800

As can be seen from the illustrations in section 1.3, a number of energy storage options are available for use in an OTI device. The selection of the appropriate device depends on the pattern of use of the vehicle, and the level of activity when the vehicle is stationary. If a high output harvester (such as the displacement harvester) is used, good performance can be achieved with low levels of activity and significant amounts of energy may be discarded if the vehicle is usually running. For a lower output device such as a VEH, more storage may be required, to avoid discarding energy when the train is running (since it takes longer to recharge).

5. DISCUSSION

Deliverables D2.2, D3.2 and D3.4, together with inputs from X2Rail-2 have set out a proposed model for power consumption by an OTI device, together with a pattern of usage that defines both the potential for energy harvesting and the requirement for energy storage. These energy sources and demands have been considered, and it has been shown that for vibration energy harvesting it is possible to power an OTI system that includes regular (every 5 seconds) communication, and vehicle to vehicle distance measurement (yet to be tested). The vehicle to vehicle distance measurement is proposed as a “per vehicle” train integrity sensor (more sensitive than simple radio integrity) and is able to identify the sequence of vehicles in the same train.

Other methods of reporting train integrity are possible, but due to the restrictions on available radio frequencies in Europe, a harvester powered communication link from one end of the train to the other is still required. In which case only the harvester and communication system described in this work would be necessary (in addition to the other OTI method).

Two types of vibration energy harvester are shown; the Perpetuum Vibration Energy Harvester, (currently deployed for bearing, track and wheel monitoring) and a displacement harvester technology which would be new to a production rail application (but has been tested in motor applications). The amount of development or adaptation work required for the displacement harvester is considered excessive with the scope of ETALON, and it has been decided not to pursue this further.

Assessment of the energy requirements for low power wireless communications and a method for detecting vehicle to vehicle separation (a possible method for OTI confirmation) show that with careful power management and typical good practice for wireless networks, good performance can be achieved with average power consumption well within the capabilities of a VEH mounted on the axle box or bogie frame. A displacement energy harvester mounted between the bogie and axlebox would also be capable of providing sufficient energy.

The rail freight industry is very cost sensitive, and due to the fragmentation of maintenance, operation and ownership activities the impact of adding operational cost saving devices at the expense of increased maintenance needs to be considered. This has been considered by X2Rail-2, and a requirement for the OTI device to provide other cost beneficial services has been stated. The impact of fitting, configuring and maintaining a VEH that is mounted on or near the wheelset should also be considered. Fitment of either the displacement harvester or the Perpetuum VEH should be considered in the impact on wheelset maintenance (exchange) operations.

6. CONCLUSIONS

Examination of the data rates and potential other activities required for OTI in the context of modern electronics and low power wireless technology shows that it is possible to implement the functions necessary within a 5mW energy budget (average, during in-service train hours). Comparison of this energy demand with a conservative estimate of energy output from a vibration energy harvester show that it is possible to meet this energy demand, although careful selection of energy storage technology is also needed for best performance.

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