SHM-Enriched High-Speed Rail Systems

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Outline

1. Why SHM needed for HSR?
2. Vision for rail-SHM systems
3. Sensory systems for rail application
4. Predictive modelling tools
5. Looking into the future
1. Why SHM needed for HSR (1)?

- The development of HSR in some countries is being tied to several grand issues such as:
  - Globalization;
  - Urbanization;
  - Carbon footprint;
  - Energy efficiency;
  - Regional economic/resource rebalancing.
1. Why SHM needed for HSR (2)?

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Reportable damage</th>
<th>Casualty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Count</td>
<td>Amount ($)</td>
<td>%</td>
</tr>
<tr>
<td>2010</td>
<td>1,337</td>
<td>214,484,420</td>
<td>80.9</td>
</tr>
<tr>
<td>2009</td>
<td>1,358</td>
<td>189,880,057</td>
<td>81.8</td>
</tr>
<tr>
<td>2008</td>
<td>1,772</td>
<td>238,981,334</td>
<td>76.6</td>
</tr>
<tr>
<td>2007</td>
<td>1,918</td>
<td>256,345,360</td>
<td>79.9</td>
</tr>
<tr>
<td>2006</td>
<td>2,171</td>
<td>264,995,385</td>
<td>79.3</td>
</tr>
<tr>
<td>2005</td>
<td>2,280</td>
<td>248,827,584</td>
<td>71.5</td>
</tr>
<tr>
<td>2004</td>
<td>2,367</td>
<td>257,669,474</td>
<td>76.6</td>
</tr>
<tr>
<td>2003</td>
<td>2,113</td>
<td>237,370,531</td>
<td>77.5</td>
</tr>
<tr>
<td>2002</td>
<td>1,989</td>
<td>210,325,825</td>
<td>76.2</td>
</tr>
<tr>
<td>2001</td>
<td>2,234</td>
<td>236,572,759</td>
<td>73.3</td>
</tr>
<tr>
<td>2000</td>
<td>2,112</td>
<td>214,656,118</td>
<td>77.2</td>
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<tr>
<td>1999</td>
<td>1,961</td>
<td>189,888,914</td>
<td>70.8</td>
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<tr>
<td>1998</td>
<td>1,757</td>
<td>189,797,985</td>
<td>76.4</td>
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<tr>
<td>1997</td>
<td>1,741</td>
<td>168,322,227</td>
<td>74.6</td>
</tr>
<tr>
<td>Total</td>
<td>27,110</td>
<td>3,118,117,973</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>1,936</td>
<td>222,722,712</td>
<td>76.5</td>
</tr>
</tbody>
</table>

1. Why SHM needed for HSR (3)?

(Failure analysis chart of on-board train protection devices based on a report by RTRI: M. Ogasa, 2015).
1. Why SHM needed for HSR (4)?

Evidence-based classification of faults in trains

<table>
<thead>
<tr>
<th>Control System</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traction control system</td>
<td>67%</td>
</tr>
<tr>
<td>Braking control system</td>
<td>1%</td>
</tr>
<tr>
<td>Operational control system</td>
<td>12%</td>
</tr>
<tr>
<td>Network control system</td>
<td>20%</td>
</tr>
</tbody>
</table>

Why SHM needed for HSR:

- Network control system: 20%
- Operational control system: 12%
- Traction control system: 67%
- Braking control system: 1%
1. Why SHM needed for HSR (5)?

- **Justifications:**
  - SHM systems provide **online** and **on-board** monitoring to enhance HSR’s safety and operational efficiency;
  - Incorporating SHM systems into HSR makes the sensors ‘**mobile**’ in collecting external effect and system response data when the instrumented train travels on railroads;
  - SHM systems with the aid of appropriate predictive modelling tools enable **prognosis of breakdown before it occurs**;
  - SHM systems enable the detection of **structural performance evolution** from micro-structural damage to macro-structural damage.
1. Why SHM needed for HSR (6)?

- **Requirements:**
  - The requirements on **fidelity, accuracy, adaptability and environment-tolerance** for the sensors used in HSR are almost the same as those in airplane application;
  - The operators of HSR hate any unstable sensors used in the existing ATO (Automatic Train Operation), ATP (Automatic Train Protection) and ATS (Automatic Train Supervision), which sometimes offer **false-positive alarming** and cease the running of trains;
  - SHM systems deployed on HSR should be greatly helpful in eliminating the **false-positive alarming** and unnecessary train stop caused by abnormal performance or malfunction of the inspection sensors in the existing ATO, ATP and ATS.
2. Vision for rail-SHM systems (1)

Features:

- Provide **online, in-operation monitoring** for all critical train components, track system and trackside objects (obstacles);
- Enable **cross-check of information from the signaling and control systems** so as to enhance the accuracy of fault detection and reduce false defect indications;
- Enable **real-time diagnosis of faults and timely prognosis of breakdown before it occurs**;
- Enable **prediction of degrading and deterioration in component level and estimation of remaining service life**;
- Help **make decisions** and implement remedy measures to prevent the occurrence of catastrophic failure.
3. Sensory systems for rail application (1)

- A Smart Railway System (SRS) based on fiber optic sensors has been developed by a joint team from HK Polytechnic University and MTR Corporation in HK (Tam, Ho, Liu, Lee) to monitor rail in real time.

![Diagram showing sensory systems for rail application](image)
3. Sensory systems for rail application (2)

Prototype of SRS and implementation on East Rail Line (since 2005)

Prototype of SRS

Hong Kong: East Rail Line
3. Sensory systems for rail application (3)

SRS – application in different countries

- **India**: rail clamp breakage, exploring for derailment prevention;
  - **Singapore**: metro – wheel rail interaction & third rail.

- **Australia**: Metro Transit, Cross Rail, and Spanish Railways;
  - **UK**: Network Rail – overhead line of the mainline railway network in England.

- **Hong Kong**: the entire railway network.

- **Australia**: NWRL – critical components;
  - **Netherlands**: Lloyds Railway – critical components, Axle Counting.

- **Turkey**: State Railway – wheel rail interaction.
3. Sensory systems for rail application (4)

- A PZT-based rail switch/turnout online monitoring system has been developed by Southwest Jiaotong University in collaboration with HK Polytechnic University.
An on-board instrumentation system has been developed by a joint team from HK Polytechnic University and Dalian Jiaotong University for rail vehicle condition monitoring of high-speed trains.
3. Sensory systems for rail application (6)

A joint team from HK Polytechnic University, Polish Academy of Sciences, AGH University of Science & Technology (Cheng, Su, Ostachowicz, Staszewski) is developing a nonlinear ultrasonic sensing system for online, in-operation monitoring of fatigue crack on bogies and wheel axles.
3. Sensory systems for rail application (7)

- A joint team from TNO (Netherlands Organization for Applied Scientific Research), HK Polytechnic University and Southwest Jiaotong University is developing a fiber optic based ultrasonic guided wave technique (with ultrasensitive interrogation system) for online monitoring of rail tracks.

Target Specifications:
- Sampling frequency: MHz to GHz;
- FBG bandwidth: About 0.1 nanometer;
- Detectable wavelength shift: 1 picometer (10^{-12} m);
- Multiplexing: > 10 FBGs for MHz sampling rate.

FBG data sampled in 1 MHz

100 times lower noise level
3. Sensory systems for rail application (8)

- Interconnectivity and trackside online monitoring:
  - Online monitoring of contact force between the pantograph and catenary. The monitored contact force can serve as feedback to an active control or variable stiffness system equipped to suppress excessive contact force fluctuation;
  - Fault detection of dampers in suspensions to prevent the failure caused by malfunction of the dampers;
  - Online or offline monitoring of rail axial stress of continuously welded rail as an indicator of track system’s condition;
  - Online monitoring of obstruction to early alert drivers to the presence of an obstacle or abnormality in the front of the running train;
  - Earthquake early warning system enabled by wireless sensor network.
How about the feasibility to develop PZT or piezoresistive skins, films, coatings, or patches for online and distributed monitoring of aerodynamic forces acting on four surfaces of an in-service high-speed rail vehicle?
Predictive modelling tools would be able to:

- harness the **highly heterogeneous data** (physical and non-physical data) acquired from different sensor types;
- cater for the **uncertainties** associated with changing operational and environmental conditions and stemming from measurement noise;
- identify **false positives** resulting from sensor fault;
- formulate **data-driven models** for defect diagnosis; and
- develop **evolutionarily updatable models** for prognosis of breakdown before its occurrence and prediction of structural and system deterioration/degrading over time or mileage.
4. Predictive modelling tools (2)

Predictive modelling tools in a Bayesian framework

- The **Bayesian modelling approach** is straightforward and powerful in dealing with the heterogeneous and uncertain monitoring data;

- The **Bayesian updating and inference approaches** are perfect in formulating models for successive evaluation and updating the models with progressively cumulated monitoring data;

- The **Bayesian source separation technique**, which enables blind source separation from noisy and nonstationary signals, would be competent to identify a specific subsystem with fault and discriminate between true defect and false-positive;

- The **Bayesian forecasting and dynamic modelling method** is feasible for the development of time-dependent evolutionary models purposed for prognosis of possible breakdown upon minor symptom and prediction of degrading or deterioration in component or system level.
5. Looking into the Future (1)

1. The SHM-enriched smart railway system is more than providing merits to the existing HSR. Capitalizing on the living laboratory of HSR networks, the ‘mobile’ sensors which move on vasty railroads provide the most authentic and comprehensive data to facilitate optimal design of the next-generation HSR;

2. If looking ahead, a more imaginative step forward is to blend climatic- and environmental-related sensors into this global-mobile-enabled sensing environment, collecting spatio-temporal data for the research of grand issues such as global sustainability, energy efficiency, carbon footprint and climate change.
Two postboxes in Taipei, Taiwan become cute when being damaged during Typhoon Soudelor on August 8th, 2015.

For most of us, it is enjoyable to work with recognizing a new pattern.