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Railway Energy Efficiency through Monitoring, Optimization and Innovation

Dr Clive Roberts Director of Railway Research Birmingham Centre for Railway Research and Education

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Presentation Overview



- Birmingham Centre for Railway Research and Education
- Railway Energy Simulation
- Optimisation Methods
- New Approaches to Railway Traction
- Hybrid Traction System Integration Laboratory
- Condition Monitoring
- □ Conclusions

University of Birmingham



- □ Founded in 1900
- 26,000 postgraduate and undergraduate students
- □ Placed 5th in the UK for quality of research
- One of only 11 UK institutions listed in the top 100 universities of the world
- Five Nobel Prize winners among staff and alumni
- □ Railway research since 1968





Birmingham Centre for Railway Research and Education



- Currently covers research interests in the schools of:
 - Electronic, Electrical and Computer Engineering
 - Civil Engineering
 - Metallurgy and Materials
 - Mechanical Engineering
 - Computer Science
 - Geography



Birmingham Centre for Railway Research and Education



- Director Professor Chris Baker (Civil)
 - Group income of £1.6 million/year
 - 10 Academic Staff
- □ Director of Research Dr Clive Roberts (EECE)
 - 22 Research Staff
 - 20 PhD Students
 - 2 Support Staff
- Director of Education Assoc. Prof. Felix Schmid (Civil)
 - ~70 Postgraduate Students
 - 2 Support Staff



MSc in Railway Systems Engineering and Integration



Railway Operations and Management
 Mechanical Aspects of Railway Systems
 Fundamentals of Railway Traction Systems
 Systems Engineering and Dependability
 Track Design and Infrastructure Systems
 Signalling and Train Control Systems
 Railway Strategy and Economics
 Human Factors and Ergonomics





Railway Research UK (RRUK)



- Centre of Excellence in Railway Systems Research
- Collaboration between 8 universities
- □ £7m funding from UK government research agency
- Led jointly by Birmingham and Southampton Universities, with:
 - Loughborough University
 - University of Leeds
 - Imperial College London
 - Manchester Metropolitan University
 - University of Nottingham
 - University of Newcastle



Railway Research UK

Rail Research UK



- University of Birmingham condition monitoring, systems engineering, energy, traffic management, geotechnics, aerodynamics, metallurgy
- □ <u>University of Leeds</u> transport economics
- Imperial College London metal fatigue, novel technologies
- Loughborough University mechatronics
- Manchester Metropolitan University vehicle dynamics
- □ <u>University of Newcastle</u> metallurgy, safety, policy
- University of Nottingham human factors
- University of Southampton geotechnics, noise and vibration, policy and regulation
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University of Birmingham Research Areas



- Aerodynamics
- □ Asset management
- □ <u>Condition monitoring</u>*
- Environment
- Geotechnical engineering
- Materials and metallurgy
- Modelling and computation



- □ <u>Network capacity</u>
- □ <u>Non-destructive testing</u>
- Power and traction *
- □ Risk and safety
- Signalling and train control
- □ Systems engineering *
 - The University's research programme contributes to improving Britain's railways now and into the future.
 - Dr Jeff Allan, Rail Safety and Standards Board



Key Research Partners



Collaborators and Funders

 Network Rail, Grant Rail, Serco, SNCF, Deutsche Bahn (DB), Siemens, Alstom, Bombardier, Arup, Atkins, DeltaRail, Corus, Voelst Alpine, UNIFE, UIC, Railway Safety and Standards Board, Department for Transport, EPSRC, European Commission.



Overview of Energy Research at Birmingham



- □ At Birmingham we are considering the following issues:
 - Energy consumption of new rolling stock (diesel and electric)
 - Energy consumption and practicalities of new traction technologies
 - Hybrid trains (diesel hybrids, onboard storage for electric...)
 - Hydrogen trains
 - Power system requirements for new metro systems
 - Consideration of train trajectories (energy/time trade-off)
 - Optimisation of train system movements
 - Headway regulation (train control)
 - System wide optimisation for energy efficiency
 - Driving style improvements (driver support)
 - Energy monitoring



Current Projects in Power and traction



- Department for Transport Calculation of Energy Consumption
 - Phase 1 Intercity Express Project (IEP)
 - Phase 2 DMU (Class 150 and Pacer replacement)
- □ Department for Transport Discontinuous electrification
- Department for Transport Novel train propulsion
- Mersey Rail Evaluation of Energy Saving Strategies (inc. driver variance)
- EC Environmental Management Tools for Infrastructure Managers (InfraGuider)
- □ Atkins Multi-train Simulator Development
- □ KTP (Atkins) AC railway power network simulator
- □ *PhD Student* Improving Regenerative Braking Systems
- □ *PhD Student* Optimised Supervisory Control for Hybrid Rail Vehicles
- □ *PhD Student* Cost modelling for future propulsion systems
- □ *MPhil Student* Measurement and monitoring of battery systems





Motivation for Railway Energy Research



Energy accounts on average for around 15% of the operational costs for railway companies, and it is growing

In 5 years the cost of energy for SNCB (Belgium Train Operator) grew by 30%

Nowadays, the energy costs during the life cycle of a train in the UK is almost as much as the original investment costs



Fuel Consumption in UK railways

| | | <u> </u> | | | | |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Diesel | Electric | Total | Diesel | | Electric | |
| | | | | Vehicle | | Vehicle |
| (kWh) | (kWh) | (kWh) | Unit KM | KM | Unit KM | KM |
| (Million) |
| 4,450 | 2,763 | 7,213 | 250 | 847 | 298 | 1,334 |

□ 45% of vehicle km are diesel powered

Electricity can be produced with significantly reduced CO2 through nuclear power, renewable energy (wind, solar, hydroelectric), coal carbon capture





University of Birmingham Train

Simulators

University of Birmingham MTS (with Atkins)

- Full power system simulation
- Multi-train operation
- Configurable to specific applications/outputs
- Used by Hong Kong Metro, London Underground, Singapore Metro, Docklands Light Railway

University of Birmingham STS

- Matlab based
- Simple to configure
- Quick simulation time for optimisation processes
- Extremely modular and able to deal with a range of traction systems
- Used by UK Department for Transport, Singapore Metro







Hybrid Trains



1. Capture and reuse of braking energy
2. Able to operate prime mover at optimum efficiency

Hybridisation degree is dependent on the type of duty cycle

- High speed no downsizing but energy saving
- Sub-urban moderate downsizing possible
- Shunting loco significant downsizing possible













Official Report for UK Government

HST hybrid – 8-16% saving (depending on route)
 DMU saving – up to 26% saving (depending on route)

See for full reports <u>http://www.railway.bham.ac.uk/documents/Hybird_concept_final_5.pdf</u>

<u>http://www.railway.bham.ac.uk/documents/Hybrid_Ra</u> <u>il_Report_DMU_V1.pdf</u>

Train Control and Scheduling Energy Efficiencies

□ Initially single train trajectory optimisation

- Increasing the opportunity for reuse of regenerative energy by making adjustments in the timetable
- Can be considered at both the timetable design stage and dynamically
- In DC electrification areas, consideration of system receptivity improvements

Train Trajectory Solution Space Non-linear system optimisation Driver 'input' can only be acceleration, coasting or deceleration



Single Train Simulation



□ Input

- Coasting rate, K_v
- Motoring rate, K_f
- Braking rate, K_{br}

Output

- Journey time, T_{run}
- Energy consumption, E
- Train trajectory



- Fuzzy functions provides a non-binary assessment of a particular solution
- □ Fuzzy functions can be designed to suit a railway's KPIs



Train Trajectory Optimisation

Case study for: 6km section; $\omega_{\rm E}$ =0.5; $\omega_{\rm T}$ =0.5

| Solutions reasine space. | Solutions | feasible | space: |
|--------------------------|-----------|----------|--------|
|--------------------------|-----------|----------|--------|

| Inputs | | | Outputs | | Ranking | | |
|----------------|------------------|-----------------|-------------------|---------------------------|----------------------|------|--|
| K _v | K_{f} | K _{br} | <i>E</i> , kWh | T _{run} , min | $\mu(E,T_{\rm run})$ | Rank | |
| 0.86 | 1 | 0.85 | 36.13 | 6.50 | 0.8626 | 1 | |
| 0.87 | 0.85 | 1 | 36.95 | 6.50 | 0.8141 | 2 | |
| 0.92 | 0.75 | 0.8 | 36.84 | 6.57 | 0.7972 | 3 | |
| 0.98 | 0.75 | 0.7 | 37.82 | 6.53 | 0.7623 | 4 | |
| 0.89 | 0.85 | 0.5 | 35.94 | 6.73 | 0.7361 | 5 | |
| 1 | 1 | 1 | 42.48 | 6.03 | 0.0000 | n/a | |



Simulated Train Trajectories



-> Train trajectory for fastest journey
6 min 2 sec
42.48 kWh

->Train trajectory for energy efficient solution 6 min 30 sec 36.13 kWh UNIVERSITYOF BIRM34NGHAM

Energy Saving Opportunities

System Receptivity Improvements

- Building on train trajectory optimisation
- Increasing the opportunity for reuse of regenerative energy by making adjustments in the timetable
- Can be considered at both the timetable design stage and dynamically
- For optimum results a number of trains must be considered resulting in a high level of data interchange

System Receptivity Improvements

- Simulation between 6.25-7.30am
- □ Maximum net energy saving up to 30%

Case studies: 1: train trajectories for fastest journey 2: optimised train trajectories with highest rank 3: timetable changed for better reus

3: timetable changed for better reuse of regenerative energy

4: train trajectories with 10% journey time increase

| | Case 1 | Case 2 | Case 3 | Case 4 | |
|---------------------|--------|--------|--------|--------|-------|
| Total energy | 405.8 | 325.1 | 305.4 | 283.7 | |
| Consumption (kWh) | | | | | |
| Energy saving | 0% | 19.9% | 24.7% | 30.0% | UNIVE |
| Energy saving (kWh) | 0 | 80.7 | 100.4 | 122.1 | BIRM |

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Hybrid Traction Laboratory

- Battery Cycler
 - Dynamic cycle simulation
 - Voltage: 8 VDC ~ 420 VDC
 - Current: -640 ADC ~ +530 ADC
 - Power: -170 kW ~ +125 kW

Dynamometer Rig

- Dynamic Load Simulation
- Power (+/- 110 kW)
- Torque (<700 Nm)
- Speed (<3000 rpm)







Current Projects in Systems Engineering



- □ EC Integrated Railway Data Management (InteGRail)
- EC Innovative track technologies (InnoTrack)
- EC Safer European Level Crossing Assessments and Technology (SELCAT)
- EPSRC (RRUK) Cost Modelling New Railway Technology (with Leeds and Imperial)
- Network Rail Thameslink and CrossRail Train Control
- □ Network Rail Railway Capacity Metrics
- □ *PhD Students* Dynamic Re-scheduling of Trains
- PhD Student Safety Critical Design Processes using Constraint Satisfaction (with TRW Conekt)
- PhD Student Benefits of Adopting Systems Integration Approaches in Rail Projects





Distributed railway traffic control

- The physical railway infrastructure need not be changed
- Each junction or station can be an intelligent "agent" in the software environment for real-time train traffic control (making decision individually)
- A group of "agents" can work together for collaborative rescheduling (multi-agent)
- Coordination mechanisms / rules among agents must be developed



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To build or not to build a flyover?



Bishton flyover: photo by Jamie Squibbs (http://jamie7354.fotopic.net/)

NAMES OF TAXABLE PARTY.

Neubaustrecke Mannheim-Stuttgart



Result analysis



Comparison of total cost of delay for a representative scenario (No. 40)



A flat junction with a better junction control strategy can be more economical than a flyover using the FCFS strategy

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Current Projects in Remote Condition Monitoring



- EC Innovative track technologies (InnoTrack)
- EPSRC (RRUK) Condition monitoring of vehicle/track (with Loughborough and Southampton)
- □ Network Rail Intelligent infrastructure
- Network Rail TI21 track circuit monitoring
- Network Rail Test and Simulation to Understand Conductor Shoe Dynamics
- □ Network Rail Intelligent Infrastructure data analysis
- PhD Student DC power system monitoring
- PhD Student Hybrid qualitative/quantitative monitoring algorithms
- PhD Student Fault detection and diagnosis of pneumatic railway assets







Railway Industry

- Two main subsystems:
 - Infrastructure
 - Signalling, Electricity Supply, Track, Substructure...
 - Parallels with highways, power and water
 - Rolling stock
 - Traction motors, Bogies, Doors, Air Con...
 - Parallels with aerospace and automotive



Rail Research Ūk

- There are a large number of simple, distributed assets used in the railway industry which are critical to successful movement of trains (e.g. point machines)
- There are many different designs, operating in varying environmental conditions



Rail Research UK Points Monitoring Current Practice

- Acquires both analogue and digital signals
- Includes hardware and data anaylsis
- Currently requires data signatures to be interpreted by an expert user on a daily basis in order to pre-empt a failure
- Limited success with many false alarms and missed faults

| Trackwatch POINTS OVERVIEW 1: Parks Bridge | | | | | | | | | | | | | | | | | | |
|--|----------------|------------------------|------------------------|---------------------------|------------------------------|--------------------------------|---------------------------|------------------------------|--------------------------------|-----------------------|--------------------------|----------------------------|-----------------------|--------------------------|----------------------------|--------------|-----------|--------|
| Point End | Time (Secs) | High Time (Secs) | H.H. Time (Secs) | Ave. Current (Amps) | H. Ave. Current (Amps) | H.H. Ave. Current (Amps) | Peak Current (Amps) | H. Peak Current (Amps) | H.H. Peak Current (Amps) | Ave. Force (KN) | H. Ave. Force (KN) | H.H. Ave. Force (KN) | Peak Force (KN) | H. Peak Force (KN) | H.H. Peak Force (KN) | No of Ops | Profile | Trend |
| NR 857A | 1.66 | 2.40 | 3.90 | 3.43 | 4.00 | 5.00 | 19.74 | 20.00 | 20.00 | 2.695 | 3.2 | 3.5 | 7.423 | 9.0 | 10.0 | 8788 | Drofilo | Trend |
| RN 857A | 1.63 | 2.40 | 3.90 | 2.95 | 4.50 | 5.50 | 19.73 | 20.00 | 13.25 | 1.286 | 3.7 | 3.8 | 5.311 | 9.9 | 10.0 | 8780 | Profile | riena |
| NR 857B | 1.89 | 2.50 | 3.25 | 3.57 | 4.50 | 5.50 | 20.00 | 20.00 | 17.00 | 2.470 | 3.0 | 3.5 | 4.982 | 8.0 | 10.0 | 8782 | Duefile | Trand |
| RN 857B | 1.84 | 2.25 | 2.80 | 3.52 | 4.50 | 5.50 | 20.00 | 20.00 | 13.00 | -0.434 | 2.5 | 3.5 | 1.906 | 8.0 | 10.0 | 8774 | Profile | rrena |
| NR 858 | 3.46 | 3.75 | 4.50 | 4.64 | 4.50 | 5.00 | 12.54 | 13.00 | 13.00 | -2.258 | 2.5 | 3.5 | -0.193 | 8.0 | 10.0 | 5219 | Ductile | Trand |
| RN 858 | 3.15 | 3.25 | 4.25 | 4.33 | 4.25 | 5.25 | 12.27 | 13.00 | 13.00 | 2.394 | 3.1 | 3.5 | 3.698 | 8.0 | 10.0 | 5219 | 9 Profile | Trend |
| NR 859 | 3.01 | 3.60 | 4.25 | 4.21 | 5.00 | 5.25 | 13.11 | 14.00 | 14.00 | 1.066 | 2.5 | 3.5 | 3.554 | 9.5 | 10.0 | 6708 | Drofilo | T |
| RN 859 | 2.59 | 3.10 | 4.00 | 5.82 | 4.90 | 6.50 | 18.26 | 19.50 | 20.00 | -1.166 | 2.5 | 3.5 | 0.954 | 8.0 | 10.0 | 6693 | Profile | Trep() |

Practical Point Condition Monitoring

- Research at the University has focussed on distributed instrumentation, sensor selection, algorithm development and cost benefit
- Future work will consider data visualisation and human factors





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Practical Point Monitoring

- Features of the throw are observed
- All instances of the same type of point machine (asset) will perform differently
- Features relate to an intuitive understanding of the operation of the asset





Simple fault detection & Marid Research UK diagnosis

- The characteristics of a particular feature can be seen to change
- The position, consistency and magnitude provide diagnosis
- Symptoms will be similar for all assets of the same type







Rail Research UK More sophisticated fault diagnosis



- We are now using a qualitative trend analysis technique
- We have found this works with many different asset



Outputs from Siemens machine



0: no fault
1: LH tight lock
2: LH loose lock
3: RH tight lock
4: RH loose lock
5: fulcrum point

Direction: Right to left

DB BAHN





Potter's Bar (UK) May 2002

Grayrigg (UK) February 2007



Track Circuits

- Track circuits form part of the train control system
- Each railway has many thousand circuits



Rail Research UK Track Circuit Right Side Failure

| Failure | Failure Mode | Failure Rate/Year | | | | |
|---------------|-------------------------------|-------------------|--|--|--|--|
| Track circuit | IBJ insulation failure | 0.0856 | | | | |
| erroneously | Receiver failure | 0.0635 | | | | |
| occupied | Ballast low resistance | 0.0468 | | | | |
| 1 | Transmitter failure | 0.0419 | | | | |
| | Track tuning unit failure | 0.0269 | | | | |
| | Bonding failure at rail joint | 0.0241 | | | | |
| | Impedance bond failure | 0.0241 | | | | |
| | Loose/broken side leads | 0.0197 | | | | |
| | Broken rail | 0.00844 | | | | |
| | Power supply unit failure | 0.00675 | | | | |



Rail Research UK Track Circuit Wrong Side Failure

| Failure | Failure Mode | Failure Rate/Year |
|--|--|-------------------|
| Track circuit | Receiver failure | 0.00857 |
| erroneously | Relay fails closed circuit | 0.00016 |
| clear | Train shunt high resistance | 0.0000333 |
| | Interference from adjacent instrumentation | 0.0000324 |
| Track circuit intermittently shows section | Train shunt high resistance | 0.0000333 |
| clear when train moving along the track | Poor contact between train shunt and rails | ? |



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Track circuit condition monitoring

 Using a model based approach for condition monitoring, transmitter, receiver, termination bond, track (ballast) and shunt faults can be detected and diagnosed.

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Vehicles monitoring infrastructure

- Using bogie mounted instrumentation we are able to assess:
 - Track geometry from in-service vehicles
 - Third rail position
 - Switch and crossing health
- The challenge is to move this technology off of dedicated trains, for in-service autonomous inspection

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Bogie pitch rate gyroscope



 \bigcap

Bogie pitch varies along track – measure with pitch rate gyro; observe vertical alignment

Works at lower speeds (1 m/s) than an equivalent accelerometer

Sensor location is unimportant

Shortest measurable wavelength defined by bogie wheelbase and primary suspension resonances (with vehicle speed)

Left and right axlebox-mounted Research UK accelerometers

Left and right rail vertical reconstruction at shorter wavelengths – where pitch rate gyro cannot go

Corrugation; dipped joints; other short wavelength irregularities

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Bogie yaw rate gyroscope



Bogie yaw varies along track – measure with yaw rate gyro; observe response to lateral alignment

Works at lower speeds (1 m/s) than an equivalent accelerometer Independent of bogie roll – contrast lateral accelerometer

Shortest measurable wavelength defined by bogie wheelbase and primary suspension resonances (with vehicle speed) Bogie kinematic mode response 66

Rail Research UK Track Monitoring Current Practice









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Vehicles monitoring vehicles

- Fault detection and diagnosis of vehicles is more advanced
- Increasingly sensors are manufactured or retro-fitted into vehicles
- Critical subsystems include:
 - Train doors
 - Bogie suspension components
 - Conductor shoes



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Train door monitoring




Rail Research UK Train Door Incipient Failures



Reduced Lubrication

Drop in Supply Voltage

1.5

Time(s)

2

2.5

3

Actual Prediction

Rail Research UK Vehicle Dynamic Condition Monitoring

| Application | Detection | Sensors | Detection technique | Estimator | References |
|-------------------------|--|-----------------------|------------------------|---|--------------|
| Suspension | Yaw damper fault Lateral damper fault Conicity | Accelerometer Gyro | Model based | Kalman-Bucy filter | [91] |
| Suspension | Yaw damper fault Lateral damper fault Conicity | Accelerometer Gyro | Model based | Extended Kalman filter Particle filter | [92] [93] |
| Suspension | Yaw damper fault Sensor fault | Accelerometer Gyro | Model based | Kalman filter based IMM | [94] |
| Braking control | Creep force | Accelerometer Gyro | Model based | Extended Kalman filter | [90] |
| Bogie | Wheel-rail profile | Accelerometer Gyro | Model based | Extended Kalman filter | [89] |
| Unstable running | | Accelerometer | Model based | Time domain signal analysis | [99] |
| Derailment detection | Creep force Derailment coefficient | Gap sensors | Model free | | [96] |
| Derailment detection | | Accelerometer | Model free | | [97], [98] |
| Derailment detection | Creep force Derailment coefficient | Accelerometer | Model based | from Bruni et al 200 | [95] 7 |

Rail Research UK

Energy monitoring

- The group have been working on power simulation software for over 30 years
- The work is focussing on variation in driver performance and fault detection and diagnosis of the traction drives
- The results of the simulator can be validated using monitoring data

MerseyRail Instrumentational Research UK





Train based:

- Traction and auxiliary voltages and currents
- Cam shaft position
- Driver's handle position
- Position on track
- Inertial measurement
- Temperature
- Sub-station based:
- Traction and voltages and currents

Conclusion...



- My research is about a <u>system solution</u> that delivers value (e.g. Energy Savings, High dependability)
- This includes people, processes and tools. This means it's a <u>business</u> problem, not just a computer or electronics problem...



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The presentation includes the work of many others including: Stuart Hillmansen, Yury Bocharnikov, Shaofeng Lu, Dan Meegahawatte, Gavin Hull, Joe Silmon, Edd Stewart, Paul Weston

