Institution: University of Dundee

Unit of Assessment: UoA 14 – Civil and Construction Engineering

Title of case study: Complex Transportation Tunnel Systems

1. Summary of the impact (indicative maximum 100 words)

Research by Professor Vardy's team on unsteady pipe-flows has found direct application in road/rail tunnel design practice and in offshore engineering. The impact is exemplified by Vardy's participation in the design of many of the world's longest road and rail tunnels and in his work with industry on the detection and location of blockages in offshore pipelines. His flagship software *ThermoTun*, which predicts transient velocities, pressures and temperatures in complex train:tunnel systems, is licensed internationally by several major engineering consultancies and his software (*MPVC*) controls ventilation systems in seven Japanese road tunnels. His oil pipeline software (*PipePulse*) is used currently in the offshore oil industry to identify and clear flow obstructions in pipelines.

2. Underpinning research (indicative maximum 500 words).

The principal focus of Professor Vardy's underpinning research[1,2,3,4,5,6] is the development of generalised methods of numerical solution of the analytical equations of highly transient flows in complex networks – a task that poses formidable challenges, even in fixed-geometry applications. For train:tunnel aerodynamics, multiple boundaries move through the numerical grid and cross one another within it. In typical simulations with *ThermoTun*, dozens of such crossing events occur. A fundamental choice has to be made between methods that are potentially accurate at boundaries, but poorer between them and methods that are accurate between boundaries, but poorer at them. Likewise, generic choices are inevitable between accuracy and robustness. In software intended for general purposes in design offices, neither is sufficient without the other. These issues have driven much of Vardy's numerical research[5] and underpin its practical acceptance. No alternative software can match the accuracy and robustness of *ThermoTun*, *MPVC* and *PipePulse*.

Until about 10 years ago, Dundee's tunnel research focussed on the amplitudes of transient events. These determine pressure comfort inside trains and pollution concentrations in road tunnels, for example. The focus has since widened to include a far more detailed phenomenon, namely the evolving shapes of propagating wavefronts. These determine whether tunnels will emit sonic booms into the surrounding atmosphere[4]. For this purpose, it is necessary to model[2,3] unsteady skin friction on pipe/tunnel walls and this requires detailed understanding of wave/boundary-layer interactions. Unsteady skin fiction is inherently 3D in nature[8]. Axial accelerations/decelerations of the mean flow induce changes to radial velocity gradients which, in turn, cause redistributions of turbulence in all three coordinate directions. Dundee works closely with teams at the Universities of Aberdeen and Sheffield, using detailed physical experiments and extensive 3D numerical simulations (DNS, LES & RANS) to investigate the inherent characteristics of turbulence in non-equilibrium flows[6,7]. This underpins the development of generic methods of modelling rapidly varying wall shear stresses in highly unsteady flows.

Another research focus has been on the use of inverse transient analysis. Instead of predicting pressure/velocity histories for known geometrical and kinematic conditions, this involves "predicting" (inferring) geometrical and kinematic conditions for known (*i.e*. measured) pressure/velocity histories[8]. It is inherently impossible to do this with 100% reliability even in the absence of inevitable noise in the measured signals, but the research is showing how to distinguish between fundamentally different causes (*e.g*. friction or area change) of closely similar measurements.

The research on tunnel airflows has extended into a method of controlling tunnel ventilation equipment in real time[1]. Whereas conventional tunnel control is usually based on empirical feed-back and/or feed-forward algorithms, MPVC maintains an on-line simulator of current conditions throughout the tunnel network, allowing for exhaust emissions from measured traffic flows. The simulator is used to predict future conditions based on trial fan operations and an optimisation method selects the case that gives the most desirable outcome. The biggest academic challenge is to maintain compatibility between the simulated and actual conditions in the tunnel systems even though the input to the model cannot be perfect (e.g. vehicle dynamics, exhaust emission rates, errors in sensors).

3. References to the research (indicative maximum of six references)

[1] Ichikawa, A., Vardy, A.E, & Brown, J.M.B. (2001) Model-based predictive control using genetic algorithms. *Proc. I.Mech.E., Journal of Power & Energy*, **215**, Part A, 623-638. http://dx.doi.org/10.1243/0957650011538857.
[NB: This paper was awarded the Donald Julius Groen Prize]

[2] Vardy, A.E & Brown,JMB (2004) Transient turbulent friction in fully-rough pipe flows. *Journal of Sound & Vibration*, **270**(2), 233-257. http://dx.doi.org/10.1016/S0022-460X(03)00492-9.

[3] Vardy, A.E. & Brown, J.M.B. (2007) Approximation of turbulent wall shear stresses in highly transient pipe flows. *Journal of Hydraulic Engineering, ASCE*, **133**(11), 1219-1228. http://dx.doi.org/10.1061/(ASCE)0733-9429(2007)133:11(1219).

[4] Vardy, A.E. (2008) Generation and alleviation of sonic booms from railway tunnels. *Engineering & Computational Mechanics, Proc. ICE*, **161** (EM3), 107-119. http://dx.doi.org/10.1680/eacm.2008.161.3.107.
[NB: This paper was awarded the Telford Gold Medal - the highest ICE award for any paper published in any its journals]

[5] Shimada, M., Brown, J.M.B. & Vardy, A.E. (2008) Interpolation errors in rectangular and diamond characteristic grids. *Journal of Hydraulic Engineering, ASCE*, **134**(10), 1480-1490 http://dx.doi.org/10.1061/(ASCE)0733-9429(2008)134:10(1480).

[6] He, S., Ariyaratne, C. & Vardy,A.E. (2011) Wall shear stress in accelerating turbulent pipe flow. *Journal of Fluid Mechanics*, **685**, 440-460 http://dx.doi.org/10.1017/jfm.2011.328

Key Research Grants

[7] EPSRC (EP/C015479/1 & EP/G069441/1): Turbulence and wall shear stress in unsteady internal flows with smooth and rough surfaces. 2005-2008 & 2010-2013, £134,364. Prof A.E.Vardy (P.I.)

[8] EPSRC (EP/C003063/1): Full-scale field measurements of 3-D flows in a railway tunnel airshaft in Switzerland 2004-2005, £20,233. Prof A.E.Vardy (P.I.)

4. Details of the impact (indicative maximum 750 words)

The impact is epitomised by Vardy's services through Dundee Tunnel Research (DTR)[9], specialising in air flow in road and rail tunnels and embracing software licensing, design consultancy, research and the promotion of tunnel safety. The impact is economic (cost savings achieved by optimum design), environmental and societal (facilitating "clean" transport systems and reducing fossil fuel pollution) and health-related (improving passenger comfort and tunnel safety). Licences for *ThermoTun* granted by the university and DTR are targeted expressly at knowledgeable users offering a specialist service to their clients[10,11,12,13]. Since 2008, licences have been granted in Austria, Hong Kong, Korea, Spain, Switzerland, UK and USA. *MPVC* is licensed only in Japan and Vardy provides technical expertise for each application[14]. The oil-related software *PipePulse* is licensed exclusively to a Scottish company, Paradigm Flow Services[15].

ThermoTun is regarded internationally as "the top software available for 1-D simulations of rapidly-varying pressure, velocity and temperature in railway tunnels"[12]. Since 2008, it has been used in the design of many of the largest tunnels in the world[16,17], including the 57km Gotthard Base and 35km Lötschberg Base tunnels (Switzerland); the 28km Guadarrama and 25km Pajares tunnels (Spain), the 18km Fehmarn Link (Denmark-Germany) and high speed lines under design or construction in China, Korea, continental Europe and the UK. *ThermoTun* has also been used for an ultra-high-speed Munich Mag-Lev Railway, more than 200 shorter high speed tunnels worldwide and more than 30 metro systems. It is regarded by UK Rail Standards & Safety Board as being "without peer in predicting aerodynamic effects of trains travelling in underground tunnel systems"[13]. *MPVC* is currently used to control seven long road tunnels in Japan[14], including the two longest (11km Kan-Etsu, 11km Hida), where it has delivered large savings in power consumption.

Impact is evident through Vardy's frequent involvement in design, predominantly at the feasibility stage, when it is still possible for current research to have a significant influence on the eventual outcome. This is also the stage at which the need for new research is most easily identified. Thus, the need to understand sonic booms from tunnels led to long-standing research on unsteady friction and on wave flows over porous media (ballast-track rail). Likewise, concern about excessive temperatures (> 50°C) in tunnels under the Alps led to research having impact on prediction of heat conduction in seepage flows around tunnels. Exposure to practical tunnel operation led to research on model-based ventilation control and new proposals for safe ventilation in the event of fire. All have fed back into practical design. For designers, the impact of these activities occurs at the design stage whereas, for constructors, it occurs a few years later. For users, it occurs many years later (and is then on-going). For instance, current high speed rail design for the UK[16,13] is directly influenced by Vardy's publications and by a *ThermoTun* licensee, but passengers and people close to portals will not benefit until 2025 or beyond. Arup confirm[11] that Vardy's research on aural pressure comfort is the critical factor in optimising tunnel sizes and thereby achieving savings for national governments of "tens or hundreds of millions of pounds"[11] in unnecessary expenditure.

The development of *MPVC* was triggered by a realisation that, in many tunnels, ventilation control systems were highly wasteful of power and often failed to achieve the desired conditions. Vardy's paper with Ichikawa[1] led to strong interest in Japan where there are thousands of road tunnels. The Japan Highway Public Corporation (now NEXCO) now regards *MPVC* as its preferred control system for long highway tunnels and is installing it at the rate of about one tunnel per year. Design services are provided by Sohatsu Ltd with project-specific guidance from Vardy[14,18]. This link with Sohatsu has evolved to include further research underpinning the development of a new system (*FCVC*) now used successfully in simpler tunnels than those for which *MPVC* is installed[14]. *FCVC* provides automatic control in a fire emergency, with special (but not exclusive) application in bi-directional tunnels with no exhaust shafts.

Impact in the oil industry is through Paradigm Flow Solutions, an SME that specialises in detecting, locating and removing restrictions and blockages from offshore pipelines. Typical lines are tens of kilometres long and diameters range from 15mm-250mm. Paradigm's work focuses on the common case when access for intervention is possible only at the ends of the long lines. Vardy's inverse-transient software enables the mapping of local and distributed blockages. The long-term research on unsteady friction is informing methods of removing the blockages and, more recently, in preventing their development. Paradigm Flow Solutions credit the recent application of Vardy's technique to the unblocking of a pipeline with a saving of £4M in intervention costs for its client and significant enhancement of the company's reputation[15]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[9]. http://www.thermotun.com
(This is Dundee Tunnel Research's Website. It lists Vardy's research and *ThermoTun*. Some licensees are identified on the *ThermoTun* pages. Others prefer not to be identified in this manner).

[10]. http://www.hbi.ch/en/services/aero-and-thermodynamics.html
(This is the website of Swiss company HBI AG. Click on "PDF Aero- and Thermodynamics (91 KB)" near the top of the page to see citation of *ThermoTun* - http://www.hbi.ch/fileadmin/media/pdf/dienstleistungen/thermodynamik/2_DIE_A_002_AeroUndThermo_E_2013-09-01.pdf)
[11]. Factual Statement: Director and Arup Fellow, Arup (UK)
[12]. Factual Statement: Director, HBI Haerter AG (Switzerland)
[13]. Factual Statement: Professional Head, Aerodynamics, UK Railway Safety & Standards Board
[14]. http://www.sohatsu.com/Esite/04_c.htm
(This is the website of a Japanese company that specialises in road tunnel equipment and control. The home page lists *DTR* and *ThermoTun-Online*. Vardy's position as Technical Adviser is listed on this website).

[15]. Factual Statement: Technical Director, Paradigm Flow Solutions (UK)

[16]. UIC CODE 779-11 Determination of railway tunnel cross-sectional areas on the basis of aerodynamic considerations. International Union of Railways, Paris, ISBN, 2-7461-0814-3, 91pp (2005) (see p32) - http://www.uic.org/etf/codex/codex-detail.php?codeFiche=779-11&langue_fiche=E
(This international guideline is current. *ThermoTun* was used to create the main charts indicating required tunnel cross-sections).

[17]. BUSSLINGER, A, HAGENAH, B, REINKE, P & RUDIN, C., Aerodynamics in Lötschberg Base Tunnel – simulations and measurements in the second longest European high-speed rail tunnel. *Proc. 13th Int'l Symposium on Aerodynamics and Ventilation of Tunnels*, New Brunswick, USA, 13-15 May 2009, BHR Group, Ed: I A Sweetland, 767-781 (2009)
(This paper, authored by practitioners,is one of many that cite the practical use of *ThermoTun*)

[18]. Factual Statement: President, Sohatsu Systems Laboratory (Japan)