Institution: University of York

Unit of Assessment: 10, Mathematical Sciences

Title of case study: Mathematical Modelling to Improve Traffic Flow and Control

1. Summary of the impact

Improvements in traffic flow on urban road networks have a direct daily impact on citizens, business and tourism. To make improvements, transportation planners and signal engineers rely on modelling and control software that implements mathematical methods designed to optimize traffic flows, signal timings or both. Research by **Mike Smith**'s group at York since 1993 has led to:

- the implementation of some of **Smith's** older ideas in the SATURN (Simulation and Assignment of Traffic in Urban Road Networks) software suite, which is routinely utilised to model proposed network changes in over 100 cities, including London, and was used to help design and assess traffic schemes for the 2012 Olympics;
- the evaluation by Italian company *SISTeMA* of **Smith's** ideas for possible inclusion in its Optima transportation software;
- the incorporation and use of **Smith's** associated recent work on pattern-matching in a number of commercial projects by York firm *Cybula* in its Signal Data Explorer software.

2. Underpinning research

Professor **Mike Smith** has been a member of the Mathematics Department at the University of York since 1964. On retirement in 2006, he was appointed Emeritus Professor, and was re-employed by York on a 30% basis as a Researcher Co-investigator on the FREEFLOW grant from 1 January 2008 - 30 June 2011. **Smith** has made influential contributions to the field of traffic modelling over a long timescale, starting with the introduction of the "P0" responsive traffic control policy (1979) and his "Algorithm D" for solving network equilibrium problems (1984). Since 1993 **Smith** has worked on the interlocking problems of (1) the design of signal control adjustments to achieve economical routeing; (2) the design of traffic models that can evaluate these signal control adjustments and (3) pattern matching techniques to recognise when signal timing interventions should be implemented on-street. This post-1993 research has established that P0 and Algorithm D have many desirable properties (especially stability properties) and has led to their implementation (in modified form) in SATURN, the on-going evaluation of P0 by *SISTeMA* and also to a commercial application of the pattern matching technique by *Cybula.*

Since 1993, **Smith** has worked with his RAs Dr **Y. Xiang** (1995-2002), Dr **M. Ghali** (1996-1998), Dr **J. Clegg** (1999-2000 and for various short periods thereafter until she became a lecturer in the Department of Electronics in 2006) and Dr **R. Mounce** (2004-2005 (Mathematics) and 2009 (Computer Science)). **Smith's** work draws on variational inequality theory; indeed, he was the first to apply this theory to traffic equilibria, and it is now the standard framework. His contribution was recognized in 2007 through the award of the Robert Herman Lifetime Achievement Award by INFORMS ("the largest professional society in the world for operations research, management science, and business analytics"; the award is made annually to an individual who has "made fundamental and sustained contributions to transportation science and logistics").

Key results since 1993 underpinning the Impact described here include the following.

- Papers [1,4,5] show that **Smith's** P0 policy is more stable than others (particularly the standard equisaturation and delay minimisation policies) and can significantly reduce congestion by encouraging route switches, especially in high congestion situations.
- Wide area network modelling, involving the solution of large network equilibrium models, has been shown to be much more feasible using **Smith's** algorithm D and related algorithms than with the Frank-Wolfe methods previously used. Ref [1] is central to establishing that P0, rather than other control policies, is by far the most natural policy for implementation in transportation models which permit signals to change in response to flow changes following algorithm D.
- A main theme in [1,4,5] was to show that signal timing policies such as P0 are well-suited to implementation within network models (perhaps using algorithm D as the basic solution

method), to give both an equilibrium flow solution and a set of good consistent signal timings.

- Refs [2] and [3] showed how the best possible control may be calculated. Ref [2] gave new results comparing standard control systems' performance with P0 when route choices vary. Ref [3] developed the method for calculating the optimal control and shows that in an example P0 performance is very close to the best that can be achieved.
- Ref [6] introduced a new (and more meaningful) metric to identify when a current traffic pattern is "similar" to a previous traffic pattern, enabling a previously proven intervention to be recovered and re-utilised in the current situation. The metric is being used in a number of industry development projects by *Cybula* in general pattern matching applications.

Accordingly, **Smith's** research since 1993 has provided very strong evidence of the desirability of both P0 and Algorithm D, especially when used in conjunction. As described below, Refs [1,2] were crucial in the decision to implement P0 and a "social pressure algorithm" based on Algorithm D in SATURN; the later work [3,4,5] provides further support; Refs [4,5] motivated *SISTeMA's* current evaluation of the P0 policy; finally, Ref [6] underpins the *Cybula* impact.

3. References to the research

Transportation Science and *Transportation Research* Parts B and C regularly publish mathematical innovations designed to address the particular characteristics of both equilibrium and dynamical transportation and traffic modelling. (Citations: Google Scholar 20/9/2013.)

*[1] **Smith, M. J.,** van Vuren, T (1993). Traffic equilibrium with responsive traffic control. *Transportation Science*, 27, 118–132 doi: 10.1287/trsc.27.2.118. (Leading journal; 80 citations)

[2] **Smith, M. J., Xiang, Y.,** Yarrow, R., **Ghali, M. O.** (1996). Bilevel and Other Modelling Approaches to Urban Traffic Management and Control*. Proceedings, Equilibrium and Advanced Transportation Modelling* (1998); Editors: Patrice Marcotte and Sang Nguyen), Kluwer, 283 – 325. DOI: 10.1007/978-1-4615-5757-9_12 (Invited presentation; high quality conference; 14 cites)

*[3] **Clegg, J., Smith, M. J., Xiang, Y.,** Yarrow, R. (2001). Bilevel Programming Applied to Optimising Urban Transportation, *Transportation Research* B 35, 41–70. (Top journal; 58 cites) doi:10.1016/S0191-2615(00)00018-7

[4] **Smith, M. J.** (2010). Intelligent Network Control: Using an Assignment-Control Model to Design Fixed Time Signal Timings. *New Developments in Transport Planning – Advances in Dynamic Traffic Assignment* (Eds: Tampere, C., Viti, F. and Immers, L.), Edward Elgar, 57 – 72. DOI: 10.4337/9781781000809. (The first in a prestigious series of conferences titled *Models and Technologies for Intelligent Transportation Systems* organised with the specific aim of bringing theorists and practitioners together; 6 cites)

*[5] **Smith, M. J., Mounce, R.** (2011) A splitting rate model of traffic re-routeing and traffic control. *Transportation Research* Part B, 45 (2011), 1389-1409. doi:10.1016/j.trb.2011.05.013 (Also in the *Proceedings of the Nineteenth International Symposium on Transportation and Traffic Theory* Procedia Social and Behavioral Sciences 17 (2011) 316–340) (Top class journal; Very high quality, peer-reviewed conference and conference proceedings; 9 cites)

[6] **Mounce, R.**, Hollier, G., **Smith, M. J.,** Hodge, V.J., Jackson, T., Austin, J., (2013) A Metric For Pattern-Matching Applications To Traffic Management, *Transportation Research* C, 29, 148-155. DOI: 10.1016/j.trc.2012.04.019 (A top journal in the field; NB submitted to journal in Nov 2010.)

Funding for this research 1993 – 2011:
Nine EPSRC grants on which **Smith** was PI: Congestion Pricing Via the Urban Traffic Control System GR/R33274/01 £58,546, Experimental Investigation Of The Dynamics Of Driver Route Choice GR/M80093/01 £83,626, Bilevel Optimisation Of Signal Timings To Minimise Urban Traffic Congestion GR/M22482/01 £140,784, Assessment Of Road-User Charging Systems Taking Account Of Public Transport And Equity GR/K08901/01 £112,617, RONETS: A New Microsimulation Model For Designing And Assessing Road Pricing And Traffic Control Schemes GR/J73919/01 £58,226, The Development Of A New Theory Of Parallel Dynamic Traffic Assignment Using Splitting Rates GR/J71847/01 £57,550, Network Wide Redistributional Effects Of Traffic Control And Road Pricing Together GR/J97793/01 £69,320, Distributed Computation Of Dynamic Traffic Equilibria On Large Networks GR/H43540/01 £53,482, Dynamic Traffic

Assignment And Dynamic Traffic Control in Congested Signal-Controlled Road Networks GR/H39710/01 £45,349. Plus two EPSRC grants on which **Smith** was CI: FREEFLOW EP/F005156/1 £1,442,820, Development Of Combined Assignment & Control Models & Their Applications To Traffic Management GR/K78447/01 £81,606.

EU grant (PI: **Smith**) MUSIC (Management of traffic USIng Control) project (£2.5 million; 1996-1999; contract: UR-95-SC.173.). MUSIC applied **Smith's** ideas in York, Thessaloniki & Porto. Partners: Univ. York (co-ordinator), TRIAS SA (Greece), Univ. Porto (Portugal), Hague Consulting Group (Holland), City of York Council (UK), Univ. of Coimbra (Portugal). Grant from City of York Council, JAH83/UTMC (2001-2002) £50,000; Grant from the City of Dublin, (2002) £23,750

4. Details of the impact

4.1 Impact through transport planning software

Smith has a longstanding relationship with the developers of the SATURN (Simulation and Assignment of Traffic in Urban Road Networks) software suite, which is now developed and marketed by *Atkins Global* ("one of the world's leading design, engineering and project management consultancies"). Since 2008 SATURN *"has been utilised to evaluate 80 significant changes to transport networks in the UK and 20 changes to transport networks overseas. It is currently used to some degree by 400 users in the UK and by 100 users overseas and generates an annual income in excess of £500K."* [7] (95% of the user-base is estimated to be non-academic [7]). **Smith** has a longstanding collaboration with Dr Dirck van Vliet, the designer and developer of SATURN; **Smith**'s former research assistant **Xiang** was employed by *Atkins* until recently.

The impact of papers [1,2] was to convince the SATURN team that Smith's policy P0 and developments of "Algorithm D" should be incorporated in their product. Van Vliet writes in [7] that *"The SATURN model has made extensive use of the concept of Social Pressure developed from the 'Algorithm D' originally proposed in the mid 1980s by **Mike Smith**. This is used in solving the algorithmic problems that arise in traffic assignment models where different streams of traffic interact with one another (e.g. traffic on a minor arm at a T-junction giving way to traffic on a major arm). In addition, SATURN contains an implementation of the responsive control policy called P0 previously proposed by **Smith**… [The SATURN implementations of the late 1990's] were informed and supported by the stability results obtained by **Smith** and van Vuren in [1] and by **Smith** et al in [2]. More generally, without the ideas of **Mike** the convergence of SATURN and its ability to provide a single self-consistent answer to traffic problems would be extremely restricted. Moreover, his results on the stability of these algorithms (going beyond the previously standard work of Frank-Wolfe) allow us to market SATURN with confidence. SATURN is under continual development and **Mike Smith** and I have had many conversations about the details of the proportional method and about the SATURN Social Pressure implementation. His research continues to be a significant influence on our thinking."* Van Vliet's published work acknowledges "ideas pinched from" **Smith.**

A significant application of the SATURN suite, demonstrating its flexibility and utility, was in the preparation for the London 2012 Olympic and Paralympic Games in both "helping to define [traffic] plans around venues" and "to provide a strategic overview of the impact of the ORN [Olympic Route Network], road events/management and the venues themselves on roads in London", which was applied in particular to inform the "Get Ahead of the Games" advertising campaign on likely road impact [8]. More generally, Transport for London "has recently developed a comprehensive set of new sub-regional highway assignment models, based on the SATURN suite of software" [9].

Very recently, the Italian company *SISTeMA* has stated *"We propose to investigate a revised iterative process (using the P0 policy) and we are likely to implement it within our software if that investigation shows benefits."* [13] Crucially, their interest arises because *"Smith's mathematical analysis suggests that with this policy the control/routeing iterations may be expected to converge both more quickly and more reliably."* Smith's mathematical analysis is reported in [1, 4, 5] above; [4] is cited explicitly by *SISTeMA* [13]. *SISTeMA*'s portfolio includes traffic projects in Brussels, Bogotà, London, Moscow, New Delhi and Rome [13].

4.2 Impact on practitioners and external collaboration

Smith has stimulated and informed the international traffic planning debate and influenced traffic planners and signal engineers by communicating his results in a wide range of forums. Examples include: (1) a lecture at the 17th *JCT Traffic Signal Symposium* (September 2012), the main forum

for signal engineers in the UK, with an emphasis on papers and presentations from working signal engineers and manufacturers [10], where his paper *Traffic control and route choice: modelling and optimisation* received a prize for "the most thought-provoking paper" and (2) a lecture at the *Modelling World* conference in June 2013 (a central forum for modelling practitioners).

Smith also works to develop and test new ideas via on-road pilot schemes locally, which he considers essential to generate confidence and so enable on-street impact. He has a long-standing relationship with the City of York Council and the York-based specialist traffic control consultants *Ian Routledge Consultancy.* **Smith** has been involved with various innovative modelling projects aimed at reducing congestion, and in Ian Routledge's words *"was the catalyst in bringing together a team that led to the FREEFLOW project (2008 - 2011; funded by DfT, TSB, EPSRC, ESRC and the project partners, including five industrial partners, to the value of £6.4M)"* [11], an exemplar of the combined *"local academia/local authority/local consultancy platform Mike had pioneered"*. Routledge continues *"Mike has over the last decade shown how academic research can be combined with local authority and local industry partners to demonstrate in major national and international projects the potential of integrating new academic thinking into fields that have tended in many ways to be reluctant to try new approaches and techniques."* [11]

The FREEFLOW project (2008–2011) enabled proof-of-concept of a new responsive gating system on the main arterial York to Hull A1079. It achieved significant reductions in mean and variance of bus journey times [6]. A long-term goal is to implement it nationally and internationally through its incorporation into standard modelling programs and bus routeing and timetabling software.

4.3 Impact through pattern recognition software

The novel pattern matching metric of [6] has been taken up for more general applications by *Cybula*, a successful company with 10 employees set up in 2000 by Prof. Jim Austin, who leads a research group in computer science at the University of York. *Cybula* licences technology from the University and others to undertake its business; however the University has no equity holding in the company. The risk capital behind *Cybula* comes from private investors, who evaluate technology carefully before investing their funds and the company's profits in the methods. *Cybula*'s Business Director John McAvoy writes [12] *"Cybula's main business is in high performance pattern matching… The cumulative encoding method described in [6] is being used by the company within a number of projects. It's ideal for encoding the data in many problems prior to recognition with [the existing match engine]. We are using it in a project with Simulation Software Ltd on data from BP for possible detection of leaks in oil pipelines and it also forms a part of a project with Sheffield University and Thames Water. We are also using it in a project with EDF Energy… Thus Cybula is using the technology regularly, furthermore, if the projects' outputs are taken up by the companies, the method will also be used on a daily basis with these companies… [this technology] is critical in making the company competitive in the world market."* The projects in which *Cybula* uses the methods of [6] are collectively worth £200k per annum [12].

5. Sources to corroborate the impact

[7] Letter and emails from Dr Dirck van Vliet, developer of SATURN in conjunction with the Institute for Transport Studies (University of Leeds) and *Atkins Global*.

[8] 'Delivering transport for the London 2012 games', (London: Olympic Delivery Authority, 2012), p39, at www.ice.org.uk/Information-resources/Document-Library/Delivering-Transport-for-the-London-2012-Games

[9] 'Travel in London Report 4' (London: Transport for London, 2011), p9, at www.tfl.gov.uk/assets/downloads/travel-in-london-report-4.pdf

[10] http://www.jctconsultancy.co.uk/Symposium/Symposium2012/symposium2012.php

[11] Letter from Mr Ian Routledge, of *Ian Routledge Consultancy,* York.

[12] Letter from Mr John McAvoy, Business Director, *Cybula* & information from Prof. J. Austin.

[13] Letter from Dott. Ing. Lorenzo Meschini (Sapienza Universita di Roma and CEO of *SISTeMA,* a PTV Group Company and Sapienza spin-off). *SISTeMA*'s portfolio: www.sistemaits.com/portfolio/