An ESRC Strategic Network
Data and Cities as Complex Adaptive Systems (DACAS)

SUMMER SCHOOL

UNDERSTANDING URBAN TRANSFORMATIONS THROUGH DATA

12-16 SEPTEMBER 2016
MANCHESTER SCHOOL OF ARCHITECTURE

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COMMITTEE
Deljana Iossifova
Ulysses Sengupta

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MANCHESTER SCHOOL OF ARCHITECTURE

BACKGROUND

Understanding Urban Transformations through Data is the third of a series of events funded through the ESRC Strategic Network Data and Cities as Complex Adaptive Systems (DACAS). The aim of DACAS is to promote an interdisciplinary complexity science approach to the study of urban data and the links between soft and hard systems as the basis for the development of innovative technological applications. DACAS connects non-academic stakeholders from the public, private and third sectors and noted academics with backgrounds in various relevant disciplines in China, Brazil and the UK.

The international summer school for PhD students and Early Career Researchers aims at improving our understanding of urban transformations through dynamic data analysis and modelling from a complexity perspective. The week-long event takes place from 12 to 16 September at the Manchester School of Architecture (University of Manchester & Manchester Metropolitan University) and includes high profile keynotes, lectures and workshops.

Early Career Researchers and PhD students are invited to test different approaches to modelling hands-on using a complexity science framework. They will work with 'hard' and 'soft' datasets. 'Hard' refers to datasets describing spatial morphology, infrastructural provision, etc., as dynamic adaptive systems. 'Soft' refers to datasets describing social epidemiology, family structure, changing norms, personal narratives, etc., as dynamic evolutionary systems. The focus will be on a number of selected case studies.

Keynote Speakers:

- Juval Portugali (Tel Aviv University)
- Denise Pumain (National Center for Scientific Research, CNRS)
- Piyushimita Thakuriah (University of Glasgow)

Invited Guests:

- Peter Allen (Cranfield University)
- Michael Weinstock (Architectural Association)
- Katharina Willis (Plymouth University)

Expected Outputs:

- ECR/PhD researchers: a team report on their workshop activities in the form of a working paper. This should include the clear concept, hypothesis being tested, the methodology applied and the results obtained. This paper will serve as the basis for the development of digital tools and innovative technological applications that reflect closely the linked and relational behaviour of real urban systems and aid their planning and design. The deadline for the submission of this report to Solon Solomou (solon.solomou@stu.mmu.ac.uk) is 21 October 2016.
- DACAS researchers: a short report on your informal PechaKucha networking activities. This should include a clear outline of identified possibilities for future collaboration and key outputs, including the names of specific partners, the timing of next steps, etc. A first outline is to be submitted at the end of the event week, 16 September. The full report should be sent to Ivana Tosheva (ivana.tosheva@stu.mmu.ac.uk) by 21 September 2016.

PROGRAMME OVERVIEW

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<tr><th></th><th>MON
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15/09</th><th>FRI
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<tr><td>8:30 - 9:00</td><td colspan="5">Welcome & Registration</td></tr>
<tr><td>9:00 – 09:45</td><td rowspan="2">Keynote: Piyushimita Thakuriah</td><td rowspan="2">Keynote: Denise Pumain</td><td rowspan="2">Keynote: Juval Portugali</td><td rowspan="2">Break-out/ Work Session</td><td rowspan="2">Parallel Break-out & DACAS Strategy Sessions</td></tr>
<tr><td>09:45 – 10:30</td></tr>
<tr><td>10:30 – 10:45</td><td colspan="5">Coffee Break</td></tr>
<tr><td>10:45 – 11:30</td><td rowspan="2">Introduction & Case Study Presentations</td><td>K Wallis</td><td>P Allen</td><td rowspan="2">Break-out/ Work Session</td><td rowspan="2">ECR Result Presentations</td></tr>
<tr><td>11:30 – 12:15</td><td>DACAS Pecha Kucha</td><td>Break-out/ Work Session</td></tr>
<tr><td>12:15 – 13:45</td><td colspan="5">Lunch Break</td></tr>
<tr><td>13:45 – 14:30</td><td rowspan="2">ECR Presentations</td><td rowspan="2">Parallel Break-out & DACAS Agenda Sessions</td><td rowspan="2">Break-out/ Work Session</td><td rowspan="2">Break-out/ Work Session</td><td rowspan="2">ECR Result Presentations</td></tr>
<tr><td>14:30 – 15:15</td></tr>
<tr><td>15:15 – 15:30</td><td colspan="4">Coffee Break</td><td rowspan="3">Departure</td></tr>
<tr><td>15:30 – 16:15</td><td rowspan="2">Break-out Session</td><td rowspan="2">Break-out/ Work Session</td><td rowspan="2">ECR Feedback Presentations</td><td rowspan="2">Break-out/ Work Session</td></tr>
<tr><td>16:15 – 17:00</td></tr>
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KEYNOTE: SEEING CITIES THROUGH BIG DATA: EMERGING TOPICS IN URBAN INFORMATICS

Piyushimita Thakuriah (Vonu) is the Ch2M Chair of Transport and Professor of Urban Studies in the University of Glasgow. She is the founding Director and Principal Investigator of the Urban Big Data Centre funded by ESRC. She is interested in smart, socially-just and sustainable transport and in the analytics of emerging sources of Big Data to understand complex urban problems. Vonu has published over 170 journal papers, conference proceedings and technical reports on these topics. She is the author of the book Transportation and Information: Trends in Technology and Policy(2013) and lead editor of the forthcoming volume Seeing Cities with Big Data: Research, Methods and Applications in Urban Informatics (expected 2016). Prior to her current position, she was a professor in the University of Illinois at Chicago. Vonu has advised major transportation projects in Malaysia, China, India, Australia, Colombia and the Dominican Republic. She is a founding co-chair of the Computational Transportation and Society joint subcommittee of the Transportation Research Board, National Academy of Sciences, and a co-chair of the Urban Data Interest group of the Research Data Alliance, a joint data-related effort of the European Commission, National Science Foundation and National Institute of Standards and Technology, and the Australian Government.

Abstract: This talk will discuss the use of emerging sources of data for urban informatics. Big Data is the term being used to describe a wide spectrum of naturally-occurring data generated through transactional, operational, planning and social activities which are not specifically designed for research and, which, due to their structure or access conditions, add considerable complexity to research and analysis. The specific objective of this talk is to describe emerging sources of urban Big Data and the challenges that arise with their use, with a focus on detection of short-term episodes and events in cities, medium-term changes due to fluctuations in the economy or policy changes (e.g., the economic recession), and longer-term structural changes in the urban environment, and land-use and consumption patterns. Examples will be given using social media and other forms of Internet-based data as well as GPS and lifelogging data. The talk will survey the kinds of challenges in going from a data-poor environment to a data-rich world, with specific comments on four challenges that are likely to arise: technological, methodological, theoretical/epistemological, and the emerging political economy of Big Data. The talk will conclude with an introduction to the Urban Big Data Centre, funded by the Economic and Social Research Council.

COFFEE

INTRODUCTION TO THE WEEK

Ulysses Sengupta & Deljana Iossifova

CASE STUDY PRESENTATIONS

Christopher Doll
Sustaining the transition – A tale of two cities

Nils Goldbeck
Interdependent Urban Infrastructure Systems: How can the public transportation network in London be made more resilient and robust to flooding?

Nir Oren (via Skype)
The Co-Evolution of Autonomous Mobility-On-Demand (AMoD) Systems and Human-Driven Vehicles

Please see at the back of this booklet for a full description of individual case studies.

LUNCH

ECR PRESENTATIONS

Young researchers will present their data analysis or systems modelling methods from their disciplinary perspective. This can refer to their current research or to one of the case studies and has the aim to illustrate existing experience and interest. Presentations will enrich the mix of methods available at the Summer School and will include mention of existing datasets or knowledge of how to obtain required multiple datasets; and a clear approach to the selected case study. Four minutes per presentation:

- Adam Brennan
- Claire Little
- Eda Acara
- Gabriela Depetri
- Gemma Todd
- Martin Schulwitz
- Moozhan Shakeri
- Nir Fulman
- Oana Ilnitchi
- Patrizia Sulis
- Peter Bus
- Sandro Sousa
- Shanaire Blythe
- Sibtay Haider
- Solon Solomou

COFFEE

BREAK-OUT SESSION

ECRs will form teams of three to four group members who will work together for the duration of the Summer School.

Participants will work together to test different modelling approaches. They are invited to seek input from DACAS researchers and invited guests in informal sessions.

Participants are asked to take notes during discussions and work together to produce coherent summaries of workshop activities, progress and findings. This should form the basis for a progress report, to be delivered by each group within four weeks of the closing of the summer school.

CLOSING

KEYNOTE: URBAN DYNAMICS AND GEO-DIVERSITY: FROM THEORY TO MODELING

Denise Pumain trained in geography at Ecole Normale Supérieure, she was lecturer at University Paris I from 1970, researcher at the National Institute of Demography (1981-86), Professor at University Paris 13 (1986-89) then at University Paris I Pantheon-Sorbonne, member of the Institut Universitaire de France. Former Chair of the Commission on Urban Development and Urban Life of the IGU (1992-2000), founder of the research laboratory P.A.R.I.S. (1984), Director of the UMR Géographie-cités (CNRS 1992-2000), the European Research Group S4 (Spatial Simulation for Social Sciences, 2006-2013), Cybergeo, European Journal of Geography (founded 1996), Principal Investigator of the ERC advanced grant GeoDiverCity, http://geodivercity.parisgeo.cnrs.fr/blog/ (2011-2016).

Her main scientific contribution is about building an evolutionary theory of urban systems and transferring concepts and models from self-organising complex systems towards social sciences. She was chief executive of education and research for the Académie de Grenoble (2000-2001) and first scientific coordinator for social sciences at the French Agency for research assessment (2007-2008). Doctor honoris causa at University of Lausanne and Liege, silver medal of the CNRS and Vautrin Lud International prize in Geography in 2010. Corresponding member of the Austrian Academy of Sciences since 2009 and corresponding fellow of the British Academy since 2012. Officer in French Order “Legion d’honneur” and “Ordre du merite”. .

Among recent publications:

- Pumain D. (ed.) 2006, Hierarchy in natural and social sciences. Dordrecht, Springer.
- Lane D., Pumain D., van der Leeuw S., West G. (eds.), 2009, Complexity perspectives on innovation and social change, ISCOM, Springer.
- Pumain D. 2012, Multi-agents System Modelling for Urban Systems : the Series of SIMPOP models, in Heppenstall A. J., Crooks A.T., See L.M., Batty M. (eds), Agent-based Models of Geographical Systems. Springer..
- Pumain D., Swerts E., Cottineau C. Vacchiani-Marcuzzo C., Ignazzi A., Bretagnolle A., Delisle F., Cura R., Lizzi L, Baffi S. 2015 : Multi-level comparison of large urban systems. Cybergeo, 706

Abstract: The evolution of cities is a major issue because it affects the majority of the world population. It is in cities that solutions must be invented to solve the problems of sustainable development in terms of quality of life, of resource management, of intelligent integration of technological and cultural innovation and of social cohesion, at the local and the global scales. The diversity of cities is such that it might seem

difficult to develop a scientific knowledge about them for sustaining policies. However, cities have long been interdependent and organized into systems of cities, they co-evolve through the multiple relationships which connect them into networks for the exchange of materials, investments, people or information. These interdependencies drive and constrain the evolution of each city in the system, according to a complex set of dynamics which exhibit patterns regular enough to help understanding and even predicting certain trends.

For anticipating urban future, geographers have since long developed a theoretical framework relying on the observation, not only of the few megacities global stars but of thousands of cities and towns taken in a variety of world regions. These empirical observations were scrutinized through analytic methods inspired from the dynamics of complex systems and data and processes are now integrated into computer simulation models which are able to reconstruct the stylized facts and trends observed. The theory and the results of these modelling experiments emphasize the importance of interactions between the cities in the evolution of their size and the effects of the spatial diffusion of large innovations waves, which tend to reinforce the hierarchical unevenness and explain the reversal of trajectories in the specialized cities.

The path-dependent role of the precocity and sustainability of settlement systems is confirmed as well as the bifurcations associated with colonization in having created at world scale a diversity of systems of cities which has been maintained for decades in terms of hierarchical inequality and the primacy of their metropolises. Adapted urban policies might partly counteract such self-organized trends. In any case, the urban geodiversity has to be taken into account in order to continue the major function of cities and towns which still are altogether remarkably efficient socio-spatial adaptors on the long run in the human history.

COFFEE

WHOSE RIGHT TO THE SMART CITY: DATA AND CITIZENSHIP

Katharine Willis is Associate Professor (Reader) in digital environments in the School of Art, Design and Architecture at Plymouth University, UK. Her research investigates the effects and implications of digital networks on the experience and design of urban space and place. She is PI on the Digital Neighbourhoods research project (2013-2017) that investigates the impact of superfast broadband on social and spatial inclusion on rural communities in South West UK and leads the AHRC International Research Network: Whose right to the Smart City (2016-2018). Recent books include:

- Digital and Smart Cities (with Alex Aurigi, 2017 forthcoming Routledge),
- Netspaces: Space and Place in a Networked Wold (Routledge 2016)
- Locative Media: Multidisciplinary Perspectives on Media and Locality (co-edited, Transcript Press 2013)
- 'Shared Encounters' (co-edited, Springer 2010).

Katharine Willis trained as an Architect with a Masters in Architecture from the Bartlett, University College London, and a PHD from the Bauhaus University of Weimar, Germany where she was an EU Marie Curie Fellow on the MEDIACITY research project.

Abstract: In the context of global smart city initiatives, what are the potentials and challenges ICTs for marginalised communities to appropriate and benefit from the impacts of 'smart city' projects? This talk addresses the topic of 'smart citizenship': or how ICT led developments can involve not only engineers, coders or systems scientists - but also civic hacktivists, local associations and longstanding community groups. This looks at the role, not of 'big data', but of a process where interested publics are actively solicited to co-create potentially transformative civic 'information'.

Smart city initiatives tend to leave little space for bottom-up or citizen-led engagements and in particular overlook the needs of disadvantaged and marginalised communities. This is set in a context where efficiency, optimisation and convenience are fashionable buzz words, but where citizens are relegated to being seen as data sources moving across various databases. Such communities have neither the information nor the tools by which to participate in the decision-making process. Underlying this is a lack of data about the urban poor, and their access to water, sanitation, housing, health and transport services. This talk will outline some of the issues raised and discuss possible models and tools to support smart citizenship within marginalised communities, drawing on work from Brazil, India and UK.

This work is part of an AHRC International Research Network: Whose right to the Smart City; a UK/Brazil/India collaboration that draws on knowledge and perspectives from marginalised city contexts'. Network Partners are Ava Fatah (UCL) Satyarupa Shekhar (CAG India) and Ana Paula Baltazar (UFMG, Brazil).

DACAS PECHAKUCHA

In three minutes and a maximum of 10 slides, each DACAS partner will pitch one research or publication idea, current project or funding proposal to DACAS partners and guests. The audience will be invited to express their desire to enter into further discussions on the possibilities of collaboration. Thus, all partners are given the opportunity to collaborate with each other in order to develop specific strategies for research and publication with others.

The discussions are expected to be undertaken in informal groups during working sessions, in parallel with the ECR break-out sessions. A short report (including a clear outline of identified possibilities for future collaboration and key outputs, the names of specific partners, the timing of next steps, etc.) will be required from all DACAS members as a summary at the end of the event week and in full by 21 September.

Presentation order:

- Alexandros Gasparatos
- Christopher Doll
- Deljana Iossifova
- Eric Cheung
- Jun Luo
- Rene Doursat
- Robert Hyde
- Roberto Kraenkel
- Shidan Cheng
- Ulysses Sengupta

LUNCH

BREAK-OUT SESSION

ECR team work with informal input from DACAS researchers.

IN PARALLEL: DACAS INTERNAL (AGENDA SESSION)

This session is intended as an opportunity to discuss specific ideas, agendas and questions as they refer to Data and Cities as Complex Adaptive Systems. DACAS partners and guests are invited to attend.

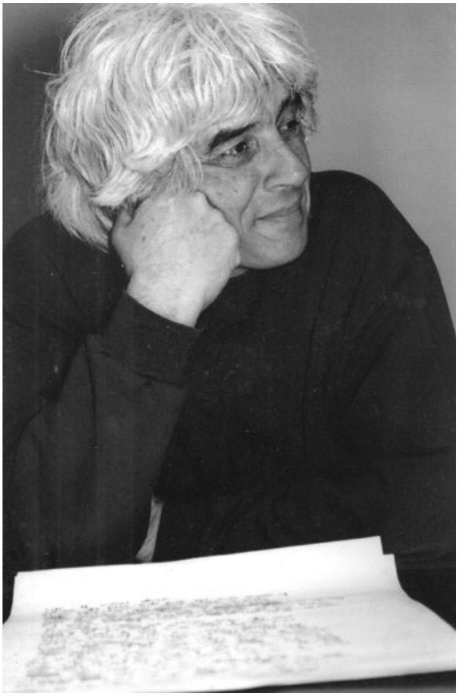
COFFEE

BREAK-OUT SESSION

ECR team work with informal input from DACAS researchers.

CLOSING

DAY 3



KEYNOTE: COMPLEXITY, COGNITION, INFORMATION AND THE CITY

Juval Portugali is Professor of Human Geography at the Department of Geography and the Human Environment Tel Aviv University. He is the Head of the Environmental Simulation Laboratory (ESLab) and of the Environment, Society and Planning Graduate Program of Tel Aviv University. Juval Portugali received his BA degree from the Hebrew University of Jerusalem, did his MA studies at the Technion Haifa, and received a London University PhD from The London School of Economics and Political sciences. His research integrates complexity and self-organization theories, environmental-spatial cognition, urban dynamics and planning in modern and ancient periods. His publications includemore than 70 research articles and 16 scientific books, among them the following:

- Implicate Relations: Society and space in the Israeli-Palestinian conflict, Kluwer 1993.
- The Construction of Cognitive Maps, Kluwer, 1996 (Ed.).
- Self-Organization and the city, Springer, 2000.
- Complex Artificial Environments. Springer Complexity Series, 2005 (Ed.).
- Complexity, Cognition and the City, Springer, Complexity Series2011.
- Complexity Theories of Cities Have Come of Age, Springer, Complexity Series 2012 (Ed. With Han Meyer, Egbert Stolk and Ekim Tan).
- Information Adaptation: The Interplay Between Shannon Information and Semantic Information in Cognition.By Hermann Haken and Juval Portugali. SpringerBriefs in Complexity.2015, XIV, 90 p. 49 illus., 12 illus. in color.
- Complexity, Cognition, Urban Planning and Design, Springer, Complexity Series 2016(Ed. With Egbert Stolk).

Abstract: The last decades have witnessed the emergence of CTC (complexity theories of cities) – a domain of research that applies the various complexity theories developed with respect to natural complex systems to the study of cities [1]. While CTC have added important insight into our understanding of cities, they also entail a dual dilemma: Firstly, human beings, the parts of cities, fundamentally differ from the parts of natural complex systems. Secondly, unlike natural complex systems, cities are hybrid complex systems composed, partly of artifacts (buildings, roads, etc.) which are essentially simple systems, and human agents which are themselves complex systems. The response to the first dilemma was to add the insight gained in cognitive science about human behavior tothe study of cities as complex systems, while to the second, to develop a theoretical approachescapable of modelling the dynamics of hybrid complex systems such as a city. The result of both responses are the notions of SIRN (synergetic inter-representation networks) [1], and IA (information adaptation) [2]. In my talk I'll follow the evolution of ideas from complexity theoryto CTC and then to SIRN and IA and the implications thereof to our understanding urban transformations through data.

- [1] Portugali, J. (2011). Complexity Cognition and the City.Springer, Heidelberg, Berlin.
- [2] Haken, H. and Portugali, J. (2015). Information Adaptation: The interplay between Shannonian and semantic information in cognition. Springer, Berlin. SpringerBriefs series.

COFFEE

THE CO-EVOLVING COMPLEXITY OF CITIES: TOWARDS SUSTAINABILITY?

Peter Allen , Complex Systems Research Centre, Cranfield University. founded the Complex Systems Research Centre that is now headed by Dr Liz Varga. The Centre is and has been involved in a wide range of research projects. Peter's research has demonstrated the relevance of complex systems modelling for many domains: ecology and ecological modelling; natural resource management; urban and regional systems; economic markets and the strategies of firms; for organizational structures as well as distribution and supply chains and networks. This work is continuing as there is now more understanding and demand for bottom-up, learning models for decision support of many kinds. Recent research projects include: an EPSRC funded research project with De Montfort University on creating Smart Grid models to help policies and infrastructure decisions for future energy production and distribution; and an ESRC funded joint project with Sheffield University "Modelling the Evolution of the Aerospace Supply Chain". Currently he is involved in the Falcon project with the IVHM Centre in Cranfield developing models relevant to the management of local electricity supply networks faced with growing demand for (low carbon) electricity. Another current project concerns the development of models to examine the way that multi-utility service firms may provide satisfactory levels of comfort with reduced resource demands. Peter is Editor in Chief of the journal Emergence: Complexity and Organization.

He has a PhD in Theoretical Physics, was a Royal Society European Research Fellow 1969 - 71 and a Senior Research Fellow at the Universite Libre de Bruxelles from 1972 - 1987, where he worked with Nobel Laureate, Ilya Prigogine. Since 1987 he has run two Research Centres at Cranfield University. For over 40 years Peter has been working on the mathematical modelling of change and innovation in social, economic, financial and ecological systems, and the development of integrated systems models linking the physical, ecological and socio-economic aspects of complex systems as a basis for improved decision support systems. A range of dynamic integrated models has been developed in such diverse domains as industrial networks, supply chains, river catchments, urban and regional development, fisheries and also economic and financial markets. Professor Allen has written and edited several books and published well over 200 articles in a range of fields including ecology, social science, urban and regional science, economics, systems theory, and physics. He has been a consultant to the Cambridge Econometrics, the Asian Development Bank, the Canadian Fishing Industry, Elf Aquitaine, BT, GlaxoSmithKline, DERA, DSTL, the United Nations University, and the European Commission.

Abstract: This presentation will elaborate the view that cities as complex systems are typified by co-evolutionary behaviour and organization. As a consequence, cities change, adapt and maintain rich, diverse and varied strategies, sub-optimal behaviours, imperfect information, mistaken inferences and creativity. In particular their dynamic spatial structures change as a result of the co-evolution not only of residences, meeting and working places, transport and communication networks, and leisure activities, but also the ideas, thoughts, desires and aspirations of their populations. The study of cities and regions as evolving complex systems was begun in the 1970s, with dynamic simulation models of cities and regions together with their land-use and transportation systems, and with studies of the evolution of single cities, regional city systems and urban hierarchies. Today, we are faced with the issue of sustainability as the effects of our successful growth lead to real questions of material and energy resources and of emissions and potential catastrophic climate change impacts. An agent based model has been developed of at least 10,000 randomly chosen households in terms of four domains: Living, Food, Mobility and Energy. The model looks at the adoption of possible innovations that can take us towards more sustainable lifestyles. The model explores changes in living space, occupancy and architecture, improved insulation, much reduced use of cars, increased community living, and the adoption of renewable energy production and the decentralization of the energy system. We will see some early results of the model and look at the prospects of ever attaining sustainable lifestyles.

Hopefully these models of Cities as complex, evolving systems can help guide policy and

decision making towards possible, realistic trajectories into the future that will allow the survival of our civilization.

BREAK-OUT SESSION

ECR team work with informal input from DACAS researchers.

LUNCH

BREAK-OUT SESSION

ECR team work with informal input from DACAS researchers.

COFFEE

ECR FEEDBACK PRESENTATIONS

This is a formal feedback session, in addition to the smaller informal tutorials that ECRs are expected to arrange with DACAS researchers. Here, ECR teams will present their progress to obtain interim feedback from DACAS researchers and other teams. Feedback will inform the final phase of collaborative work in preparation for final presentations on Day 5.

CLOSING

DAY 4

PARALLEL ECR BREAK-OUT SESSIONS AND WORK SESSIONS

ECR team work with informal input from DACAS researchers.

DAY 5

BREAK-OUT SESSION

ECR team work with informal input from DACAS researchers.

IN PARALLEL: DACAS INTERNAL

DACAS members will meet to discuss the outcomes (and outputs) from the summer school. Ideas for the forthcoming and final event in Wuhan (April 2017) will be exchanged and a strategy for preparation activities will be decided. Further to be discussed: potential joint publication and policy report for publication in June 2017.

COFFEE

ECR RESULT PRESENTATIONS PART 1

PhD/ECR teams will present their work. Specific instructions will be provided during the event.

LUNCH

ECR RESULT PRESENTATIONS PART 2

PhD/ECR teams will present their work. Specific instructions will be provided during the event.

DEPARTURE

CASE STUDY 01: SUSTAINING THE TRANSITION – A TALE OF TWO CITIES

Christopher Doll

with Allison Bridges, Christopher Bouch, Christopher Doll, Leandro GarciaCase Overview

Case Overview

This case contrasts the response to two health crises in India. One of the most recent outbreaks of pneumonic plague occurred in the city of Surat, Gujarat in 1994. A series of changes were made to the structural organisation of the city and improvements in sanitation brought many co-benefits. The city has gone from being one of the filthiest cities in India to being recognized as one of the cleanest. By contrast, Delhi struggles to manage ever increasing air pollution despite a raft of measures that have been introduced and constant legislative pressure. Why have measures worked in one case and not the other?

Problem Formulation

In the city of Surat, a serious health issue was tackled successfully with an approach based on 'localism'; and this approach seems to have had lasting benefits. In the city of Delhi, however, a range of approaches have been used to tackle what is arguably an equally serious health problem – that of air pollution – but with limited long term success. What has led to these markedly different outcomes?

Both cities chose to address the issues by changing existing governance processes and legislation. The changes were made against a background of the high levels of complexity inherent in today's large cities generally. The success of the changes will have been dependent to a large extent on how well they addressed the complexity of each city.

To some extent, Surat case is more straightforward than Delhi given the trigger for the plague was largely due to a single cause, in contrast to that of Delhi. It was concluded therefore, that attempting to identify the reasons for success in Surat, and then seeking to apply the lessons learned to air pollution control in Delhi would be the wrong approach; Surat's solutions were unlikely to address properly the complexity exhibited by Delhi. Instead, it was decided to concentrate problem formulation on consideration of Delhi itself.

Initially, problem formulation focused quite narrowly on thoughts of identifying the different types of pollutants, their relative importance in terms of the contribution they make to overall air pollution, and the sources of those pollutants; this approach seemed to have the benefit of being relatively tractable from a mathematically point-of-view. As policy and regulation is designed to incentivise changes in the point sources of various pollutants, such as large power plants or vehicles, evaluation of local polices normally begins with an understanding of the origin of the problem. As discussions progressed, however, it became clear that answering those questions was only a small part of the problem, and that the big issue was why steps taken by city government to tackle these pollutants had failed. From that the idea grew that the problem was one of governance, rather than chemistry (even if all air policy is based on the results of measuring the quality of the air), and that problem formulation should focus on that. The problem was then broadened to comprehensively take into account the various social and political factors that influence the degree to which governance action effectively decreases levels of pollutants that are a threat to human health

A wide range of governance strategies with the potential to influence the development of city air pollution policy and strategy, were identified. With globalisation in mind, it was recognised that actions to curb air pollution would have to take account of interests at global, national, regional, district and city scales. As there is a need for consensus among various stakeholders in designing and implementing action plans to address air quality, the importance of political cycles was also noted. This temporal element extended to consideration of horizon-scanning for emerging technologies that could have a beneficial effect and to the freedom of government to act quickly within the confines of existing supply chains. Alignment of physical/political boundaries was seen as important, with misalignment leading to conflicts in decision-making (either through overlapping jurisdictions or absence of control). Stakeholder identification was seen as a necessity, together with a clear understanding of the extent to which they were to be involved in establishing the 'root definition' of the problem, and arriving at a mutually acceptable accommodating solution. Linked with this was consideration of cultural issues such as local traditions and the likelihood of corruption; health, including physical and mental wellbeing; education; social standing and the power to influence; and existing transport and economic policies. Some of these factors are shown in the diagram in Figure 1.

Figure 1 indicates that problem definition must consider soft and hard systems: soft systems being those involving predominantly the actions of human beings, and hard systems being those involved in the design, construction and operation of infrastructure. Existing hard systems can be described through a process of reverse engineering aimed at eliciting system data for integration in system models. The level to which such systems should be defined is dependent on the question being addressed, and is something that would emerge in the course of an investigation. Soft systems, on the other hand, can be more difficult to describe for a variety of reasons, including difficulty in obtaining the necessary data. For soft systems the level of system definition again depends on the question being addressed: for example, from a quite detailed analysis of behaviour using agent-based techniques, to a higher level analysis employing heuristics of human behaviour.

Concept Transferability

During the discussions, several concepts, elements and methods of systems and complexity sciences stood out, suggesting that these two fields can offer helpful insights and approaches to deal with the air pollution issue in Delhi.

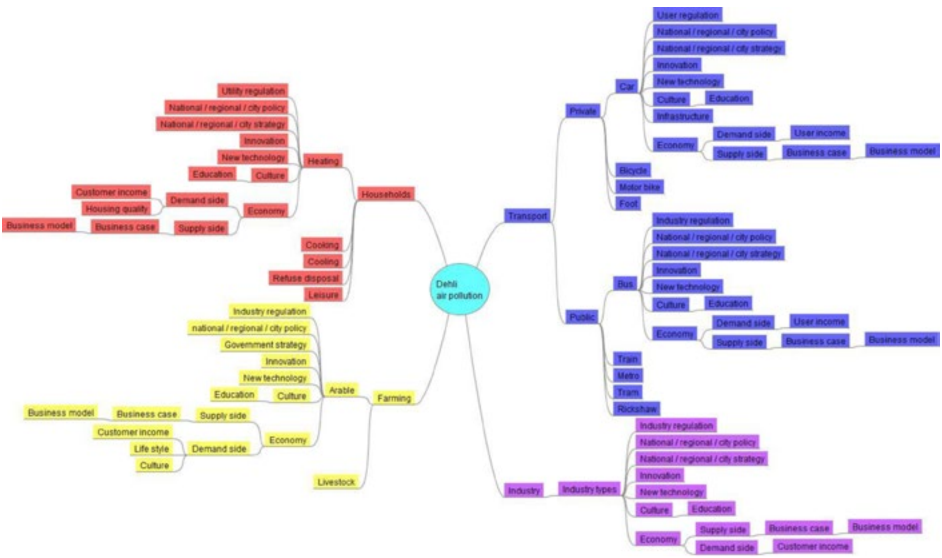
Phase transitions

Can phase transition analysis techniques from chemistry and biology be used to predict sharp changes in policy, as generally arising from a change of government following an election? As suggested above, positive alignment of government policies across national, regional and city scales is helpful to successful implementation of government initiatives. Alignment can change for better or worse during elections, with changes often being sudden and unexpected. Viewing these phase transitions may help generate knowledge that could be used to promote positive change, or militate against negative change (though this latter option may be seen as undemocratic).

Behavioural heuristics and game theory

Can human behaviour heuristics emerging from studies of psychology and behavioural economics help provide a better understanding of the decision-

Figure 1. Factors with the potential to influence governance actions to tackle air pollution in cities.



making processes around air pollution, and about how the population will respond to them? What sort of 'hard-wired' decision-making heuristics do humans use, and do these heuristics come with probability distributions? An example of such a heuristic is the 'hot hand syndrome', which takes its name from basketball. Basically, it is saying that if people observe a number of successful actions, they will expect subsequent actions to be successful as well. Can these heuristics be used to inform decision-making based on game theory?

Collective behaviour

To what extent can existing knowledge about the behaviour of large groups (for example, swarms and flocking) be applied to predict the response of city populations to actions aimed at curbing air pollution?

System dynamics and causal loops

Soft systems methodology has identified the importance of understanding how a system works as a first step towards improving things. Can the reverse engineering techniques of systems engineering help in this area? Can causal loop diagrams developed through reverse engineered models involving the stakeholders provide a framework for identifying sources of system value, which might help to promote adoption of better air pollution control measures?

Agent-based modelling

To what extent can agent-based modelling be used to tie all these approaches together? Work on collective behaviour etc. can contribute to development of the rules governing agent behaviour.

Morphogenetic engineering and urban metabolism

What can we learn from the way in which cells deal with waste management that could be applied to cities? To what extent does this tie in with the science of urban metabolism – particularly Pincetl's 'expanded', holistic view of urban metabolism, which takes account of politics etc.?

Appropriate Methods

As we advanced the discussions, it became clearer to us that the solution for the air pollution issue in Delhi should pass through to re-organizing the system, to better implement and operationalize schemes to lower pollutant emissions. That is, the several different sectors and stakeholders involved in the problem might reconcile or steer their individual goals and actions, and the best level of governance for critical points in the system might be found in order to deal with the problem.

The best course of action for us was, then, to use soft systems methodologies, which would help stakeholders (1) to have a broader sense of the systems' dynamics and structure, (2) to understand their role in the system and (3) to think of strategies to change the whole system to a more desirable state.

Bringing stakeholders together to discuss the air pollution issue in Delhi using soft systems methodologies would allow them to put their perspectives on the table, moving from individual mental models to a collective understanding about the problem. It is also an important empowerment exercise, as those involved in the problem would contribute to its solution, re-orienting the systems goals and functions.

Additionally, this approach would rely less on the knowledge we have about the India and Delhi context (governance structure, cultural context, legal issues etc.) and the scarcity of data to build a simulation model – two important limitations to adequately solve the problem – and more on shared knowledge and information by those within the system.

Model Typology

We suggest a three-step community-based participatory modelling. First, we would develop a causal loop (influence) diagram to map the elements and relationships, within and across levels of governance, involved in the air pollution issue in Delhi. Key sectors and stakeholders must be identified and invited to participate. The diagram would be constructed collectively by the stakeholders in two or three half-day workshops. These workshops would introduce the process of modelling and symbolism of a model to participants, create a shared vision of a modelling project and lead to the elaboration of a causal loop diagram. More details can be found elsewhere (see the Hovmand's works on 'Bibliography').

In the second step we would build a systems dynamics model based on the casual loop diagram and inputs from other stakeholders about the real system. This model would have an educational and experimental purpose. It would be a tool that allows stakeholders to test and 'play' with different decisions, strategies and governance levels in order to broaden the understanding of what factors influence the actual functioning of the system (pathways, delays, feedbacks, flows of information, bottlenecks etc.) and to gain insights into how to achieve more desirable outcomes.

Finally, further workshops with stakeholders would take place to allow them to put their hands on the systems dynamics model and facilitate the co-creation of a new governance architecture to tackle the air pollution issue in Delhi.

Conclusion

This case study showed us that successful experiences are not always fully transferable to other contexts, as from Surat to Delhi. Sometimes, the systems' structures and dynamics are too different and a fresh look is needed. Important lessons are often learnt the hard way.

Not all complex problems must rely only on mathematical and simulation methods. In complex social systems, the observed systemic resistance to changes comes, many times, from opposite goals and actions among stakeholders, each one pushing in a different direction. In these situations, a soft systems methodology would have great potential to solve these antagonisms and bring the whole system to a more desirable state for everyone.

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CASE STUDY 02: INTERDEPENDENT URBAN INFRASTRUCTURE SYSTEMS: HOW CAN THE PUBLIC TRANSPORTATION NETWORK IN LONDON BE MADE MORE RESILIENT AND ROBUST TO FLOODING?

Nils Goldbeck

with Eleanor Murtagh, Gabriela Depetri, Marcello R. A. F. Mello and Sandro Sousa

Case Overview: The functioning of large and populated cities is highly dependent on the operation and efficiency of local public transportation. Acute shocks and chronic stresses can have serious impacts on transportation networks when affecting streets and transport links. The aim of this paper is to suggest potential mechanisms to enhance the resilience of London's transportation network (bus, metro and train) to flood events. Firstly, the key flood threats to London's transport network are introduced, before the authors debate the concepts of resilience and robustness in relation to this scenario and propose appropriate definitions for this case, associating resilience to temporary measures, and robustness to permanent and long-term measures allowing the system to function even if a few links are removed. The addition of extra bus lines is proposed to make London's transport both more resilient and robust, according to outlined definitions. A model is offered to assess and analyse the benefits of additions of such extra lines to the London public transportation network.

Introduction

Public transportation systems are a vital component of any major city. By moving goods and people around the city, the public transport system is responsible for the majority of commutes occurred within the city. With approximately 8,6 million people [1], London is one of the largest capitals in the world. The public transport accounts for 33 % of all daily trips made in the city [2]. Transport for London has recorded nearly 3 billion passenger journeys per year in 2015 [3], including buses, London Underground, Docklands Light Railway and London Overground.

The expansion of urban centres, the subsequent modification of the environment and the effects of climate change on rain patterns have increased the risks and occurrence of flooding phenomena [4] which has an impact on public transport system. The flooding phenomena in London can be divided in two types: fluvial flood caused the elevation of the Thames produced by tidal movements, and pluvial flood caused by rain knowns as flash flood. Both phenomena are considered to be risks to the functioning of the public transport system, and can create shocks or disruptions altering the status of the system. This can cause a large-scale impact to the users and on the economy of the city due to delays. Whilst flood risk can never be completely eradicated, its impacts can be mitigated. Well-designed transportation systems are an essential factor in the economic welfare of major cities. Planning and designing the transport system requires a quantitative understanding of traffic patterns and relies on the ability to predict the effects of disruptions to such patterns, both planned and unplanned [5].

The determination of conditions under which complex networks are stable is an important challenge. In critical infrastructure networks, meeting the most important (or vulnerable) elements is crucial for providing more efficient and robust systems. In this context, robustness is understood as the ability of the system to absorb disturbance to its nodes (stops) or links (service lines) and continue to operate under the same conditions found in a normal situation, that is, continue connecting users to their destinations [6].

Robustness vs. Resilience

The concepts of resilience and robustness share similarities, but there can be subtle differences between them. Resilience is most associated with adaptation, the ability to self-recover from large-scale disturbances, returning to its original state or to adjust to a new state [7]. It was Holling's 1973 seminal work on resilience that stressed the importance of a system's ability to maintain its structure under duress and defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" [8].However, in academic works there are two distinct interpretations of how resilience relates to system state and disturbance: the engineering and ecological resilience approaches. Engineering resilience focuses on time spent to return to equilibrium after a disturbance, whereas ecological resilience refers to amount of stress or disturbance a system can withstand or absorb before altering state. The engineering resilience focuses on ensuring functional efficiency whereas ecological resilience is based on maintaining existence of function. On the other hand, robustness refers to the ability to absorb shocks and maintain continuous operating despite disruptions. Therefore a system is robust when it is able to continue functioning despite external shocks and changes to the original system. One may also think about robustness as a property of resilience, in the sense that, when a system has to recover it implies that the robustness has failed on a shorter time scale [9].

In any complex system, the structure that is seen depends on the level that one is observing. The debate on required characteristics for a transport system to be resilient and robust is still on-going; however when the authors, look at it being compounded by all of its sub systems, including personal staff, resilience properties are identified like self-healing for example, where transport personnel act immediately to restore the system to its original state in instances of failures or shock events. In a public transport network, resilience can be interpreted as emergency measures, such as the existence of maintenance staff and a series of contingency plans, including abandoning subway tunnels and activation of multiple extra bus service lines, based on demand, in case of flooding. Robustness would be associated to permanent changes in the network, such as the existence of permanent redundant routes, what would allow the system to keep functioning without the removed links.

Model

Models are one of the main instruments of modern science, with dozens of variations created to investigate different phenomena in nature and provide a simplified mathematical representation of a system of interest [10]. One of the main aspects in the definition of a model is the selection of variables and system's characteristics to be exploited, with the most important agents and variables identified in relation to the phenomenon under observation.

To investigate the identified problem, a hybrid model is proposed, merging different approaches to capture the properties that are being investigated (see Fig. 1). Transportation systems can be represented as a network, where the stations, terminals and stops can be interpreted as nodes and their lines and routes as links. The following diagram shows an abstract model combining a network flow model and a genetic algorithm that consumes input data and returns outputs to improve the system capabilities. This process works as a continuum flow, where outputs can be reintroduced to the system, updating its status and providing a method instead of a statical solution.

The diagram shows a data-driven model, that is, input data is used to tune the behaviour during simulations. The current system structure compounded by its stops and lines is used as the network topology input, with flood maps showing the areas with higher flood risk and origin-destination survey for transport demand. With this empirical data, the network flow model can calculate the most demanded lines, the stops with higher connectivity and proximity of stations to flood-risk areas. In the next step, the genetic algorithm uses this model to propose additional lines and paths that could improve the robustness of the network, avoiding risk areas. A variable with the number of buses is included to help planning agencies get more realistic results based on their budget.

After some interactions, the model returns the flows of the network with a proposal of new lines to be added temporarily. According to our definition, this

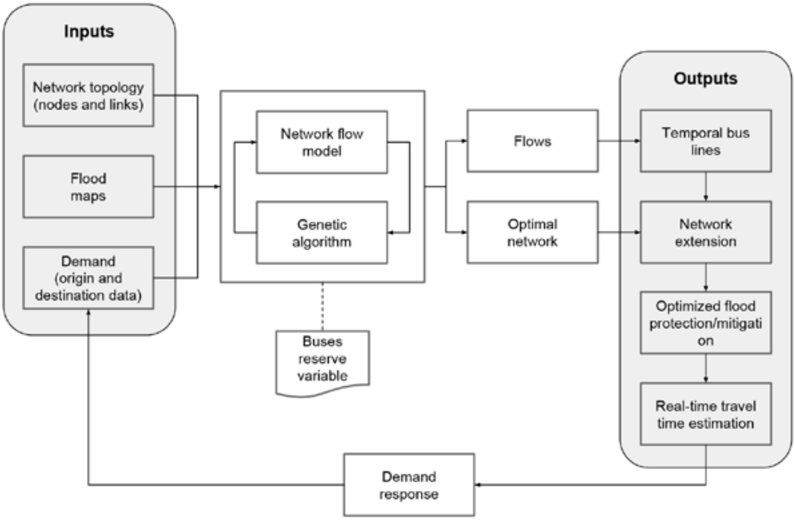

Figure 2: Hybrid model that uses a network flow and a genetic algorithm to propose new lines to the transport system. The results are used again as inputs, providing a continuous framework to evaluate the transport in long and real-time.

measure would make the network more resilient. Also, based on passenger usage, or even on the decrease of the average time of travel per passenger, they can become permanent, which would contribute to make the network more robust. With this new topology, the flooding areas can be avoided or at least have alternative routes proposed in the case of interruptions. These outputs can be used again as inputs to the model as a monitoring framework, using real-time data, allowing the system to learn and adapt to any kind of interruption, not only floods.

Data and Methods

One of the biggest challenges of modelling real systems is to acquire data and process it to obtain useful information. This data is required to drive the modelling process and to validate it against reality, comparing simulated results with empirical observations. The network topology can be easily obtained from traffic agencies, requiring some adjustments to correct data gaps and create the graph. The network connectivity can be built based on bus stops and subway lines that are serviced by at least one line. The sequence of two stops attended by a line characterize the link between them, as can be seen in Fig. 3.

In the same way, flood risk maps can be obtained from meteorological agencies or estimated based on rain and terrain elevation. In fact, there are terrain models that can simulate how rain water could behave based on surface topology [11], but more attention is required in the case of cities as they possess water flow systems for this situations. Another way is to track statistics data from past incidents and map where they are frequently located.

Origin and destination surveys are commonly carried out by traffic agencies and historic data can be obtained, however data often has large decade-long time intervals. In best situations, ticketing data can be extracted from the system's billing, granting a richer and more precise picture of traveller's behaviour. With this ticketing information, the location where the passenger boarded can be obtained based on the GPS of buses, or in the case of subway, the location of the station of first use. Analysing this data for a period (week for example), the origin and destination of a passenger can be inferred based on frequencies and periods that the system is used.

Conclusions

Cities are made up of systems, including ecosystems, utilities, economies and transportation systems to form complex systems. Each part of this system and its subsystems are reliant on other parts. This is the case of London's transportation network, which is highly interconnected. Whilst flood risk is a significant concern to London, the impacts of flood events on the

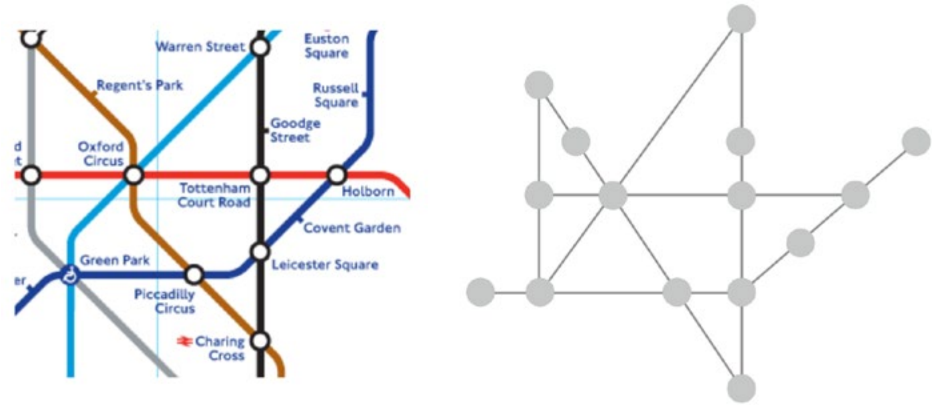

Figure 3. Part of London tube network represented as a network (graph). Service lines are interpreted as edges and stations as vertex. Source: Transport for London https://tfl.gov.uk/maps/track/tube.

transportation system can be mitigated and reduced. The authors suggest the use of a hybrid network flow and genetic algorithm model to assess the risk of flooding at station level, and suggest alternative routes to avoid disturbance and maintain functioning of the system as a whole. Interpretations of resilience within complex adaptive systems see it as the ability of system to withstand, recover from and reorganise after a crisis event, with function maintained but system structure potentially altered. Resilience is then associated with temporary measures to recover from interrupted links in the short-term scale, whereas robustness is associated with permanent, long-term changes in the network, allowing it to keep functioning even when some links are removed. It is discussed in the study here, where the transportation system of London's future resilience may be due to the flexibility of being able to add or alter lines in the case of a flood incident, while its robustness may be due to the existence of redundant routes.

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CASE STUDY 03: THE CO-EVOLUTION OF AUTONOMOUS MOBILITY-ON-DEMAND (AMOD) SYSTEMS AND HUMAN-DRIVEN VEHICLES

Cuauhtemoc Anda

with Nir Oren, Ulysses Sengupta and Ana Bazzan

Introduction

Mobility-on-demand (MoD) services under the flag of Uber's disruptive business model have made a breakthrough in the way we travel in big cities. New door-to-door mobility options have been added to the available options from which a commuter can choose. These new transportation systems leverage on information and communication technologies, enabling service requests from a smartphone and online payments.

However, urban mobility is just entering a tipping point1 with four mayor innovations in the car manufacturing industry coming through: in-vehicle connectivity, electric vehicles, car sharing, and autonomous driving. Big firms such as Google and Tesla have started testing their autonomous vehicles (AVs) with plans from Google to make them available to the public in 20202. In addition, smaller competitors like nuTonomy a spinup from MIT has recently partnered up with Singapore's Land Transport Authority (LTA) to deliver a fleet of autonomous taxis by 20183.

It is then in the research community outlook, not only to finalise the development of the self-driving technology, but also address the implications in a broader scale, the city scale. What sort of interactions from self-driving and manned vehicles can we expect from a higher perspective? Understanding the general panorama of both systems competing in the same urban space to service the cities' travelling needs will make us realise the real contributions of AV's in a multi-modal transport setting, and if we can consider AVs as part of the sustainable transport ecosystem.

In this perspective we analysed autonomous mobility-on-demand (AMoD) systems/services constituted by a fleet of AVs. AMoD has emerged as a promising solution for urban transportation. Compared to prevailing systems, AMoD promises sustainable, affordable personal mobility through the use of self-driving shared vehicles. For instance, AMoD systems are a future prospect to solve the last-mile problem, balance the overall efficiency of the transportation network, and, due to its autonomy, overcome the fundamental load balancing problem of conventional mobility-on-demand services.

Hence, the current case study analyses the interactions and evolution of three players: the commuters, the traditional manned-vehicle services (e.g. taxi), and the inclusion of an AMoD service. All parties are represented as agents with their own utility/fitness functions they seek to optimise. The simulation will output the emergent behaviour derived from the different dynamics and interactions of the three players and their inherent evolution towards their optimisation in time, cost, and space. This will ultimately help us understand from the city level perspective the interactions between self-driving and man-driven vehicles and to assess under what conditions AMoD systems are a sustainable option.

Problem Definition

Parting from the travel demand data generated in the New York City Taxi and Uber datasets, we would like to understand the indirect interactions of AMoD systems and conventional transportation services (taxi) on servicing the NYC's travel demand. Find the optimal parameters and operation policies for an AMoD fleet and analyse the evolution of users' choice in a mixed-traffic setting. From the fleet management perspective, find out the optimal number of dispatch units needed to cover the demand of NYC, and find the optimal coordinated dispatching, route choice, and rebalancing policies for the AMoD fleet. Furthermore, we would like to explore under what market penetration rates, are AMoD systems improving the overall transportation performance, and if the inclusion of AVs can be considered part of sustainable solution. Hence, the aims of the proposed case scenario are two-fold:

1) Explore suitable fleet management strategies for AMOD systems. Find optimal control strategies for request assignment, route choice and the rebalancing problem. And also on the economic dimension: fleet sizing and financial analyses.

2) On a higher level (city level) assess the interactions with manned vehicles and how the competition between both services affects the user's choice and the transportation system overall performance.

Concept Transferability

1. Multi-agent based simulations

Agent-based models (ABM) from the Complex Systems domain are computational models to simulate the actions and interactions of autonomous agents with a view of assessing their effects on the system as a whole. In the concept of multi-agent simulations, the goal is to search for explanatory insight into the collective behaviour of agents obeying simple rules. They are a type of micro scale model that simulates the simultaneous operations and interactions of multiple agents in an attempt to re-create and predict the appearance of complex phenomena. In this sense, a key notion is that simple behavioural rules generate complex behaviour.

For large-scale transportation systems, activity based models can be implemented through multi –agent base simulations. Agents represent people willing or in need to travel to perform activities. Thus, each agent has a set of daily activities. They are able to make their own decisions such as route choice, mode choice and time of departure. In the case study, user agents, will be represented by the demand generated from the NYC Taxi and Uber datasets. The study will explore the evolution of the agents' decision towards which mode of transport maximises their own utility (mainly driven by waiting time and cost) between AMoD services and conventional personal mobility services (e.g. Taxis, Uber).

For the supply side, we need another type of agents to represent the AMoD fleet and the fleet of Taxis. On a mesoscopic level the main difference in the salient behaviour between the two is not the model but the control strategies (e.g. closed-loop, coordinated, intelligent) for the assignment, routing and rebalancing tasks. Hence, the dynamics and control of an AMoD system can be divided in two tasks: firstly, when an AMoD unit is active, the route can be selected to balance the overall system performance by routing vehicles through less-congested roads; and secondly, when the unit is not in use (i.e. idle state), the AMoD system can redistribute AVs to better meet demand through an automated balancing strategy. These control strategies should be built along the coordination capabilities of the AV fleet to respond to a diversity of stochastic events in an uncertain and complex setting. Interactions between the AMoD, the conventional taxi service and the NYC travel demand will result in emergent phenomena such as traffic jams.

For this task, the case study can be implemented in one of the two most widely used available open frameworks to develop multi-agent transportation simulations on a large scale: MATSim4 (java-based) or SimMobility5 (c++-based).

Reinforcement Learning

Once the multi-agent scenario has been set, the second challenge to be solved is the fleet management strategy implementation for the AMoD system. By leveraging on the self-driving technology and coordinated algorithms, the control strategies for the AMoD system make the significant difference in the mesoscopic simulation in comparison to the fleet of conventional taxis. Hence, to find optimal policies for the AMoD fleet management tasks, routing and rebalancing, a promise approach is the Reinforcement Learning (RL) paradigm in the context of optimal control, and specifically, multi-agent reinforcement learning.

Reinforcement Learning is very closely related to the theory of classical optimal control, as well as dynamic programming, stochastic programming, simulation-optimization, stochastic search, and optimal stopping (Powell, 2012). Both RL and optimal control address the problem of finding an optimal policy (often also called the controller or control policy) that optimises an objective function (i.e., the accumulated cost or reward), and both rely on the notion of a system being described by an underlying set of states, controls and a plant or model that describes transitions between states. However, optimal control assumes perfect knowledge of the system's description in the form of a model (i.e., a function T that describes what the next state of the robot will be given the current state and action). For such models, optimal control ensures strong guarantees which, nevertheless, often break down due to model and computational approximations. In contrast, reinforcement learning operates directly on measured data and rewards from interaction with the environment. Reinforcement learning research has placed great focus on addressing cases which are analytically intractable using approximations and data-driven techniques. The goal of reinforcement learning is to discover an optimal policy that maps states (or observations) to actions so as to maximize the expected return J, which corresponds to the cumulative expected reward. (Kober, Bagnell, & Peters, 2013)

Why Reinforcement Learning?

For the case study, Reinforcement learning is an appropriate method since we want to find optimal policies for routing and the rebalancing problem under complex scenarios, for which we don't possess a model of the world. Thus, from the events experienced by the fleet of AVs, we would like the AMoD systems to learn what are the best actions under different stochastic conditions as to optimised travel times, energy consumption and maximised profit.

Data Availability

In order to derive the travel demand for New York City, two open datasets are available to set up the initial conditions for our multi-agent simulation framework.

- NYC Taxi Data

The official TLC trip record dataset contains data for over 1.1 billion taxi trips from January 2009 through June 2015, covering both yellow and green taxis. Each individual trip record contains precise location coordinates for where the trip started and ended, timestamps for when the trip started and ended, plus a few other variables including fare amount, payment method, and distance travelled.

Link: https://github.com/toddwschneider/nyc-taxi-data

- Uber Data

Data covering nearly 19 million Uber rides in NYC from April–September 2014 and January – June 2015. In particular Uber provides time and location for pickups only, not drop offs.

Link: https://github.com/fivethirtyeight/uber-tlc-foil-response

Literature Review

Modelling, simulation and control of AMoD systems

Autonomous on-demand (AMoD) systems, constitute a transformative and rapidly developing mode of transportation wherein robotic, self-driving vehicles transport passengers in a given environment. Specifically, Pavone (2014) addresses AMoD systems along three dimensions: (1) modeling, that is analytical models capturing salient dynamic and stochastic features of customer demand, (2) control, that is coordination algorithms for the vehicles aimed at throughput maximization, and (3) economic, that is fleet sizing and financial analyses.

Pavone (2014), Zhan and Pavone (2014), Zhang, Spieser, Frazzoli, and Pavone (2015) propose a dedicated model of an AMoD system, in which a spatial queue model is used to manage the stochastic travel requests generated in a defined map. And thus the problem to find an optimal policy for the AV's to serve the requests is turn into an operations research problem: joint task allocation and scheduling problem. They proposed a closed-loop control policy based on the Dynamic Traveling Repairman problem and on the Dynamic Traffic Assignment problem. Firstly, they transform the AMoD system into a closed Jackson network with respect to the vehicles, where the equilibrium distribution of a queueing network is possible to compute as the product has a product-form solution. Secondly, to rebalance the vehicles to ensure even vehicle availability, the strategy was to add virtual customer streams. The model and control strategy was tested for the cities of New York and Singapore.

A more recent approach for the AV fleet control is the one by Zhang, Rossi, and Pavone (2016). They proposed a model predictive control (MPC) from the control theory domain for a station-based management of an AMoD system. They firstly built a discrete-time model of the dynamics of the AV fleet, and secondly designed a model predictive control algorithm for the optimal coordination of the AMoD system. At each optimisation step, the vehicle scheduling and routing problem is solved as a mixed integer linear program where the decision variables are binary variables representing whether a vehicle will wait at a station, service a customer, or rebalance to another station. One of the major contributions was the inclusion of charging constraints associated with using electric vehicles.

However, while Pavone (2014), Zhan and Pavone (2014), Zhang, Spieser, Frazzoli, and Pavone (2015) work was tested in large-scale, the control approach cannot cope with realistic phenomenon such as congestion and interaction with human-driven vehicles. They conclude that future research should come up with efficient control algorithms for increasingly more realistic models. On the other hand, the model predictive control from Zhang, Rossi, and Pavone (2016) although it takes into account more realistic constraints (e.g. charging stations), it still needs to be scale up for city-wide systems, since the computational complexity of the mixed integer linear program scales exponentially with the number of stations and vehicles. Moreover, they conclude that the inclusion of the congestion aspect and optimal coordination algorithms in an intermodal system are a matter of future research.

With the proposal of a multi-agent simulation framework, the case study can address the limitations described with a city-scale multimodal platform, in which the interactions from human-driven vehicles and AVs, as well as congestions are capable to emerge. As for the AMoD's control strategy the inclusion of a Reinforcement Learning (RL) approach would account for the uncertainties in the real world, for both the routing and rebalancing policies.

RL paradigm leverages the robotics domain and capabilities of the AV fleet, where it has been proved successful for the solution of optimal problems under uncertain environments.

Agent-based simulation for AMoD

For large-scale transportation systems, the inclusion of a fleet of taxis and autonomous taxis as another class of agents has been already implemented in both MATSim and SimMobility. Hörl, Erath, and Axhausen (2016) have included the modelling infrastructure for the simulation of AVs in MATSim. As for SimMobility, Marczuk et al. (2015) included a module for AVs in the short-term simulator, which simulates the individual decisions and the transportation network at the sub-second level. In both cases they have initially tested the simple cases for the fleet management tasks: FIFO service and nearest assignation, routing according to the network free speeds, return to the original station or wait at drop-off rebalance strategies. However, the bases are settled for the proposal and inclusion of more efficient control algorithms in the large-scale, multimodal setting offered by both platforms.

Reinforcement Learning

Even though a formal control strategy for an AMoD system through reinforcement learning has not been proposed yet, several studies can be used as starting point for the case study development.

As an anchor point, the work by Bazzan (2008) on opportunities for multiagent systems and multiagent reinforcement learning in traffic control, highlights how can open problems in traffic engineering can be approach through coordination algorithms and reinforcement learning for multiagent systems. Later on, Tavares and Bazzan (2012) proposed a reinforcement learning approach for route choice in traffic scenarios, which relies solely on drivers' experience to guide their decisions. Experimental results demonstrate that reasonable travel times can be achieves and vehicles can be distributed themselves over the road network avoiding congestion. Along the routing choice line, Cox, Jennings, and Krukowski (2013) adapted the Q-Routing algorithm, originally developed for packet routing in communication networks and inspired by the Q-learning algorithm, for an adaptive routing strategy of AVs shortest path planning in congested networks.

Another focus of reinforcement learning in vehicle trajectories is the optimisation of a taxi route to maximise the revenue (Wang and Lampert, 2014). Although the optimisation process is set for one vehicle, if extended to a fleet of taxis, the overall fleet's efficiency could be greatly improved (less particles emitted), drivers would minimise their vacancy time and working hours, and passenger could see better Taxi coverage.

In the case study, the main motivation towards using RL is to leverage the capabilities of the AV fleet when encounter with a networked, heterogeneous, stochastic decision problem with uncertain information. In a coordinated and self-organised manner, RL is an important piece of the puzzle to learn optimal policies under uncertain events and complex scenarios. In addition, this will allow us to explore the possibility to balance the global transportation system utility using the AMoD system.

Research Questions

- Would AMoD systems decrease congestion? In general, do AMoD systems represent an economically viable, sustainable, and societally-acceptable solution to the future of personal urban mobility?
- Can the inclusion of an AMoD system be used to reach the transport system overall optimal performance?
- For which percentage of AVs inclusion can we start having increments in the overall efficiency of the network without sacrificing individual utility too much?
- How does the user's choice evolve when an AMoD system is included based on lower pick-up times, but for some penetration rates of AVs longer travel times?
- In the competition game between AMoD vs manned MoD services, what is the user's expectancy on improved waiting and travel times? Based on these factors, how do the users' choice evolve in terms of the preferred service selection?
- What is an optimal fleet size for the AMoD system under competition for a fixed demand? (see Boesch, Ciari, & Axhausen, 2016 for fleet size and quality of service)
- What is an optimal route choice algorithm for a fleet of AVs?
- What is an optimal rebalancing strategy? What are the trade-offs between different strategies?

Research Output

A platform to evaluate coordinated control strategies for AMoD systems with complex stochastic interactions in a large-scale multimodal setting.

Future research possibilities

- Trip sharing and autonomous vehicles. How to include efficient algorithms and simulations of sharing trips.
- Exploring pricing mechanism boundaries for the optimality of both service providers (cost) and users (cost and waiting time).

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PARTICIPANTS

DACAS RESEARCHERS

NAME	AFFILIATION	CONTACT
Alexandros Gasparatos	University of Tokyo, Japan	gasparatos.alex@gmail.com
Christopher Doll	United Nations University, Japan	doll@unu.edu
Deljana Iossifova	University of Manchester, United Kingdom	deljana.iossifova@manchester.ac.uk
Eric Cheung	Manchester Metropolitan University, United Kingdom	cheungpye@gmail.com
Jun LUO	Wuhan University, China	junluo_cbtgc@163.com
Murilo Batista	University of Aberdeen, United Kingdom	murilo.baptista@abdn.ac.uk
Rene Doursat	Manchester Metropolitan University, United Kingdom	r.doursat@mmu.ac.uk
Robert Hyde	Manchester Metropolitan University, United Kingdom	r.hyde@mmu.ac.uk
Roberto Kraenkel	São Paulo State University, Brazil	kraenkel@ift.unesp.br
Shidan CHENG	Wuhan University, China	chsd821@163.com
Ulysses Sengupta	Manchester Metropolitan University, United Kingdom	u.sengupta@mmu.ac.uk

INVITED GUESTS

NAME	AFFILIATION	CONTACT
Denise Pumain	National Center for Scientific Research, France	pumain@parisgeo.cnrs.fr
Juval Portugali	Tel Aviv University, Israel	juval@post.tau.ac.il
Katharine Willis	Plymouth University, United Kingdom	katharine.willis@plymouth.ac.uk
Michael Weinstock	Architectural Association, United Kingdom	mweinstock@aaschool.ac.uk
Peter Allen	Cranfield University, United Kingdom	p.m.allen@cranfield.ac.uk
Piyushimita Thakuriah	University of Glasgow, United Kingdom	Piyushimita.Thakuriah@glasgow.ac.uk

NAME	AFFILIATION	CONTACT
Adam Brennan	Manchester Metropolitan University, United Kingdom	ambrennan@live.co.uk
Claire Little	Manchester Metropolitan University, United Kingdom	clairelittle7@gmail.com
Eda Acara	Ankara University & Middle East Technical University, Turkey	edacara@gmail.com
Gabriela Depetri	University of São Paulo, Brazil	gdepetri@if.usp.br
Gemma Todd	Ifakara Health Institute, Tanzania	gemmatodd1@msn.com
Martin Schulwitz	Research Institute for Regional and Urban Development (ILS), Germany	martin.schulwitz@ils-research.de
Moozhan Shakeri	University of Manchester, United Kingdom	moozhan.shakeri@manches-ter.ac.uk
Nir Fulman	Tel Aviv University, Israel	fulmannir@gmail.com
Oana Ilnitchi	Manchester Metropolitan University, United Kingdom	oana.g.ilnitchi@stu.mmu.ac.uk
Patrizia Sulis	University College London, United Kingdom	patrizia.sulis.14@ucl.ac.uk
Peter Bus	Swiss Federal Institute of Technology, Switzerland	bus@arch.ethz.ch
Sandro Sousa	University of São Paulo, Brazil	sandrofsousa@gmail.com
Shanaire Blythe	Manchester Metropolitan University, United Kingdom	shanaire.blythe@stu.mmu.ac.uk
Sibtay Haider	State University New Jersey	sibtaylahyder@gmail.com
Solon Solomou	Manchester Metropolitan University	solon.solomou@stu.mmu.ac.ukW

PRACTICALITIES

GROUND TRANSPORTATION FROM MANCHESTER AIRPORT TO IBIS HOTEL

Option 1:

See map on next page.

Train Service to Manchester Piccadilly Station. This is the cheapest option, which costs around £5. The destination you have to take varies as train services run 7 days a week through national train operators 'TransPennine Express' and 'Northern Rail'. Trains run every 10 minutes to Manchester Piccadilly, with an average journey time of 20 minutes. From Piccadilly Station follow the steps below:

- Upon arriving to the station, exit the station following the escalators down.
- Once outside the station, you will be at the junction of Fairfield Street and A6 London Road. You can either take a taxi (situated outside the station) or walk. Follow Fairfield Street east keeping Piccadilly station on your left. After walking under the railway arch, turn left onto Travis Street. Head straight until you reach the alt of Great Ancoats Street. The hotel is located opposite on the other side of the Street.

Option 2:

By taxi - As you get out of the terminal, you will see taxi services. There are black caps located on the sidewalk just outside the airport and you can pay with credit card. The ride from the airport to the hotel will cost around £25-30.

The hotel address is: 2 Pollard Street - Manchester - M4 7DB. The trip should take 25-30 minutes depending on traffic.

GROUND TRANSPORTATION FROM MANCHESTER AIRPORT TO ARORA HOTEL

Option 1:

See map on next page.

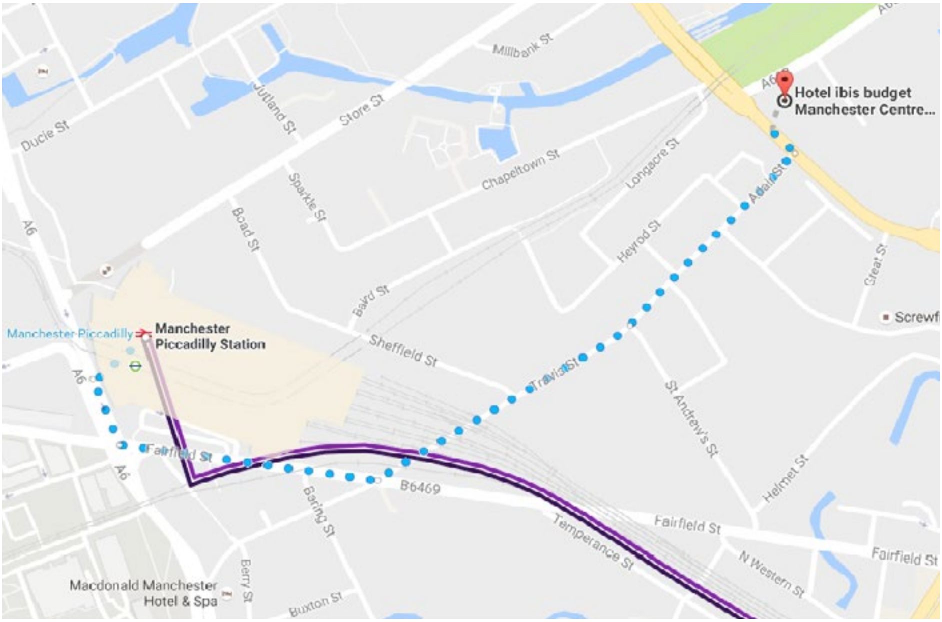
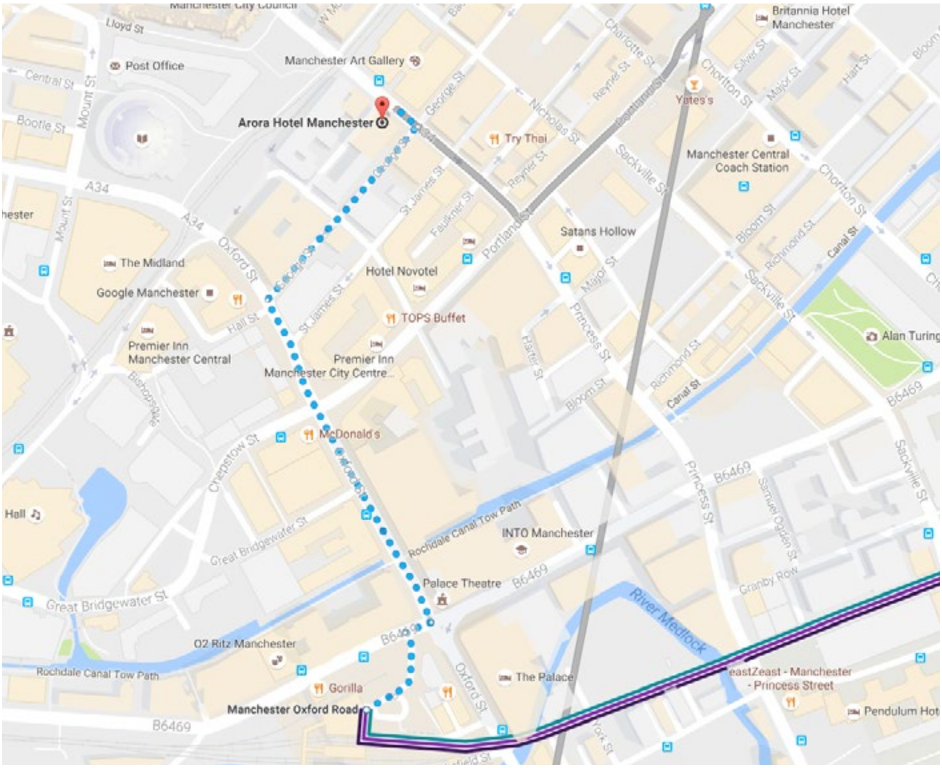
Train Service to Manchester Oxford Road Station. This is the cheapest option, which costs around £5. The destination you have to take varies as train services run 7 days a week through national train operators 'TransPennine Express' and 'Northern Rail'. Trains run every 10 minutes to Manchester Oxford Road, with an average journey time of 20 minutes. From Oxford Road Station follow the steps below:

- Upon arriving to the station, exit the station through the turnstiles.
- Once outside the station, follow the down-slopping road down to the Palace Theatre junction. You can either take a taxi (situated outside the station) or walk. Follow Oxford Street north keeping the Palace Theatre on your right. After reaching the restaurant Don Giovanni there will be a big contemporary white building on the right side of the street. Turn right onto George Street before the building. Head straight until you reach the second left turn onto Princess Street. The hotel is located opposite on your left.

Option 2:

By taxi - As you get out of the terminal, you will see taxi services. There are black caps located on the sidewalk just outside the airport and you can pay with credit card. The ride from the airport to the hotel will cost around £25-30.

The hotel address is: 18-24 Princess Street - Manchester - M1 4LG. The trip should take 25-30 minutes depending on traffic.


Hotel ibis budget Manchester Centre...
Manchester Piccadilly
Manchester Piccadilly Station
Millbank St
Ducie St
Jutland St
Store St
Chapeltown St
Longacre St
Sparkle St
Boad St
Adair St
Heyrod St
Baird St
Sheffield St
Travis St
St Andrew's St
Fairfield St
B6469
Baring St
Temperance St
Helmet St
Great St
Screwfi
N Western St
Berry St
Buxton St
Macdonald Manchester Hotel & Spa
A6

Lloyd St
Post Office
Central St
Bootle St
Mount St
Manchester Art Gallery
Arora Hotel Manchester
George St
Try Thai
Nicholas St
Charlotte St
Reyner St
Portland St
Yates's
Chorlton St
Silver St
Major St
Hart St
Britannia Hotel Manchester
Manchester Central Coach Station
Sackville St
A34
Oxford St
St James St
Faulkner St
Satans Hollow
Hotel Novotel
The Midland
Google Manchester
Hall St
TOPS Buffet
Premier Inn Manchester Central
Premier Inn Manchester City Centre...
Bishopsgate
Princess St
Harter St
Bloom St
Richmond St
Canal St
Alan Turing
B6469
McDonald's
Chepstow St
Great Bridgewater St
Rochdale Canal Tow Path
INTO Manchester
Palace Theatre
River Medlock
Granby Row
Samuel Ogden St
O2 Ritz Manchester
Gorilla
Manchester Oxford Road
The Palace
eastZeast - Manchester - Princess Street
Pendulum Hot
Hall

GROUND TRANSPORTATION FROM MANCHESTER AIRPORT TO PENDULUM HOTEL

Option 1:

See map on next page.

Train Service to Manchester Piccadilly Station. This is the cheapest option, which costs around £5. The destination you have to take varies as train services run 7 days a week through national train operators 'TransPennine Express' and 'Northern Rail'. Trains run every 10 minutes to Manchester Piccadilly, with an average journey time of 20 minutes. From Piccadilly Station follow the steps below:

- Upon arriving to the station, exit the station following the escalators down.
- Once outside the station, you will be at the junction of Fairfield Street and A6 London Road. You can either take a taxi (situated outside the station) or walk. Follow London Road south, after walking under the railway arch, turn right onto Altrincham Street. Head straight through the vehicle barriers until you reach the alt of Sackville Street. Turn left onto Sackville Street, the hotel is located on your right past Retro Bar.

Option 2:

By taxi - As you get out of the terminal, you will see taxi services. There are black caps located on the sidewalk just outside the airport and you can pay with credit card. The ride from the airport to the hotel will cost around £25-30.

The hotel address is: Sackville Street - Manchester - M1 3BB. The trip should take 25-30 minutes depending on traffic.

GROUND TRANSPORTATION FROM MANCHESTER AIRPORT TO MERCURE HOTEL

Option 1:

See map on next page.

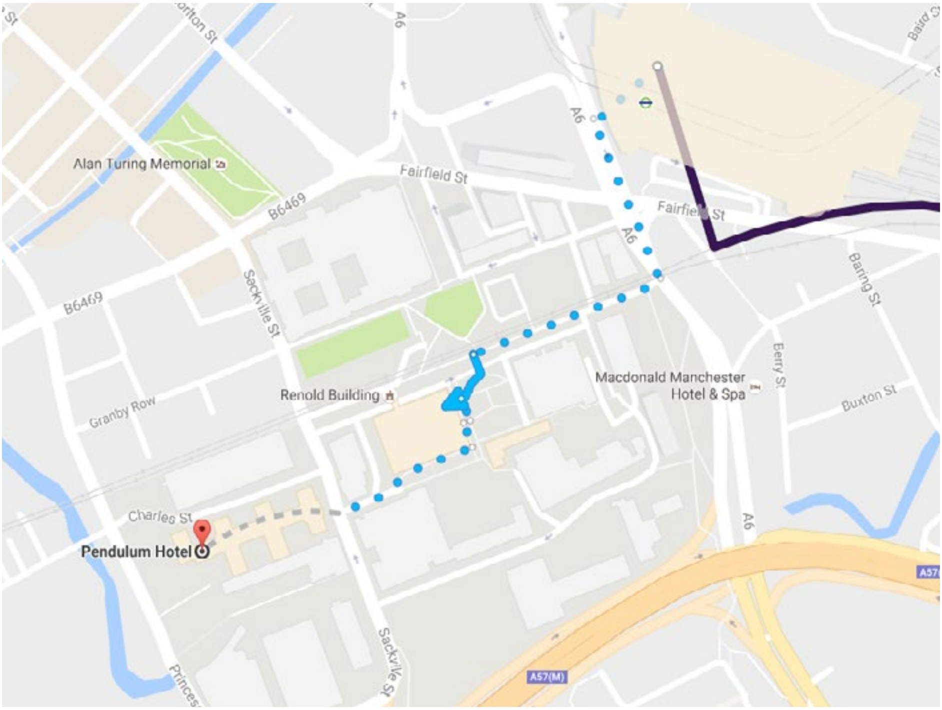
Train Service to Manchester Piccadilly Station. This is the cheapest option, which costs around £5. The destination you have to take varies as train services run 7 days a week through national train operators 'TransPennine Express' and 'Northern Rail'. Trains run every 10 minutes to Manchester Piccadilly, with an average journey time of 20 minutes. From Piccadilly Station follow the steps below:

- Upon arriving, exit the station through the exit located next to WHSmith
- Once outside the station, walk across the footbridge and down to Aytoun Street. Cross the road and walk into Auburn Street. Follow the road until the alt of Minshull Street. Turn right on Minshull Street and head straight until the alt. The hotel is located across the street.

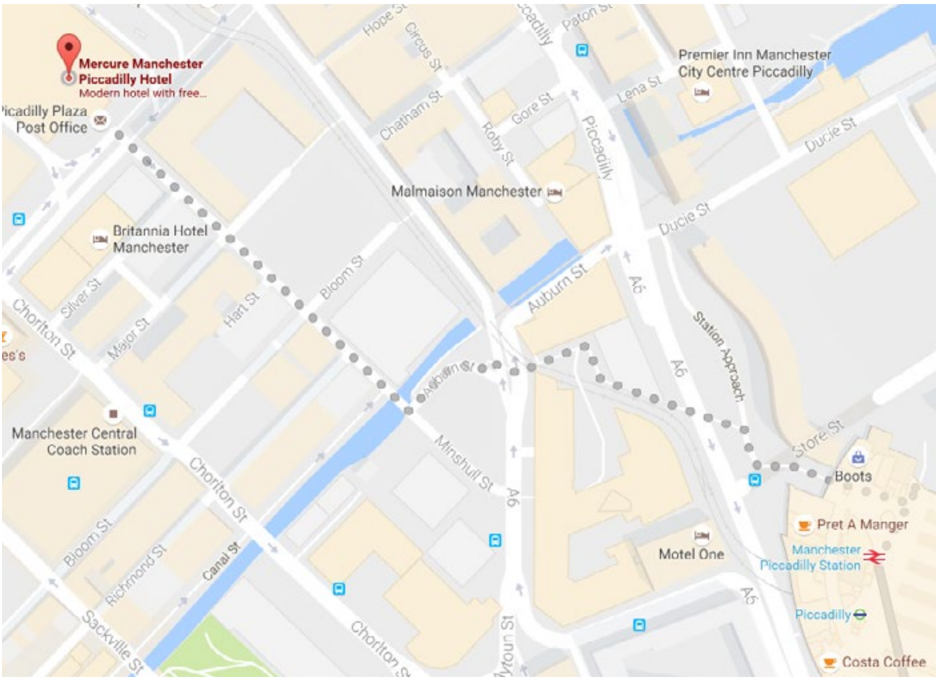
Option 2:

By taxi - As you get out of the terminal, you will see taxi services. There are black caps located on the sidewalk just outside the airport and you can pay with credit card. The ride from the airport to the hotel will cost around £25-30.

The hotel address is: Portland St - Manchester - M1 4PH. The trip should take 25-30 minutes depending on traffic.



Alan Turing Memorial
Fairfield St
B6469
A6
Sackville St
Renold Building
Macdonald Manchester Hotel & Spa
Granby Row
Charles St
Pendulum Hotel
Baring St
Berry St
Buxton St
A57(M)



Mercure Manchester Piccadilly Hotel
Modern hotel with free...
Post Office
Britannia Hotel Manchester
Manchester Central Coach Station
Malmaison Manchester
Premier Inn Manchester City Centre Piccadilly
Piccadilly
Ducie St
Auburn St
Station Approach
Store St
Boots
Pret A Manger
Manchester Piccadilly Station
Piccadilly
Costa Coffee
Motel One
Minshull St
Chorlton St
Bloom St
Chatham St
Roby St
Gore St
Lena St
Hope St
Circus St
Silver St
Major St
Hart St
Richmond St
Canal St
Sackville St
A6

GROUND TRANSPORTATION FROM IBIS HOTEL TO THE VENUE

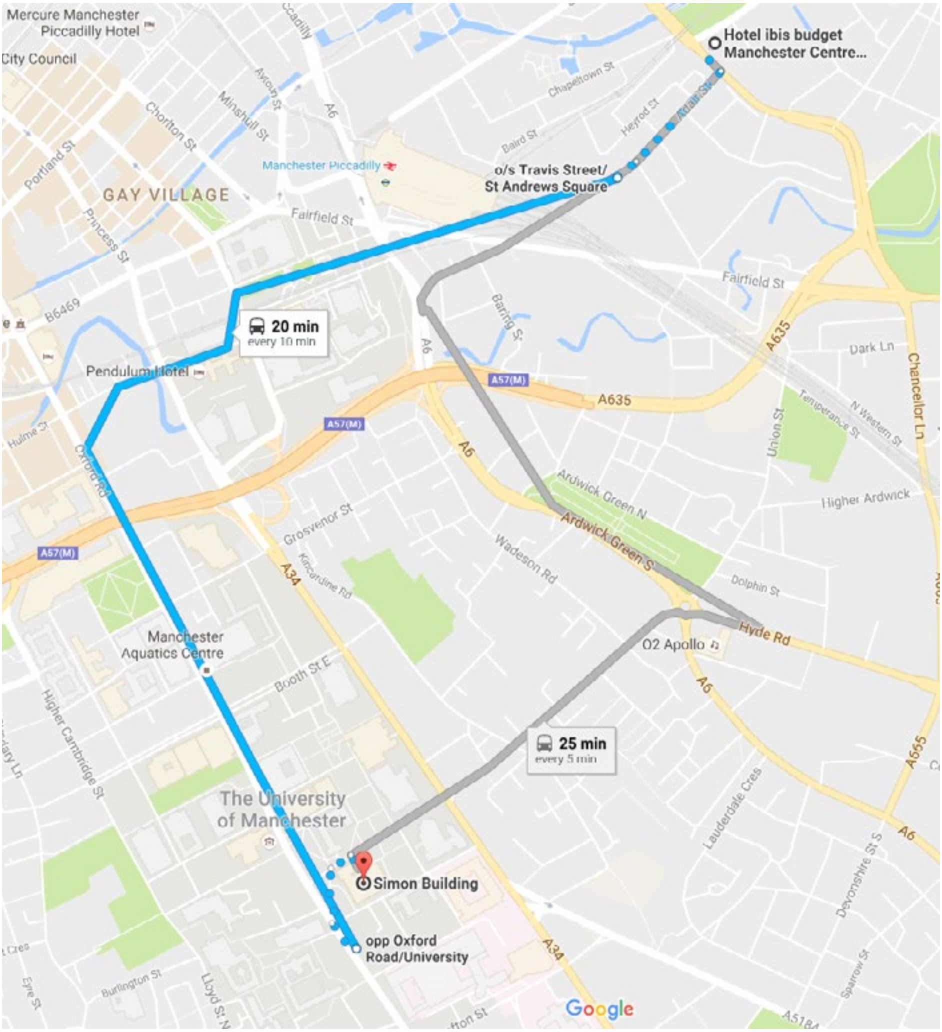
The whole journey takes around 20 minutes (see next page for map):

- Walk down Adair Street opposite the hotel until you reach Manchester Van hire down Travis Street. The bus stop is located 50 metres down the road from Manchester Van hire.
- Take the 147 bus (every 10 minutes) heading towards Chorlton upon Medlock.
- Get off the bus at KRO bar on Oxford Road / Universities. Upon exiting the bus walk towards Dover Street. The Simon building is the first one on the northern site of the street.
- Venue address: Simon Building - Manchester - M13 9PS

GROUND TRANSPORTATION FROM ARORA HOTEL TO THE VENUE

The whole journey takes around 15 minutes (see map on the right):

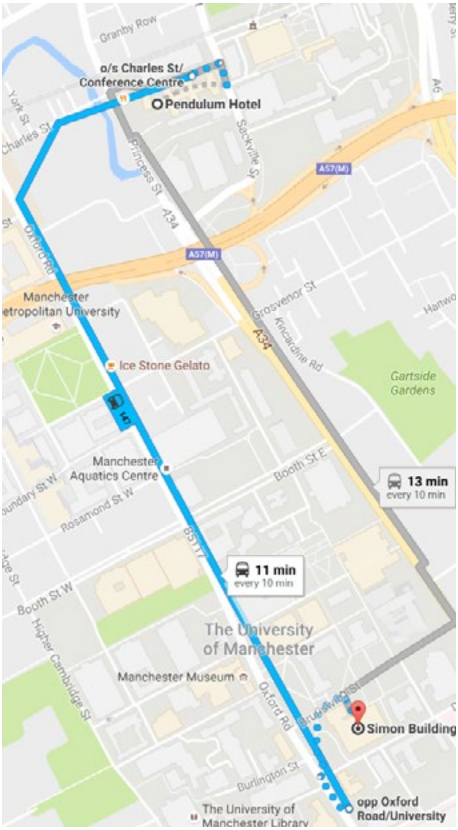
- Walk down Princess Street heading south. Once you reach the first set of traffic lights cross the road and continue down the road for another 50 metres. You will reach a bus stop.
- Take the 15/41/42/143 bus heading to Didsbury (every 2minutes).
- Get off the bus at St Peter's Church & Chaplaincy on Oxford Road, Universities. Walk south on Oxford Road for 100m until reaching Brunswick Street. The Simon building is the first one on the south side of the street.
- Venue address: Simon Building - Manchester - M13 9PS



GROUND TRANSPORTATION FROM PENDULUM HOTEL TO THE VENUE

The whole journey takes around 11 minutes (see next page for map):

- There is a bus stop located outside the hotel. Take the 147 bus (every 10 minutes) heading towards Chorlton upon Medlock.
- Get off the bus at KRO bar on Oxford Road / Universities. Upon exiting the bus walk towards Dover Street. The Simon building is the first one on the northern site of the street.
- Venue address: Simon Building - Manchester - M13 9PS



- Walk down Portland Street until you reach Yate's Bar. The bus stop is 20 metres down the road from Yate's.
- Take the 15/41/42/143 bus heading to Didsbury (every 2 minutes).
- Get off the bus at St Peter's Church & Chaplaincy on Oxford Road, Universities. Walk south on Oxford Road for 100m until reaching Brunswick Street. The Simon building is the first one on the south side of the street.
- Venue address: Simon Building - Manchester - M13 9PS

GROUND TRANSPORTATION FROM MERCURE HOTEL TO THE VENUE

The whole journey takes around 15 minutes (see map on the right):

NOTES

E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL

DACAS