An agent-based analysis of transport network vulnerability and resilience with provision of travel information

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1. Introduction

Transport networks are vital for sustainable development, wellbeing, and security of a society. However, they can be vulnerable to various natural and man-made disruptions (Jenelius, et al., 2006). With the increasing global population, urbanisation, and climate change, factors that can undermine these critical infrastructures are greater than ever. Robustness and resilience of transport networks can be enhanced by introducing redundancies. Nevertheless, the associated investment can be very expensive. Sustainable and feasible strategies call for effective management of existing infrastructure which relies on thorough understanding, modelling, and optimisation of the underlying complexity of the network systems when disruptions occur. This paper presents an agent-based modelling approach for estimating and managing the vulnerability and resilience of transport networks subject to different magnitudes of disruptions. Different from the traditional equilibrium based approaches, the network is represented by a multi-agent system developed on the MATSim (Multi-Agent Transport Simulation) platform. MATSim (Nagel and Flötteröd, 2012) is an activity-based multi-agent simulation framework which is an open-source and downloadable from the Internet (MATSim, n.d). Based on the network configuration and traffic condition, MATSim regards each traveller as an 'agent' and estimates their behaviour in terms of choices of activities and the associated durations, travel routes, modes, and departure times. Each agent will make and revise their individual travel choices such that their expected 'utility' gained from the trips is maximised. Different from the equilibrium based approaches, the agent-based model captures the transient process of the network systems and even allows the system end up in chaotic state with inappropriate measures. This feature is shown to be important for evaluating network vulnerability and resilience with disruptions under which the network systems are highly dynamic. We apply the simulation framework to a real world network in the city of Anaheim, CA. The network consists of over 32,000 links, 16,000 nodes, and 3700 facilities. We consider a set of hypothetical disruptions of different magnitudes. The results show that managing travel information and behaviour is important for maximising the network resilience. It also reveals that the amount of data incorporated and computational effort spent in the modelling process can affect significantly the corresponding evaluation of network vulnerability. By capturing the transient and chaotic behaviour of dynamic transport networks, this study generates new insights on network resilience modelling and management.

2. Methodology

In this study, transport networks are coded in the agent-based MATSim modelling platform which consists of two interacting components which represent respectively the infrastructure characteristics and travellers' behaviour in the network system. The infrastructure characteristics are represented by the network topology, as well as attributes of each link including its free-flow speed, saturation flow, and storage capacity. The traffic dynamics along each link is captured by a queueing or 'bottleneck' model with the exception that the physical capacity of each network link is taken into account in which traffic queue will be spilt over to the upstream links when the local link is full. With the link characteristics and traffic volume, the queue simulator generates estimates of queue lengths, journey times, and travel reliability on each link over time. On the behaviour side, MATSim regards each traveller as an 'agent' who will make and adjust travel decisions based upon the prevailing network conditions including queue lengths (congestion), journey times, and travel reliability. Travel decisions considered here include durations of activities that travellers spend at specific locations, routes of travel, and times of departure. MATSim adopts a random utility theory to model the travel behaviour in which each agent (traveller) will make and adjust his or her choice such the utility (or 'score' using the MATSim terminology) the traveller gains from travel is maximised. Given a chain of activities i_a of each agent a, the corresponding utility of that agent gains from these activities is measured by the following function:

$$V_a = \sum_{i_a} (V_{i_a}^{+} + V_{i_a}^{t} + V_{i_a}^{s}), \quad (1)$$

in which $V_{i_a}^{+}$ is the utility gained by the agent for performing activity i, $V_{i_a}^{t}$ is the (dis)utility that the agent has to spend on travel for performing activity i_a, $V_{i_a}^{a}$ is the (dis)utility associated with the agent's schedule for performing activity i_a. This schedule delay cost $V_{i_a}^{s}$ includes the waiting time that the agent has to spend for performing the activity due to his/her early arrival at the facility, potential penalty due to his/her late arrival, and penalty for the agent having to leave earlier than the planned end time of activity. The travel disutility $V_{i_a}^{t}$ is formulated here as a linear function of different attributes including journey times, delays, ease of transfer between modes, comfortablility (e.g. level of congestion and crowdedness on route). It is noted that travellers' understanding of their utility to be gained from travel is imperfect due to their limited knowledge of the prevailing traffic condition. Given a predefined list of activities to perform and modes of transport to choose, the simulation starts with assigning all agents to the shortest routes connecting the locations of these activities, and times of departures from each location when performing these activities. It turns out that some agents may end up with having a utility lower than the nominal values due to congestion caused by too many agents choosing the same route or time of departure. To mimic the (day-to-day) learning process of travellers, MATSim then re-distributes the agents to different routes and times in the next iteration by taking into the utility values experienced in the previous iteration. Assuming no changes on the travel demand and network characteristics, a steady state or the so-called 'equilibrium' could be reached in the system where no change in travel choices further occurs.

3. Case study

The simulation framework is applied to the Anaheim network (see Figure 1) in Los Angeles, CA as a case study. The network configuration (GIS shape file) and its origin-destination matrix which are used for constructing the test network are downloaded from the open source made available by Bar-Gera (n.d). To investigate the sensitivity of results with respect to amount of input data, we build the road network in full version (Figure 1, right) as well as a simplified version (Figure 1, left). The simplified version contains only freeways and tier-1 arterials. There are a total of 32,768 links and 16,384 nodes in the full network, while they are reduced to 8,192 links and 4,096 nodes in the simplified version. In addition to the network topology, we also specify locations of 3627 'facilities' which corresponds to various locations of where activities (e.g. home, work, leisure, shop, school, etc) are performed. The characteristics of these activities are set based upon the survey conducted by United States Census Bureau (2010). Moreover, a total number of 150,000 agents, each with associated trip plan specifying facilities to visit for various activities over a 24-hr period, are generated for running the simulation. It is further estimated that 76% of these agents will travel by using personal vehicles and the rest (24%) will travel by public transport (United States Census Bureau, 2010b). The simulation horizon is set to be 24-hr and we adopt the utility functions V_a with default settings as in the current MATSim package (see MATSim, n.d.). It should be noted the objective of this study is not to replicate the actual travel pattern observed in the city, but to study the dynamics of such a large scale network under different circumstances.

The MATSim simulation is first run to solve for the dynamic equilibrium (DUE) assignment of agents over time and space in both full and simplified networks. This equilibrium assignment will represent the travel pattern under the normal circumstance without disruption in both networks. We define an equilibrium is reached if the percentage change in the average values of utilities of all agents before and after re-assignment is less than 0.1%. It is found that both networks can reach equilibrium while it takes 29 iterations for the complete network to achieve so, and 46 iterations for the simplified network. Taking both complexity and number of iterations required into account, the full network takes 17 mins to solve on a standard Windows 7 (64 bit) desktop computer, while the simplified network takes 11 mins to compute. Interestingly, it is found that the full network indeed takes lesser iterations to reach equilibrium due to the more road capacity in the network and the more route options for the agents to choose. For similar reason, the average utilities (in monetary unit) gained by all agents is 179 in the full network, which is higher than the 175 in the simplified network case.

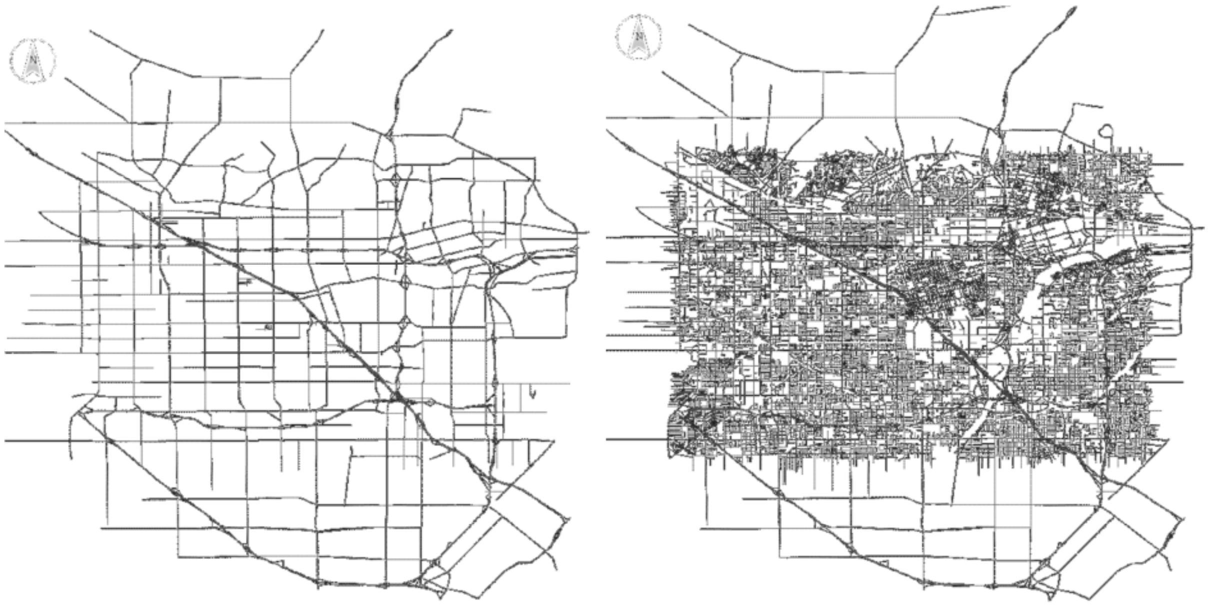
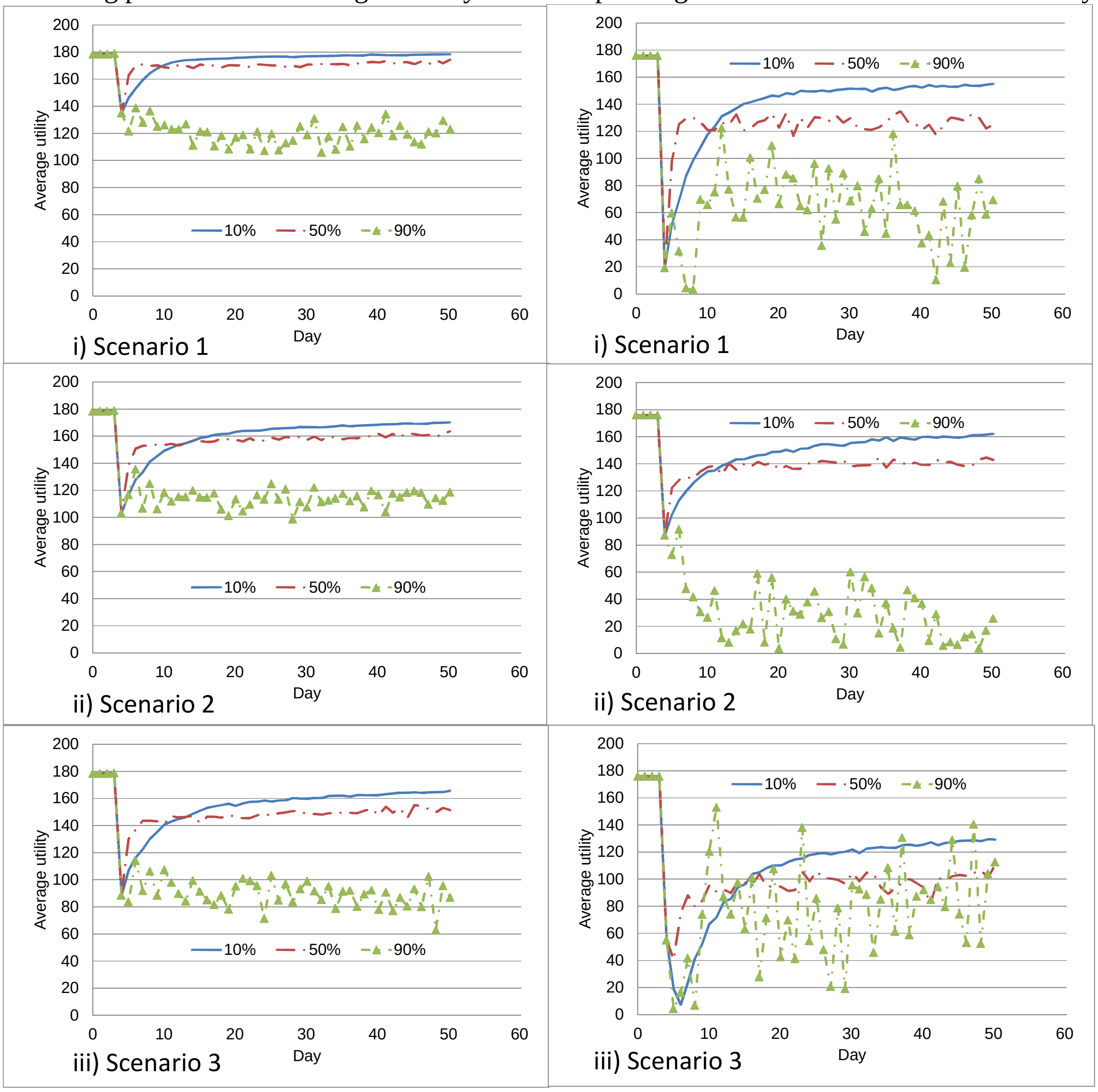


Figure 1: Simplified network (Left), full Anaheim network (Right)

In addition to the base case equilibrium solution, we further construct three different scenarios representing various disruptions. The first scenario is a link closure due to incident(s) in which we assume that a section of the freeway (I-5) is closed. The second and third scenarios are due to extreme weather (e.g. flooding) and natural disasters (e.g. earthquake) respectively. In the second scenario, we assume that capacities of all roads in the network are reduced by 30%, while in the third scenario we assume that the capacities of all roads are reduced by 20% and the entire I-5 freeway is not able to use. The first scenario would have a higher probability of occurrence, but lower impact to the overall system. On the other hand, the second and third scenarios will have a lower probability of occurrence, yet, higher consequence to the city with longer period required to restore the infrastructures. In each scenario, we consider three different proportion, 10%, 50%, and 90%, of agents will have access to information and guidance related to the incident and prevailing traffic and hence will be able to adjust their decisions accordingly. Other agents will be assumed to be ignorant of the network conditions and hence will stay with their original travel plans as in the normal circumstance. This is to investigate the impact of dissemination of travel information and guidance on the dynamics of transport networks under different disruptions.

4. Results and conclusions

With the experiments set up, Figure 2 summarises all profiles of average utility values of all agents in the system over a 50-day simulation horizon in which we assume that all incidents occur on ‘Day 4’ in all experiments. The percentages (10%, 50%, 90%) in the legend indicate the proportion of agents receiving information and hence would be changing their trip plans over the simulation period. The results first show that providing more information would facilitate the recovery of the network after the impact if we compare the difference between the ‘10%’ and ‘50%’ cases, while limiting the information provision to agents (and hence their adaptability) could indeed help restoring system performance in long run. Moreover, it is seen that the system ends up in ‘chaos’ and cannot restore if too much information (90% of population) is disseminated as the population becomes over-sensitive to the network changes. This highlights the importance of managing the dissemination of information under disruptions. In particular, too much information disseminated apparently could bring the systems into chaotic state. It is also found that higher utility values are achieved in all cases in the complete network. This reveals the amount of data incorporated and computation effort spent in the modelling process can affect significantly the corresponding evaluation of network vulnerability.



a) Complete network

b) Simplified network

Figure 2 Summary of results

References

Bar-Gera, H (n.d.) Transportation Test Problems. URL: www.bgu.ac.il/~bargera/tntp/

Jenelius, E, Petersen, T, Mattsson, L (2006) Importance and exposure in road network vulnerability analysis. *Transportation Research Part A*, 40(7), 537-560.

MATSim (n,d) Multi-Agent Transport Simulation, Technische Universität Berlin, URL: http://www.matsim.org.

Nagel, K. and Flötteröd, G. (2012) Agent-based traffic assignment: going from trips to behavioural travellers. In: Bhat and Pendyala (eds), *Travel Behaviour Research in an Evolving World*, 261-293.

Rieser, M. and Nagel, K. (2007) Network breakdown “at the edge of chaos” in multi-agent traffic simulations. *The European Physical Journal B*, 63(3), 321-327.

United States Census Bureau. (2010). Centers of Population, Orange County. Retrieved from Geography Data, USA: https://www.census.gov/geo/reference/centersofpop.html