Applied Ergonomics 68 (2018) 258–266

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Distributed Cognition on the road: Using EAST to explore future road transportation systems

Victoria A. Banks[a,b,*], Neville A. Stanton[a], Gary Burnett[b], Setia Hermawati[b]

[a] Transportation Research Group, University of Southampton, UK
[b] Human Factors Research Group, University of Nottingham, UK

A R T I C L E I N F O

Keywords:
Connected and Autonomous Vehicles
Distributed Cognition
EAST
Network analysis
Network metrics

A B S T R A C T

Connected and Autonomous Vehicles (CAV) are set to revolutionise the way in which we use our transportation system. However, we do not fully understand how the integration of wireless and autonomous technology into the road transportation network affects overall network dynamism. This paper uses the theoretical principles underlying Distributed Cognition to explore the dependencies and interdependencies that exist between system agents located within the road environment, traffic management centres and other external agencies in both non-connected and connected transportation systems. This represents a significant step forward in modelling complex sociotechnical systems as it shows that the principles underlying Distributed Cognition can be applied to macro-level systems using the visual representations afforded by the Event Analysis of Systemic Teamwork (EAST) method.

1. Introduction

Over the past two decades, there have been major developments in the integration of wireless and autonomous technologies in the road transportation network (Talebpour and Mahmassani, 2016). Automated vehicles in particular are quickly becoming an engineering reality (Stanton, 2015) and whilst much research has primarily focussed upon driver-automation interaction (e.g. Banks et al., 2014; Zeeb et al., 2015; Louw and Merat, 2017), many issues remain. Some of these issues relate to how automation can be regulated, legislated and standardised but more importantly, we do not fully understand how automation will impact overall road system behaviour. For example, Atkins Mobility (2016) speculate that if automation brings about improvements to road safety, we may see a future whereby crash barriers are no longer necessary and roadway signs become redundant as information can be shared using Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastucture (V2I) communication streams and other location services (e.g. Global Positioning Systems). V2V and V2I is made possible through both the use of Dedicated Short Range Communication (DSRC) sensors and wireless network architectures such as 5G. In vehicles, DSRC represent on-board sensor units whilst external roadside units represent the means to achieve V2I communication. This wireless connectivity would enable intra-vehicle communication as well as real-time communication with traffic management systems. Essentially camera and radar based technologies enable the vehicle to "see" (e.g. vision systems that process video data and fuse with microwave radar data) whilst technologies such as DSRC enables the car to "talk" (i.e., transmit data to other vehicles and infrastructure) and "listen" (i.e., receive data from other vehicles and infrastructure).

The concept of "Connected and Autonomous Vehicles" (CAV) is not new, with research and innovation dating back to the early 1990's (De La Fortelle, 2005). The Science and Technology Select Committee (2017) cite numerous benefits associated with CAV including increased accessibility and mobility, improvements to road safety and congestion. KPMG (2015) hypothesise that by 2030, all new vehicles sold within the United Kingdom will be "fully connected". It is clear then that future transportation systems will be reliant upon the exchange of information between both human and non-human entities to ensure effective system functioning. This type of communicative behaviour is the essence of Distributed Cognition (DCOG; Hutchins, 1995) whereby interactions take place between humans, resources and materials across space and time (Hollan et al., 2000; Hutchins, 1995). DCOG is related to the theory of 'transactional memory' whereby individuals (both human and non-human entities) tend to rely upon others to remember things for them (Stanton et al., 2015). Thus, DCOG is characterised by multiple system 'agents' that work together in order to achieve a common goal (Hutchins, 1995). 'Agents' in this sense can receive, hold and share information with one another in order to pursue a common goal (Hutchins, 1995). This implicates the need for communication and coordination to exist between them (Christoffersen and Woods, 2002;

* Corresponding author. Transportation Research Group, University of Southampton, UK.
E-mail address: v.banks@soton.ac.uk (V.A. Banks).

https://doi.org/10.1016/j.apergo.2017.11.013
Received 24 March 2017; Received in revised form 10 October 2017; Accepted 28 November 2017
0003-6870/

Stanton, 2014; Eriksson and Stanton, 2017). Of course, there are many challenges associated with Vehicle-to-Anything (V2X) communication including, but not limited to, issues relating to the size of the network (both in terms of geography and availability). This means that in some instances, the exchange of information between system agents (both human and non-human) may be delayed, inaccurate or incomplete. DCOG provides a theoretical framework that can be used in the effective design of new communication and interactive technologies to support the relationship that exists between human and non-human agents by highlighting areas of potential weakness (Hollan et al., 2000). To date, DCOG has only been used to consider small sociotechnical systems in isolation such as an airline cockpit (Hutchins, 1995) and command teams (Stanton, 2014). In this paper, we argue that DCOG provides not only the theoretical foundation, but also the methods, that can be used to explore complex sociotechnical systems at a macro-level.

The road transportation system is a good example of a macro-level sociotechnical system. This is because it can dynamically configure itself to ensure that multiple subsystems acting within it (e.g. Traffic Management Centres work alongside External Agencies) can operate simultaneously to achieve various functions. Thus, the network is based upon a large number of complex interactions and interdependencies between multiple system agents at a number of levels (Salmon et al., 2014). These include system agents within the road environment (e.g. drivers, pedestrians and vehicles), traffic management centres (e.g. traffic management and CCTV operators) and external agencies (e.g. radio stations and emergency services). Whilst these categories of system agent are typically analysed independently, this paper applies the principles underpinning DCOG to all of the agents and agencies involved within the road transportation network. Given the uncertainty of how the transportation network will be affected by CAV functionality, this paper provides a comparison between non-CAV and CAV networks to explore how network dynamism may change as a result of increased connectivity. This comparison is important because it provides initial insights into how system agents will react to, and interact with, intelligent transportation systems.

2. Method

DCOG in complex sociotechnical systems can be further explored and understood using the Event Analysis of Systemic Teamwork framework (EAST; Stanton et al., 2008). EAST is a descriptive method that proposes that a system can be described using three inter-linked network representations; task, social and information (Walker et al., 2006, 2010). Task networks provide analysts with a means to show the processes involved in attaining network goals (Salmon et al., 2014). They can provide a description of the sequences and interdependencies that exist between individual subtasks that must be completed to attain these goals. Social networks are used to analyse the structure of the system in terms of the communications that take place between different system 'agents'. Finally, information networks show the information that is used by, and communicated by, system agents during a task (Stanton et al., 2008). Information networks detail aspects of communication that underpin the completion of a task as well as the relationships that exist between these different informational nodes. EAST has been used to focus upon specific tasks within varied domains including aviation (Sorensen et al., 2011), rail (Walker et al., 2006), driving (Banks and Stanton, 2016) and maritime (Stanton et al., 2006, 2017b; Stanton and Roberts., 2017a; Stanton, 2014; Baber et al., 2013) providing meso-level representations of DCOG (Grote et al., 2014). However, this paper goes further by using the representations afforded by EAST (Stanton et al., 2008) to explore DCOG at a macro-level (Grote et al., 2014). EAST makes it possible to provide an overview of how different agents and agencies within the road transportation network can function simultaneously within a shared space (i.e. the road network). The networks can then be subjected to quantitative analysis using the Applied Graphic and Network Analysis tool (AGNA, version 2.1; Benta, 2005). AGNA is a platform-independent freeware application that can be used to analyse task, social and information networks. Nodes within each network can either be analysed individually to assess agent centrality/prominence or as a whole to give an overall impression of system complexity. Network metrics can be used to identify key agents, tasks and informational elements within system operation. Within driving research, the following network metrics have been applied to analyse EAST representations; *Density* represents the level of interconnectivity between system agents. It is expressed as a value between 0 and 1, where 0 represents a network that has no connections and 1 indicates that the network is fully connected. It is calculated using the following formula;

$$Network\ \ density = 2e/n(n-1)$$

where e = total number of links within the network and n = the number of nodes within the network (Walker et al., 2015).

Diameter is used to analyse the connections and pathways that exist between nodes within the network (Walker et al., 2015). Denser networks (i.e. the route through the network is shorter and more direct) have smaller values. It is calculated using the following formula;

$$Diameter = \max_{uy} d(n_i, n_j)$$

where $d(n_i,n_j)$ is the "largest number of [agents] which must be traversed in order to travel from one [agent] to another when paths which backtrack, detour, or loop are excluded from consideration" (i.e. max_{uy}, Weisstein, 2008; Harary, 1994). *Cohesion* represents the number of reciprocal connections divided by the total number of possible connections (Stanton, 2014).

Finally, *sociometric status* provides an indication of agent prominence (Houghton et al., 2006; Salmon et al., 2014). Key agents (i.e. most prominent within the network) have higher sociometric values (Salmon et al., 2014). It is calculated using the following formula;

$$Sociometric\ \ Status = \frac{1}{g-1}\sum_{j=1}^{g}(x_{ji}, x_{ij})$$

where g is the total number of nodes in the network, i and j are individual nodes, x_{ji} are the number of communications between node j and node i, and x_{ij} are the number of communications between node i and node j (Salmon et al., 2014; Houghton et al., 2006).

3. Results

3.1. Identification of system agents

For the purposes of this analysis, a total of 21 system agents were identified from previous work conducted by Price (2016) and Banks and Stanton (2016). Their work specifically sought to identify system agents involved in Traffic Management operations (e.g. Price, 2016) and within automated driving environments (e.g. Banks and Stanton, 2016). The 21 agents broadly span three operational categories; Road Environment (RE), Traffic Management Centres (TMC) and External Agencies (EA) (see Table 1 for complete list and descriptions). These agents represent the main human and non-human entities that can be found within the road transportation network.

3.2. Task networks

From the list presented in Table 1, it is possible to consider the types of tasks in which these system agents engage in, and how they may be related. This makes it possible to construct a high level task network for the entire road transportation system involving all 21 agents. Walker et al. (2006) suggest that task networks can show how subtasks may relate to other subtasks based upon their functional or temporal properties.

The task network for the road transportation system, shown in Fig. 1, should be viewed as a continuous process to reflect the notion