SYSTEMATIC ANALYSIS OF DRIVERLESS TECHNOLOGIES

ABSTRACT

Purpose: The advent of Industry 4.0 has engendered opportunities for a coalescence of digital technologies that collectively enable driverless vehicles to operate during the construction and use of a highway. Yet, hitherto scant research has been conducted to review these collective developments and/or sample construction practitioner opinion on them. This research therefore presents a systematic review of extant literature on the application of driverless technologies in civil engineering and in particular, the highways infrastructure sector and offers insight into the limitations of associated barriers to full adoption, namely current technological development processes, legal deficiencies and societal concerns. In so doing, the work presents a vignette of contemporary developments augmented by a critical analysis from practitioners' perceptions.

Methodology: A mixed philosophical methodological approach is adopted for this inductive research study. Interpretivism is used to critically analyse the literature and post-positivism to perform content analysis of the literature and synthesis of the discourse with practitioners. A total of 44 related articles published between 1998 and 2019 have been included in this study. Emergent themes identified from literature are then discussed in some further detail; viz: 1) automation and robotics; 2) case studies and simulations; 3) safety and ergonomics). A focus group is then held with leading industrialists to discuss their experiences of advanced driverless technology applications in practice. Based upon a culmination of emergent evidence, a conceptual model of prevailing barriers is then developed to further elucidate upon the challenges facing the highways infrastructure sector.

Findings: Research into driverless technologies within the highways infrastructure sector has received relatively scant academic attention. Hitherto, most advancements made have stemmed from multidisciplinary teams consisting of engineering, information technology and social scientist researchers. There is insufficient supporting evidence of civil engineering and construction academics input into developments made - suggesting that prototype products often fail to adequately consider practical applications in the highways infrastructure sector at the design and use case stage. This view is substantiated by feedback from leading industry experts who participated in unstructured telephone interviews. Their feedback suggests that practical applications of products have been beset with problems, thus creating a perception that advanced technologies are largely 'unusable' within the highways infrastructure sector and so are unsuitable for large scale (and particularly bespoke) industrial applications.

Originality: This research critically synthesises the prevailing scientific discourse within extant literature on driverless technologies implemented but also garners practitioner feedback from leading UK industrialists on their applications in practice. Hitherto, this combined analysis approach has been rarely used despite it having significant advantages of tacit knowledge reflection on technologies employed; where such can be used as a basis for further informed discourse and/or development. Moreover, the work culminates in a conceptual model that acts as a catalyst for future research investigations.

KEYWORDS

Driverless technology, infrastructure, highways and systematic review, Industry 4.0

INTRODUCTION

"We can only see a short distance ahead, but we can see plenty there that needs to be done."
Alan Turing

The construction and civil engineering industry plays a vital role in the socio-economic development of a nation by developing and maintaining critical assets and infrastructure that constitute the built environment (Pärn and Edwards, 2019). Without sufficiently interconnected arteries of road and rail, linked to air and sea port infrastructure, national industry and commerce within global economies would grind to a halt (Blockley and Godfrey, 2017). However vital, powered transportation is a source of environmental pollution (Yang and He, 2016); a trend which is further exacerbated by a booming global population of 7.1 billion in 2017 that is set to increase to a staggering 11.2 billion by 2100 (Warner and Jones 2017). This unprecedented population growth is likely to translate into an increased reliance on and demand for transportation, with a related and significant intensification of pollution and congestion (Bharadwaj *et al.,* 2017; Higgins *et al.,* 2019). Indeed, the World Health Organisation (WHO) states that the transportation sector is a leading source of greenhouse gas (GHG) emissions and responsible for an estimated 4.2 million premature deaths due to ambient (outdoor) air pollution in 2016 (WHO, 2016). WHO state (ibid) that other air pollution-related deaths and illness are linked to small particulate matter (PM) (≤ 10 or 2.5 microns in diameter (PM10 and PM2.5)) that comprise of health harming substances including heavy metals, sulphurs, carbon compounds, and carcinogens including benzene derivatives. These small particulates bypass the body's natural defences against dust inhalation and penetrate into the respiratory system's deeper recesses (Molepo *et al.,* 2019).

Recent climate change demonstrations illustrate that air quality and GHG emissions are a significant concern to the public. Consequently, governments and individuals are suggesting that society needs to adopt a new approach to reducing emissions from transport and meeting GHG reduction targets. Against this prevailing backdrop, there has been a notable upsurge in interest in driverless vehicles which could become the dominant mode of transport particularly in cities given sprawling urbanisation and a rapidly increasing population (Duranton, 2016; Ganivet, 2020). This may catalyse a shift away from individually owned, direct GHG emitting vehicles powered by hydrocarbon energy towards driverless vehicles running on electricity generated from renewable sources that provide mobility as a service (MaaS). There are various definitions and classifications of a driverless or autonomous vehicle. For example, the SAE (2018) report upon six levels of driving automation in its standard J3016, where level five is fully autonomous; and Silberg and Wallace (2016) report upon four levels developed by the National Highway Transportation Safety Administration, where level four is deemed to be full and complete self-driving automation. Common within these classifications and definitions is the presupposition that to be 'driverless' a vehicle must navigate and manoeuvre by on-board computer and/or self-awareness of its environmental surroundings (typically using sensors connected to the Internet of Things (IoT) (Riaz *et al.*, 2006; Riaz *et al.*, 2012)) without human control or intervention (Edwards *et al.,* 2017a). Projected palpable benefits of driverless vehicles are myriad but are encapsulated within three key clusters, namely: 1) a significant improvement in journey efficiency of the transportation system when compared to manually controlled human transportation, resulting in a lowering of environmental impact and degradation as a consequence (Woldeamanuel and Nguyen, 2018; Kim *et al.,* 2017). For example, Greenblatt and Shaheen (2015) add that energy consumption rates could reduce by circa 80% from platooning and efficient traffic flow and parking. Whereas, Silberg and Wallace (2016) estimate that platooning alone could increase lane capacity by circa 500%; 2) a change in the pattern of road traffic accidents through elimination of human error (Dong *et al.,* 2019) by a projected 80-90% (Greenblatt and Shaheen, 2015). This assumes that automation will result in fewer errors or lapses than are exhibited by human drivers; for example, the UK Department of Transport (DoT) estimates that 94% of road deaths and injuries occur as a result of human error (DoT, 2015). This is a quintessentially important social-political driver given that according to WHO *"worldwide the total number of road traffic deaths has plateaued at 1.25 million per year"* (WHO, 2015); and 3) a decrease in energy use leading to cost savings made for both governments and the general public. For example, building lighter weight vehicles can achieve reduced fossil fuel consumption and emissions considerably (Kulkarni *et al.*, 2019; Burns, 2013). Moreover, Wadud (2017) estimates a 90% reduction in insurance cost when driverless transportation is widespread – largely due to improved safety. In addition, Compostella *et al.* (2020) forecast that in the long-term, 'ridesourcing' using driverless vehicles for travel will be circa 30% cheaper than vehicle ownership, promoting mobility as a service (MaaS) as the favoured model both economically and ecologically.

These aforementioned arguments and corroborating statistics are compelling and in favour of driverless vehicle adoption and yet, an antithesis to this utopian view is also apparent. Driverless vehicle technologies are pushing the boundaries of science but rely on software development processes to produce, test and prove the safe function of a system designed to carry humans safely. Errors in such a complex system are inevitable and will lead to undesired situations, which potentially diminish the absolute argument that driverless vehicles are inherently 'safe'. For example, in March 2018, Elaine Herzberg was fatally injured by an autonomous 'Uber' test car whilst pushing a bicycle across a road in Tempe, Arizona, USA. Absolute safety for driverless vehicles is improbable given they are systems which cannot predict every situation they will encounter and select the correct action every time. This leads to disassociating safety into two streams; physical safety, based around actual failure modes and error rates; and perceived safety, which looks at public perception and feelings of safety. The Tempe, Arizona incident created a media frenzy and led to a plethora of secondary research into measuring public perceptions of driverless vehicle safety (cf. de Miguel *et al.*, 2019; Tennant *et al.*, 2019; Hwang *et al.*, 2019; Bennett *et al.*, 2019). Despite the media hype around driverless vehicles, development of driverless cars and trucks has therefore been slower than initially anticipated as the technical, perceptual and legal problems that need to be addressed are considerable.

Against this contextualisation of literature and current circumstances, a notable dearth of contributions from construction and civil engineering researchers and practitioners is glaringly apparent. Indeed, many of the developments in this area have derived from engineering and information technology disciplines without due consideration being given to professional practitioners who either build or maintain the highway. Yet, this discipline is essential to future research in this area given the tacit knowledge of academics and industrialists in the fields of linear transport asset construction, operation and management and their ability to define effective use cases for driverless technology in these fields. This research therefore conducts a systematic review and content analysis of literature on the application of driverless technologies applied to highways infrastructure development and operation (i.e. construction plant as well as passenger or goods vehicles). As a secondary aim, the research also samples professional practitioners' opinions on progress made and the application of such technologies within practice. Associated objectives are to: offer insight into the limitations associated with current technological development processes; and stimulate further polemic debate geared towards generating the next generation of technological innovations to overcome barriers reported upon.

METHODOLOGY

The paper's epistemological positioning was underpinned by the use of a mixed philosophical design with inductive reasoning to explore the phenomena under investigation. This mixed philosophies approach is well established in scientific literature and has been adopted to: conduct real-time structural health monitoring of concrete beams (Gosh *et al.,* 2020); investigate industry 4.0 deployment in the construction industry (Newman *et al.,* 2020); and investigate the role of the quantity surveyor in the value management process (Spellacy *et al.,* 2020). From a research approach perspective, a three phase waterfall process was adopted (cf. Al-Saeed *et al.*, 2020) which also embraces the concept of triangulation (cf. Edwards and Holt, 2010); where literature review, content analysis and practitioner interviews coalesce to facilitate reasonable conclusions to be derived (as per a pragmatist philosophical lens) – refer to Figure 1.

In *phase one*, interpretivism was first used to critically analyse scientific literature pertaining to driverless technologies, where each published article represented a unit of analysis under investigation (Roberts *et al.,* 2019). Interpretivism has been used extensively within diverse engineering research studies and typical examples include: identifying security risks associated with of digital transformations (Nguyen and Chirumamilla, 2019); applying management studies that examined intellectual frames of resilience engineering and high reliability (Kant, 2020); and conducting a critical analysis of intercultural communication in engineering education (Handford *et al.,* 2019). Consequently this philosophical standpoint was deemed to be appropriate for the present study. To complete this undertaking, a systematic review on driverless technologies was undertaken. According to Grant and Booth (2009), this type of review has the perceived strength of drawing together all knowledge on a topic area. As part of the bibliometric analysis, the Scopus journal database was searched using the terminology '*driverless technology', 'autonomous'* and *highway*'. The terminology '*automated*' was omitted because often the term denotes that a vehicle would follow a pre-set route and destination commands and for this paper, only research into vehicles that can sense the surrounding environment to act without human intervention were sought. This could of course mean that some important materials may have been inadvertently omitted – a necessary limitation needed to ensure that only relevant materials are included in the analysis. Scopus was used because it contains arguably the most extensive source of published scientific materials available but also facilitates automated analysis of the literature itself (Al-Saeed *et al.,* 2019; Akinlolu *et al.,* 2020), and has a faster indexing process, in comparison to the other databases (Hosseini *et al*., 2018). A comma separated value (CSV.) database file was then downloaded and saved in Microsoft (MS) Excel format to generate discrete classification graphics that were used for an in-depth, yet holistic data mining process.

<Insert Figure 1 about here>

Post this holistic data analysis, a pragmatist philosophical lens (Van Bergen and Parsell, 2019) was adopted to perform content analysis of the literature contained within the MS Excel file downloaded from Scopus. Article(s) keywords and abstracts were collated into one revised master MS Excel spreadsheet and textual narrative contained within these cells was analysed using a manual codification of the article's content. Specifically, publications downloaded were then thematically clustered via arbitrary classifications (founded upon an interpretivist judgement of each publication's content) to facilitate a deeper interrogation of prevailing extant literature (Tranfield *et al.,* 2003). For example, Chamberlain *et al.* (2019) used a thematic analysis on a study into mega event orchestration to prescribe mitigation strategies for improving cost performance. Each consecutive emergent cluster (formed using interpretivism) was then analysed iteratively using advanced 'open source' content analysis software (cf. Spellacy *et al.,* 2020) to excoriate thematic sub-groupings of research activity but also identify gaps in contemporary knowledge. Knowledge emanating from this literature analysis phase was then used to formulate three main lines of open style questioning for unstructured interviews conducted.

In *phase two,* the emergent thematic clusters derived from *phase one* were then discussed in detail and the findings presented to industrial practitioners who are known to have invested in driverless technologies or aspects thereof. For example, health and safety risk mitigation technologies such as visualisation cameras augmented with artificial intelligence pattern recognition software to detect inanimate objects or people obstructing the safe movement of mobile plant and machinery. Unstructured interviews were then held either in person where circumstances permitted or via mobile communications (i.e. MS Teams and telephone) and recorded via Dictaphone as well as via hand written notes. Questions were based upon three areas of investigation viz: applications of driverless technologies, experiences accrued and future directions. Prior to commencing unstructured interviews, each participant was informed about the study's purpose, the intention to publish the results and pertinent ethical constraints guiding this research (e.g. assurances that the recording or personal information would not be disclosed, divulged or misused (deliberately or otherwise) (cf. Oliver, 2010; Fisher *et al.,* 2018).

Ten highly experienced and senior practitioners (each with a minimum of twenty years' experience) were selected from the lead researcher's network of industrial partners hence; a non-probability opportunity (or convenience) sample was adopted (Shan *et al.,* 2017). Despite their disadvantaged generalizability when compared to probability sampling, non-probability techniques (such as opportunity sampling) are the de-facto standard in developmental science and less costly to administer (Jager *et al.,* 2017; Shan *et al.,* 2017). Table I reveals the demographic profiles of participants who were either: Directors and Senior Managers in prominent construction, civil engineering or utility companies; Directors within supply chain partners (such as plant hire); or Owners of retrofit technology providers that supply safety equipment to the UK's construction, civil engineering and quarrying sectors. Notably, the minimum level of industrial experience within the sample was between 24 and 35 years – it was felt that this level of experience together with the participants' position and standing within the organisation meant that the sample was adequate for this exploratory research study.

<Insert Table I about here>

In *phase three* and based upon a culmination of evidence accrued from the literature review and unstructured interviews, a conceptual model was developed (as an infographic) to further elucidate upon the barriers facing the highways infrastructure sector. In terms of research approach, an inductive design was adopted to generate new theory/theories around driverless technologies in the highway infrastructure sector and identify future directions for subsequent research investigation. Inductive research is ideally suited for generating new theories vis-à-vis prove them and has been widely used within literature to: perform content analysis (Kyngäs, 2020); apply computer-aided qualitative data analysis software to build trustworthiness in inductive research (O'Kane *et al.,* 2019); assess the sustainability of construction practices (Goel *et al.,* 2019); and validate observational research (Bostic *et al.,* 2019).

SYSTEMATIC LITERATURE ANALYSIS

Figure 2 illustrates that contemporary research into the area of driverless technology applied to highway infrastructure development over the period 1998 to 2020. This time period was defined as early work began in this field circa the late 1990s and the ambition was to include as much literature as possible at the time of the search being conducted (namely, January 2020). Specifically, the time series reveals that the number of publications per annum remains very low (at 44 publications over the entire time series) and rarely peaking above two publications per annum, up until relatively recently in 2016 – at which point a notable surge in academic interest is apparent - possibly coinciding with rapid technological developments (and coalescence of these under the Industry 4.0 concept) occurring. However, despite this apparent surge in academic interest, publications in the field hitherto have not exceeded ten publications in a single year.

<Insert Figure 2 about here>

Table II reveals the publications by authors' country of origin. Note that the total number of publications is 56 and this is because, several of the papers included multiple authors. Interestingly, over 44% of the authors analysed stem from the USA (33.92%) and China (10.71%) illustrating that these two major regions of economic development are leading the field in this area of investigation. Closely behind these regions, the European continent (representing a frequency (*f*) of 13 separate countries) contributes circa 37.50% thus, showing that Europe is competing with the economic powerhouses of USA and China in driverless technological development. On the point of multiple authors, it is clear from a manual interrogation of the literature database (in MS Excel) that the vast majority of papers published (79.54% (*f* = 35 papers)) derived from 'multidisciplinary teams' of academic experts. Moreover, Table III illustrates that 71.76% (*f* = 61 papers) derive from: *engineering* (35.29% or *f* = 30 papers); *computer science* (20% or *f* = 17 papers); and social sciences (16.47% or *f* = 14 papers). The multidisciplinary nature of research being undertaken in driverless technologies mirrors other complex research projects involved in a diverse array of projects ranging from: medical research that involves radiological imaging of patients with subarachnoid haemorrhage (Hackenberg *et al.,* 2019); sports science research that reviewed talent identification, talent selection and athlete competition performance (Piggott *et al.*, 2019); environmental science such as integrating natural and social science in marine ecosystem-based management research (Alexander *et al.,* 2018); and optimisation in aviation engineering (Kumar *et al.,* 2020). The summary statistical analysis presented, augmented by prominent studies within extant literature, illustrate that larger research studies require multidisciplinary teams of experts who affiliate to resolve multifaceted and complex phenomena under investigation. For large scale, technologically complex projects such as developing driverless vehicles, the days of a single researcher working in isolation have largely expired.

<Insert Table II and III about here>

CONTENT ANALYSIS

A manual classification of the database publications revealed that the extant literature could be codified into five clusters of research viz: 1) automation and robotics; 2) case studies and simulations; 3) safety and ergonomics; 4) historical reviews; and 5) miscellaneous – where clusters 4) and 5) are not considered in any further detailed analysis due a shortage of publications in these two areas.

Automation and robotics

Accounting for 40.91% (f = 18) of the publications, automation and robotics represented the largest cluster of research. Diverse areas of research investigated included: studies on both transport geography for both electric and autonomous freight (Monios and Bergqvist, 2019); the development of advanced infrastructure for intelligent traffic management (Lin and Rubin, 2017); an analysis of a coalescence of digital technologies that facilitate autonomous light duty vehicles (alternatively known as 'driverless cars') including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (Shi and Prevedouros, 2016); reviews on the development of the intelligent transportation systems (ITS) and advanced technologies adopted such as machine vision (Wang *et al.*, 2010); and processing of linear infrastructure pavement markings using mobile light detection and ranging (LiDAR) systems and 3-D point clouds (Gao *et al.*, 2017). There was a paucity of research into the application of automation and robotics within the highways infrastructure sector, demonstrating the poor representation of this topic within the literature.

A mixed methods (quantitative and qualitative) analysis of the 18 research papers published utilised textual narratives contained within titles, keywords and abstracts. Such information contains the fundamental essence of the papers published and ensures that key information on content is included in subsequent analysis. A total of 3,624 words constituted the sampling frame and the top 59 terminologies (the maximum setting in the software used) were examined (that had word count frequencies ≥ six) – refer to Figure 3. Eight thematic sub-groupings were uncovered using interpretivist semantic analysis of linguistics viz: infrastructure (*f* = 179 words or 23.96%); vehicle (*f* = 162 words or 21.69%); automation (*f* = 117 words or 15.66%); research and data (*f* = 114 words or 15.26%); technology (*f* = 61 words or 8.17%); safety (f = 27 words or 3.62%); planning (f = 19 words or 2.54%); and miscellaneous (f = 68 words or 9.10%). The top three areas of research (i.e. infrastructure, vehicle and automation) illustrate extensive efforts undertaken to seamlessly integrate vehicles within infrastructure (e.g. V2I) (Shi and Prevedouros, 2016). but show a lack of effort to integrate vehicles into the infrastructure sector. While it may be argued that proof of the technology needs to precede its application, the lack of consideration of highways infrastructure sector needs evidenced within literature suggest that future application in this sector may prove challenging, given technology has been developed primarily for the transport rather than the construction sector. This will require technology to be adapted rather than designed to deliver the specific needs of the construction sector, potentially resulting in sub-optimal solutions and/or a longer development cycle. Cumulatively, this body of knowledge illustrates that a driverless vehicle's positioning and movement on the ostensibly linear asset that road network constitutes cannot be considered in isolation to the immediate highway environment. The challenge is that the immediate highway environment is not static, as the driverless vehicle must interact (in real time) with other vehicles on the highway and also with the highway physical environment, using a range of technologies and energy sources to do so. The same is true even on construction sites where traffic is under the control of the site manager, making such environments considerably more complex than 'sterile' sites such as quarries where one vehicle will be occupying one haul route at one time.

<Insert Figure 3 about here>

Case studies and simulations

Cases studies and simulations constituted the second largest cluster of research activity with 25.00% of publications published in this area (*f* = 11). Studies presented within this cluster represented practical applications and developments such as: early studies that sought to explore the use of solar energy to power transportation (Baertsch and Swenson, 2008); the development of a path planning and navigation control system for a driverless electric bus (Yu *et al.*, 2018); the construction of an automotive test track for autonomous road vehicle testing and research but also liability (Szalay *et al.*, 2018); and an assessment of V2V wireless communication within an intelligent transportation system (ITS) using 5G (Ali *et al.*, 2018). Again, there is a lack of research into applications within the highway infrastructure sector in this research activity cluster.

A total of 2,107 words were contained within titles, keywords and abstracts and from this sample – refer to Figure 4). Seven thematic sub-groupings were apparent viz: vehicle (f = 114 words or 26.51%); technology (f = 83 words or 19.30%); miscellaneous (f = 82 words or 19.07%); automation (f = 63 words or 14.65%); infrastructure (f = 57 words or 13.26%); research and data (f = 17 words or 3.95%); and planning (f = 14 words or 3.26%). Akin to the automation and robotics cluster, the top three areas (excluding miscellaneous which represents a collection of terms that lacks cohesiveness and comprehension) are vehicle, technology and automation; where the technology group has replaced the infrastructure group. Indeed, it is apparent that far more emphasis is placed upon testing the vehicle's technology adoption in practical settings but also a wider variety of driverless vehicles in this section and less on the infrastructural needs to support such. For example, D'Orey (2016) used video and audio streams of a taxi vehicle's surroundings via wireless networks to enable a human operator to remotely operate the vehicle controls via a virtual windscreen embedded within an emulated cockpit. These studies therefore, serve to demonstrate the abilities and limitations of driverless vehicles and can be broadly categorised as 'proof of concepts'. Yet as before, the focus is on transportation technology rather than the highways infrastructure sector. This is not perhaps surprising given the relative scales of the infrastructure versus transportation sectors but has the potential to limit adoption of these technologies by leading them to be viewed as applicable to transport rather than construction activity by those involved in the highways infrastructure sector.

<Insert Figure 4 about here>

Safety and ergonomics

Safety and ergonomics was the third largest cluster with 18.18% of publications in this area (f = 8). Despite the relatively small sample size, a diverse range of topics were investigated including: pedestrian perceptions of driverless vehicle safety (DeMiguel *et al.*, 2019); IoT applications to detect vehicle accidents (Dashora *et al.*, 2019); application of a zigbee technology into a novel forward collision warning system (Lei and Wu, 2016); and modelling driver behaviour in a connected system (Talebpour *et al.*, 2017).

A total of 2,047 words were contained within titles, keywords and abstracts and from this sample – refer to Figure 5). Eight thematic groupings are apparent viz: miscellaneous (f = 95 words or 27.22%); technology (f = 93 words or 26.65%); vehicle (f = 54 words or 15.47%); safety (f = 53 words or 15.19%); automation (f = 35 words or 10.03%); infrastructure (f = 10 words or 2.86%); planning (f = 5 words or 1.43%); and research and data (f = 4 words or 1.15%). Excluding miscellaneous and similar to previous clusters, technology and vehicle themes feature in the top three sub-clusters together with a new theme of safety. It is notable that whilst technology has been seen in the past as a panacea to ensuring driver and pedestrian safety and eliminating road transport casualties, it is not this but public perceptions of driverless vehicle safety that has received academic interest. Indeed, the public are generally concerned about vehicle safety and legalities stemming from foreseeable collisions, such as if a driverless vehicle is involved in a collision who is liable for the damage and injury suffered. There are also issues around mixing driverless and manual controlled vehicles on-road; this, connected to high profile driverless vehicle failures such as that described earlier appears to have changed the perception that driverless vehicles will eliminate road traffic collisions and thus will create a perfectly safe road transport system. This may therefore be influencing the readiness to adopt driverless technologies, as one of the key benefits (total safety) that offsets the general sense of forsaking control 'to the machine' has been considerably diminished, if not lost altogether.

Customer readiness to adopt is therefore a major concern for developers who see driverless vehicles as inevitable at some point in the future yet who, without significant uptake of their technologies by end users, will be unable to sell sufficient vehicles to recoup the huge investments required to develop these technologies. As this situation exists within the transportation market, which is immense compared to the highways infrastructure market, it is perhaps not surprising that there is such limited consideration of the highways infrastructure sector in development of applications for driverless technologies. This is compounded as firstly driverless technologies are still in effect prototypes under development and so are not yet sufficiently mature to be applied with ease, and secondly the highways infrastructure sector market is realistically too small to attract development of bespoke and so expensive solutions by the major players in driverless technology. The solution to mass transportation in increasingly urbanised areas required to cater for population growth (where pedestrian and driver safety are paramount) appears to reside in MaaS (Wong *et al.*, 2020). However, even here significant barriers to MaaS adoption are apparent – prominent amongst which is the public's fierce resistance to a 'locked-in' system of transportation (cf. Pel *et al.*, 2020) which removes their freedom to choose self-drive (cf. Ho *et al.*, 2020). So whilst safety remains an overriding concern, this has to be balanced with the public's civil liberties – a amicable solution to this *Gordian knot* of a conundrum has yet to transpire.

<Insert Figure 5 about here>

PRACTITIONER PERSPECTIVES AND BARRIERS TO ADOPTION

The body of knowledge presented illustrates an exciting array of multi-disciplinary research activities (including both applied and theoretical research) which appears to be gaining momentum since 2016. However, it is 'noticeable by its absence', that construction and civil engineering research does not feature prominently in the published literature despite the role of highways infrastructure being central to developments in the field. Moreover, as noted applications of driverless technologies in the realm of mobile plant and machinery used to construct or maintain highways and the built environment were also largely absent from the literature. Rather, engineers, computer scientists and social scientists are contributing almost three quarters of the innovation and application advancements (71.76%). This raises questions regards the practical application of these technologies developed without the intuitive insight and expertise of highways industry specific academics. To refine this emergent theory further, unstructured interviews were held with ten prominent construction and civil engineering industry practitioners around the subject of three core areas viz: i) applications of driverless technologies; ii) experiences accrued and perceptions garnered; and iii) future developments.

Applications of driverless technologies

Discussions on the applications on driverless technologies within the construction and civil engineering industries was largely limited to technologies that assist drivers and operators rather than remove the need for them altogether. Participant no. 1 said:

"I have worked with Universities and private companies over the years on a few of projects that claimed to have produced a labour-saving robot - the last one was a dozer [bulldozer] with ripping claw working on an earthmoving project using GIS (graphical information system) and GPS (global positioning system) combined. Not totally sure about the detail but I think it used artificial intelligence too… None of them seem to have progressed past the development stage"

Other participants said that their experiences of autonomous vehicles were rare and that more often than not, the vehicles and machinery contained some elements of automation that assisted the operator but failed to create driverless vehicles on site. Participant 7 had a similar experience but with commercial companies and said:

"I've been in a couple of self-drive lorries (a 40 tonne articulated dump truck (ADT) and a highway vehicle) – a very strange feeling and very clever too – sitting there as a passenger. I've also had experience with an automatic braking system fitted on a car."

Participant 4 echoed the views of participant 7 in terms of commercial developments and automated parts (vis-à-vis full driverless technologies) fitted to vehicles viz:

"So we have visualisation packages on forward tipping dump trucks that see pedestrians and stop accidents by cutting out the machine – we have auto-dig on XXX [manufacturer name excluded] excavators that correct inefficient operational practices and we have automated load lift indicators for machine stability. Put all these together and you could have a fully automated machine but cost of purchase is still the big factor [barrier] to adoption."

Participant 8, an owner of a retrofit technology company said:

"Most of the latest technological developments sold within the construction industry are progressively moving towards automation and we have many of the technologies to fully automate machines and vehicles – problem is, they don't yet come together as one package. It might be another ten years before they do.

The feedback illustrates that a wide range of semi-automated and/or semi-autonomous applications are already in existence and have been developed by research and development departments within commercial enterprises. These are being used for both on- and off-road applications but as yet are not fully driverless or are, driverless but are not commercially available. System integration is stated as a barrier, along with cost of acquisition of machinery with the necessary capabilities built in, or of retrofitting capability to existing machinery. This supports the observation derived from literature which suggests that proof of concepts predominate that are tested in practice but which are not yet at the point that driverless technology can be adopted as a 'fit and forget' solution within construction or civil engineering.

Experiences accrued and perceptions garnered

Experiences of professional practitioners were varied on some of the issues discussed such as safety. Participant 7 perhaps exemplified the general consensus viz:

"I think from a safety point of view is takes behavioural issues out of the equation. My concern is twofold – sometimes the guys on the vehicle get complacent with the noises of alarms and VDUs [visual display units] or disable the technology/ignore it altogether. Hackers are another big problem – the thought of someone getting in the system and shutting it down could create major incidents, particularly on the highway. The other

> *problem is that, it might be my generation, but I want to be in control of the vehicle not a passenger – that's the joy of driving."*

These perceptions reiterate previous research into the theory of 'cognitive over-processing' (cf. Cabahug *et al.*, 2002) and deliberate acts of vandalism of technology (cf. Edwards *et al.*, 2017b) predominantly fitted for the driver's or operator's protection when operating semi-autonomous vehicles or machinery. It also raises question in safety terms around whether systems exist to support humans or humans exist to support systems, and whether humans or machines are more effective at solving previously unencountered problems. Participant 1 raised an interesting issue regards industrial engagement in what often appears to be prototype developments viz:

> *"It takes a lot of time and resources to work with these guys because they are often not construction professionals or have little experience and know very little about the job. So you spend half your time teaching them about the contract, typical daily programmes of works and routine work activities. Clever people but haven't got a clue about the industry."*

Legal issues were raised as a concern eight of the ten participants but participant 9 best summed up the general fears viz:

> *"It's fabulous technology for sure – but if an accident happens – who pays, who gets prosecuted? Do you go for the machine operator or hirer [off-road/off-highway plant and machinery], the machinery manufacturer, the technology provider [software and hardware]? I can see this being a real problem and it's made me think twice before investing any large sums [of finance]."*

It would appear that although participants are generally positive about developments made, there are concerns around the readiness of the technology and the considerations around corporate liability in the event of an incident. This extends to considerations of becoming a passenger vis-à-vis a driver, cyber security and nefarious acts, and legalities and liabilities for users. Again, these views corroborate those found within extant literature particularly around customer readiness to adopt, maturity of technology and the anxieties that preclude adoption.

Future developments

Responses accrued for future developments could best be described as pragmatic rather than visionary. Participant 2 felt that mobile technology and cloud based solutions fitted onto machines and vehicles (encapsulated within the Industry 4.0 concept) was inevitable and pointed to exponential developments witnessed during their career. Participant 3 broadly concurred but felt that the infrastructure itself could be used as a broader solution viz:

> *"Driving on the motorway in the future could be like travelling on the train – cars set on visible tracks monitored by devices [sensors] fitted into the crash barriers, bridges and other infrastructure on the road – speeds and distances between cars monitored and controlled. Probably the way it'll go but it sure takes the pleasure out of driving on an open stretch of road. Maybe in big cities it might be better."*

Participant 5 had more commercial concerns and akin to participant 9 raised technology readiness and legal concerns viz:

> *"In plant hire, I just don't think that we're ready for driverless machines – there are far too many things that can change on a site within seconds and the technology can't cope. We're probably 10-15 years off and even then the applications will be limited – we also*

need clarification on the legislation and insurance companies need to get behind this too. If only it was as simple as putting a robot on a site."

Discussions held highlighted the general sense of reticence, balanced with the gravity of inevitability but also timing; namely, the feeling that developments will continue but applications will continue to be limited for the foreseeable future. Overall, these views create a sense of uncertainty as to what the future of driverless vehicles will be and what technological advancements will be worthy of substantial financial investment.

Conceptual model development of the barriers

Based on a combined synthesis of literature and practitioner interviews, a conceptual model of the barriers to adoption of driverless technologies which posits new perspectives around the barriers (Torraco, 2005) is proposed. The findings also reveal the scale of developments made but also the barriers to wider adoption of driverless vehicles within society. These barriers can be grouped into three key thematic groupings of 1) *legal* – namely a lack of a clear regulatory framework to support driverless vehicles and/or clarity about liability in the event of failure of a driverless system (cf. Williams, 2020); 2) *societal* – including aspects relating to: i) safety concerns for drivers and pedestrians; ii) the prohibitory cost of procurement compared to current manually operated vehicles; and iii) end-user readiness to adopt this technology and in the case of transport systems become virtual passengers; 3) *technological* – including: i) infrastructure and communication system issues to facilitate driverless vehicles on the highway or on construction sites; ii) cybersecurity and/or data privacy concerns together with the potentially catastrophic impact that targeted nefarious activity could have upon transport networks and society; and iii) the need to create and implement reliable digital mapping of infrastructure sites and the highways and city infrastructure these sites create, along with easy-to-update features that enable the map data to be kept current and so usable for navigation (see Figure 6). At this juncture, the technological maturity rate is perhaps best described as largely remaining 'under development' since driverless vehicles have not received sufficient testing in practice to resolve many of the initial problems and faults (and concomitant liability for these).

<Insert Figure 6 about here>

Elucidation upon these barriers reveals that whilst technological developments around the practical aspects of developing a driverless vehicle have advanced expediently and in some cases generated vehicles that can be used reliably in driverless modes (for example within the mineral products industry), the challenge for greater adoption of driverless technologies surrounds the ability of such vehicles to navigate and interact safely with other vehicles and humans. A more holistic view is required to focus on mapping smart infrastructure developments along with continual updating and learning about the interactions needed to navigate safely through a continuously changing physical space containing other vehicles (both manually and automatically controlled), humans and other potential sources of hazard.

At present, any viable solution depends on the notion of a near totalitarian centralised and inter-connected digital environment that sources information from infrastructure, the internet and vehicles occupying the operational space to facilitate a driverless solution. Within a construction or civil engineering environment this may be acceptable, given the design and control of the site is within the gift of the organisation operating it. However it is different within a transport environment context that is free at the point of use; users within such an environment become subservient to the system vis-à-vis free actors within it. The debate around whether systems exist for the benefit of humans or humans exist for the benefit of systems applies here, as does the observation that subservience to the system oddly opposes the innate spirit of human ingenuity that first created the technology which enables the system. This loss of control and loss of purpose then perhaps partly explains public reticence to surrender their empowerment rights for self-determination in favour of solutions that deliver greater efficiency, safety and environmental benefit relating to transport infrastructure and its construction. The decision to be taken is whether, collectively, there is an appetite to control individual liberties of people who wish to drive for pleasure in order to achieve greater local, societal and global benefits.

Limitations and future work

Whilst the palpable benefits of interpretivism are well defined within extant literature (such as achieving verstehen and/or stimulating a wider polemic discourse) this philosophical approach also has several major limitations. These include: the results not being reliable or generalizable because interpretivist researchers assume that reality is only achieved through social constructs such as the prevailing driverless vehicle literature (Antwi and Hamza, 2015; Kiernan and Hill, 2018); introduction of the researcher's imposition (in terms of their view of reality) and consequential bias that this may introduce (Denzin and Lincoln, 2003); poorly defined and delineated literature searching practices that may omit significant research and/or and introduce translation errors – such is particularly pertinent when constructing thematic clusters and/or sub-groupings of research endeavour (cf. Mallett *et al.*, 2012); and overall, low reliability of the findings presented (cf. Roberts *et al.*, 2019). These limitations apart, all research has a beginning and one significant benefit of an interpretivist approach is the generation of new theories that can stimulate debate and signpost future research direction. For example, Rocco and Plakhotnik (2009) acknowledge that conceptual frameworks can act as the basis for building a foundation as well a provision of reference points for interpretation of findings. Therefore, the outcomes of the systematic review have formed as the basis of knowledge development through the identified seven barriers categorised into three key thematic groupings (ref Figure 6) as the state of knowledge (Snyder, 2019). Over and above future research to target the barriers identified (e.g. legal, societal and technological barriers), there is a compelling need to create wider collaboration between scientists and practitioners with applied knowledge of infrastructure and the built environment – at present civil engineers and construction academics are conspicuous by their absence within published literature. The fusion of technological know-how with industry specific knowledge and experience should ensure that optimum future solutions developed.

CONCLUSIONS

Global pollution, prodigious consumption of scarce natural resources and a booming population have engendered monumental societal debate and progressive transition towards a greener and more sustainable future. In turn, this cultural evolution has stimulated politicians and policy makers to optimise people's movement within the built environment whilst simultaneously conserving (or improving) the natural environment. 'Driverless vehicles' represents a viable solution but this phenomenon is also an emotive technology and its application is a concept that elicits strong, polarised opinions within the general population. Conversely, it engenders visions of a utopian 'science fiction' future where humans are enabled to live within a hedonistic existence, liberated from the toils of manual labour; on the other, visions of a dystopian and uncertain future where machines are imbued with true artificial intelligence and so are capable of learning, such that liberty is unduly constrained and humans become subservient to machines. The truth perhaps resides between these two extremes as barriers to adoption of driverless technology are changing and will continue to change, as will the technologies involved and human interaction with, and perceptions of, these technologies.

Hence, the apt quotation from Alan Turing at the very outset of this manuscript viz. in the short term, extensive work is needed to fully realise the inherent capabilities of driverless technologies but in the longer term, new solutions are awaiting discovery.

Research presented in this systematic analysis of literature reveals the rapid pace of technological development enabled via a coalescence of technologies and inter-disciplinary collaboration – particularly amongst academics working within engineering, computer science and the social sciences. The research also reveals that whilst advancements made are frequently awe-inspiring and captivating, they are also often ineffectual in practice, particularly in operational environments that demand reliable performance, such as highway infrastructure sector, construction or civil engineering. Within these areas, assured delivery is essential and so any driverless technology needs to match or ideally exceed the performance of a human operator, which is a challenge for current driverless systems as they are essentially still development prototypes.

Consequently, the tendency has been to employ semi-automated components to correct or modify operator behaviour on vehicles or machinery to create symbiosis between man and machine vis-à-vis fully driverless vehicles. The research elucidates further upon present barriers to adoption of driverless technology, many of which are common problems that must be addressed to enable transport networks and the construction, civil engineering or highway infrastructure sector to adopt this technology widely. Prominent industry practitioners added an additional layer of intellectual nuance with their insightful experiences and perceptions of driverless technologies for both vehicles and mobile plant and machinery. Concerns over the prohibitive cost, legalities in the event of an accident and the readiness of the public and private practice to adopt driverless technologies were prominent within the discourse. These barriers naturally lead to lines for future research investigation which require further explication and analysis.

Notable amongst practitioners was the notion that laboratory ready technologies or development prototypes lack industry specific know-how leading to an ominous gap between theory and practice in specific niche fields such as construction, civil engineering or the highway infrastructure sector. Such a gap could arguably be reduced by inclusion of construction and civil engineering academics or practitioners at the design stage or within future research and development teams.

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Figure 1 – Research process

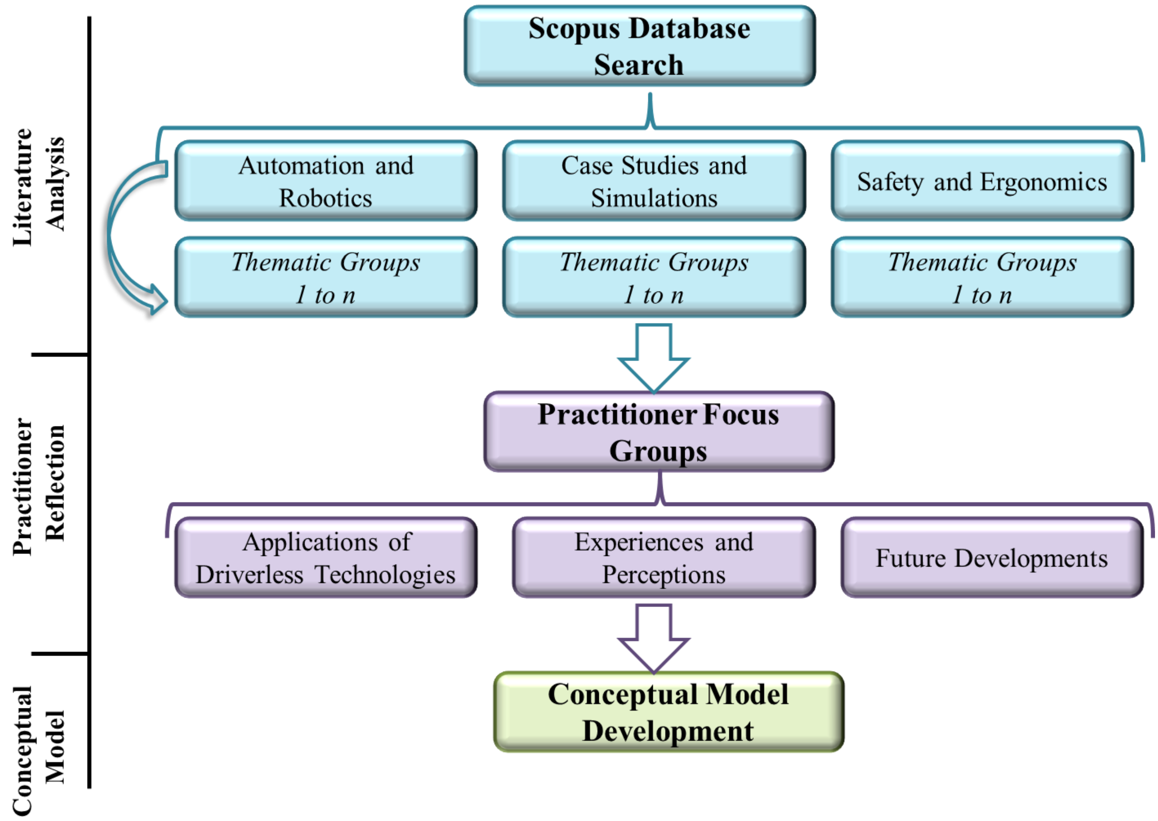

Figure 2 – Publications per Annum

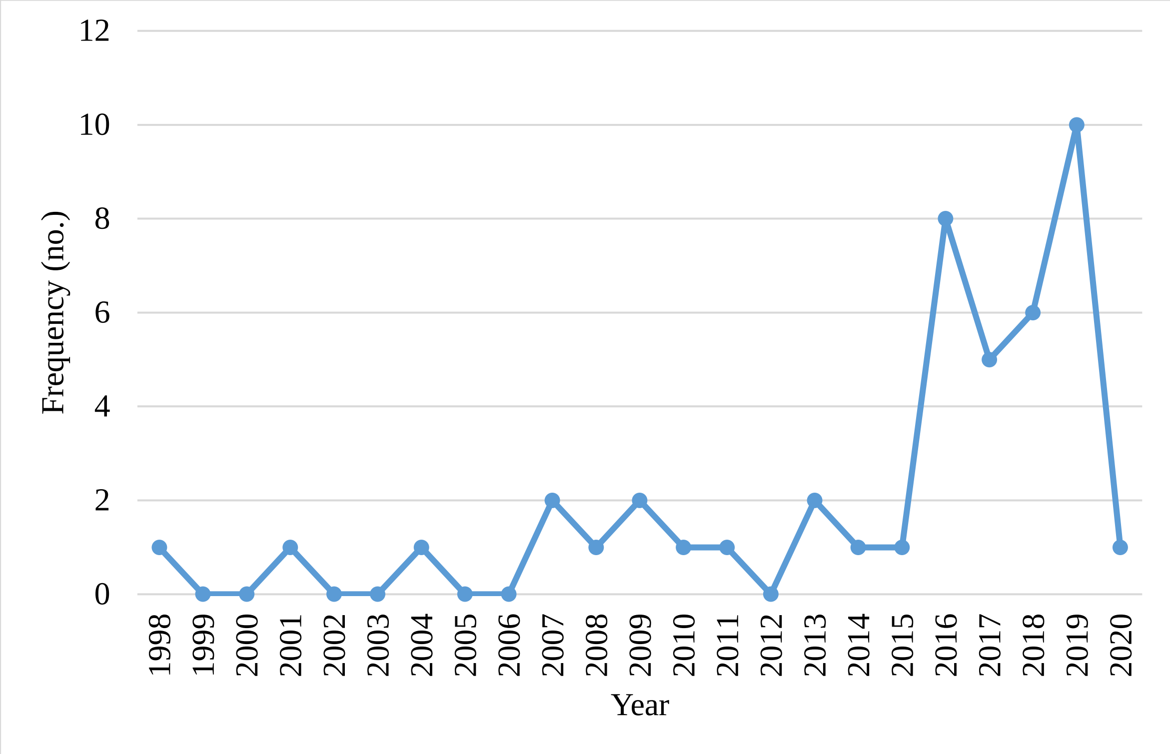

Table I – Participant demographic profile

Participant No.	Position	Industry Sector	Years of Experience
1	Safety, Health, Environment and Quality Director	Utilities	35
2	Health and Safety Director	Construction	33
3	Regional Director	Construction	31
4	Health and Safety Director	Civil Engineering	30
5	Managing Director	Plant Hire	29
6	Commercial Director	Construction	28
7	Senior Plant Manager	Utilities	27
8	Owner	Retrofit Technology Company	25
9	Marketing Director	Plant Hire	24
10	Owner	Retrofit Technology Company	25

Table II – Publications by Country

Country	**Frequency (No.)**	**Percentage (%)**
United States	19	33.92857143
China	6	10.71428571
Australia	3	5.357142857
France	3	5.357142857
Germany	3	5.357142857
Austria	2	3.571428571
Czech Republic	2	3.571428571
Spain	2	3.571428571
United Kingdom	2	3.571428571
Canada	1	1.785714286
Hungary	1	1.785714286
India	1	1.785714286
Luxembourg	1	1.785714286
Netherlands	1	1.785714286
Pakistan	1	1.785714286
Portugal	1	1.785714286
Russian Federation	1	1.785714286
Saudi Arabia	1	1.785714286
Slovakia	1	1.785714286
Sweden	1	1.785714286
Undefined	3	5.357142857

Note: Rounded to two d.p

Table III – Distribution of Authors by Discipline

Discipline	Frequency (No.)	Percentage (%)
Engineering	30	35.29
Computer Science	17	20.00
Social Sciences	14	16.47
Mathematics	7	8.24
Business, Management and Accounting	3	3.53
Economics, Econometrics and Finance	3	3.53
Environmental Science	2	2.35
Materials Science	2	2.35
Medicine	2	2.35
Physics and Astronomy	2	2.35
Arts and Humanities	1	1.18
Chemistry	1	1.18
Energy	1	1.18

Note: Rounded to two d.p

Figure 3 – Content analysis for automation and robotics

Item No.	Cluster	Word(s)	Frequency (No.)	Percentage (%)
1	Infrastructure	systems (*f* = 31); driving (*f* = 25); road (*f* = 24); traffic (*f* = 16); transit (*f* = 15); urban (*f* = 14); infrastructure (*f* = 9); markings (*f* = 9); highway (*f* = 7); network (*f* = 7); pavement (*f* = 7); roads (*f* = 7); and lane (*f* = 8).	179	23.96
2	Vehicle	Vehicle (*f* = 42); vehicles (*f* = 34); driverless (*f* = 21); mobility (*f* = 17); drivers (*f* = 12); driver (*f* = 11); cars (*f* = 10); vehicular (*f* = 8); and car (*f* = 7).	162	21.69
3	Automation	Autonomous (*f* = 37); automated (*f* = 22); intelligent (*f* = 20); transport (*f* = 14); transportation (*f* = 13); and smart (*f* = 11).	117	15.66
4	Research and Data	Data (*f* = 16); rate (*f* = 11); research (*f* = 11); results (*f* = 10); information (*f* = 7); model (*f* = 7); study (*f* = 7); time (*f* = 7); use (*f* = 7); using (*f* = 7); development (*f* = 6); flow (*f* = 6); framework (*f* = 6); and parameters (*f* = 6).	114	15.26
5	Technology	Control (*f* = 17); technologies (*f* = 13); technology (*f* = 11); electric (*f* = 7); mobile (*f* = 7); and detection (*f* = 6).	61	8.17
6	Safety	Crash (*f* = 9); safety (*f* = 9); and accidents (*f* = 8).	27	3.62
7	Planning	Planning (*f* = 11); and process (*f* = 8).	19	2.54
8	Misc.	Paper (*f* = 20); dlc (*f* = 13); future (*f* = 12); new (*f* = 8); older (*f* = 8); and deployment (*f* = 7).	68	9.10
Totals			**747**	**100**

Figure 4 – Content analysis for case studies and simulations

Item No.	Cluster	Word(s)	Frequency (No.)	Percentage (%)
1	Vehicle	Vehicle (*f* = 28); vehicles (*f* = 23); taxi (*f* = 11); traffic (*f* = 9); personal rapid transport (PRT) (8); drivers (*f* = 7); bus (*f* = 6); cars (*f* = 5); transport (*f* = 5); car (*f* = 4); automotive (*f* = 4); and driver (*f* = 4).	114	26.51
2	Technology	Technology (*f* = 16); communication (*f* = 11); networks (*f* = 9); control (*f* = 11); technologies (*f* = 7); wireless (*f* = 7); solar (*f* = 7); electric (*f* = 7); powered (*f* = 4); 5G (*f* = 4);	83	19.30
3	Misc.	Service (*f* = 10); door (*f* = 8); based (*f* = 6); center (*f* = 6); different (*f* = 5); path (*f* = 5); set (*f* = 5); track (*f* = 5); capacity (*f* = 4); challenges (*f* = 4); effects (f = 4); improve (*f* = 4); new (*f* = 4); number (*f* = 4); paper (*f* = 4); and provide (*f* = 4).	82	19.07
4	Automation	Driverless (*f* = 25); transportation (*f* = 13); driverless vehicles driverless cars (DVDC) (f = 8); autonomous (*f* = 8); intelligent (*f* = 5); and automated (*f* = 4).	63	14.65
5	Infrastructure	Driving (*f* = 9); highway (*f* = 7); road (*f* = 7); roundabout (*f* = 7); urban (*f* = 6); design (*f* = 5); highways (*f* = 4); mile (*f* = 4); miles (*f* = 4); and delay (*f* = 4).	57	13.26
6	Research and Data	Research (*f* = 9); data (*f* = 4); and analysis (*f* = 4).	17	3.95
7	Planning	Planning (*f* = 8); and systems (*f* = 6);	14	3.26
Totals			**430**	**100**

Figure 5 - Content analysis for safety and ergonomics

Item No.	Cluster	Word(s)	Frequency (No.)	Percentage (%)
1	Misc.	Model (f = 7); paper (f = 5); based (f = 4); multi (f = 4); operation (f = 4); new (f = 3); framework (f = 3); board (f = 3); deep (f = 3); proposed (f = 3); study (f = 3); efficiency (f = 3); influence (f = 3); management (f = 3); algorithm (f = 2); assistance (f = 2); applications (f = 2); and applying (f = 2).	95	27.22
2	Technology	Control (f = 11); technology (f = 10); communication (f = 9); connected (f = 8); networks (f = 8); tracking (f = 8); zigbee (f = 5); technologies (f = 4); wireless (f = 4); IoT (f = 4); simulation (f = 4); device (f = 3); communications (f = 3); neural (f = 3); simulator (f = 3); mobile (f = 3); and detector (f = 3).	93	26.65
3	Vehicle	Vehicles (f = 17); vehicle (f = 15); cars (f = 6); driver (f = 6); automobile (f = 5); and driving (f = 5).	54	15.47
4	Safety	Safety (f = 12); traffic (f = 11); pedestrian (f = 7); accident (f = 4); environment (f = 4); behaviour (f = 3); speed (f = 3); warning (f = 3); collision (f = 3); and public (f = 3).	53	15.19
5	Automation	Driverless (f = 17); transportation (f = 6); intelligent (f = 5); and automation (f = 4); and autonomous (f = 3).	35	10.03
6	Infrastructure	road (f = 6); highway (f = 4);	10	2.86
7	Planning	systems (f = 5);	5	1.43
8	Research and Data	Information (f = 4)	4	1.15
Totals			**349**	**100**

Figure 6 – Conceptual model of the barriers to adoption