Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore

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ARTICLE INFO

ABSTRACT

Despite their promise, there have been discussions surrounding the technological risks of autonomous vehicles (AVs) and the extent to which AVs are ready for large-scale deployment. Using a case study approach, this article examines the development and implementation of AVs in Singapore. Our findings reveal that AV regulatory sandboxes, the formalisation of safety assessments and the release of technical guidelines are some of the most adaptive and innovative instruments that have been adopted to govern AVs in Singapore. Furthermore, Singapore's approach to AVs has applied an adaptive strategy that is both pre-emptive and responsive. The accelerated expansion of trials and regulatory provisions for AVs demonstrates Singapore's aspiration to be nimble, and showcases the simultaneous adoption of two contrasting implementation approaches – prescriptive and experimentalist – to guide AV adoption. The regulatory lessons derived from the governance of AVs in Singapore could provide useful policy guidance, and could inform policy discussions of AVs as well as other autonomous systems.

1. Introduction

The adoption of autonomous vehicles (AVs) is expected to disrupt conventional ways of living. While AVs hold promise for improving our quality of life, there have also been discussions of their adverse implications (Crayton & Meier, 2017; Pettigrew, 2016; Thomopoulos & Givoni, 2015). From a public policy perspective, ensuring that the regulation of the various technological risks posed by AVs keeps pace with rapid technological advances in AV technology is imperative (Riehl, 2018). This article discusses the technological risks of AVs, and governance strategies for AV adoption, in Singapore using a case study approach. As one of the top seven economies in the world for investment in information and communication technology (Baller, Dutta, & Lanvin, 2016), Singapore has experienced tremendous technical progress and significant regulatory changes in the development of AVs in recent years. Singapore was ranked second in 2019 and first in 2020 in the world in the AV Readiness Index, which assesses a jurisdiction's AV ecosystem on four pillars (policy and legislation, technology and innovation, infrastructure, and consumer acceptance) across 30 countries and jurisdictions (KPMG International, 2020). These developments make Singapore an illuminating case, offering significant policy lessons for countries contemplating the deployment of AVs as a viable transport

solution. Specifically, Singapore's experience in implementing AVs demonstrates how stability in the decision-making structure and adaptability in the implementation process can be harmonised in the face of uncertainty.

In documenting the experience of AV adoption and deployment in Singapore, we pose the following research questions: (a) What are the inherent and possible technological risks associated with AV deployment? (b) How has the Singapore government employed different governance strategies to address the major technological risks involved in the deployment of AVs in the near future? By dissecting the different types of governance strategies employed, including understanding the interactive dynamics of these strategies, we investigate how they are either mutually exclusive or overlap with one another in propelling the development of a disruptive technology like AVs.

The next section provides an overview of AVs. This is followed by a description of the theoretical framework used, in Section 3. The fourth and fifth sections, respectively, describe the case of AVs in Singapore, and analyse their implementation. The sixth section discusses the unique governance experiences of AV implementation in Singapore, illustrating various agenda scenarios, policy measures, policy decisions and implementation strategies that have accelerated the rapid adoption and effective implementation of AVs. The seventh section discusses some

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unique lessons that Singapore could offer, as well as some of the ongoing learning points for various AV stakeholders in Singapore to ensure success in the long-term implementation of AVs. The eighth section proposes five policy recommendations for other jurisdictions in terms of disruptive technology adoption. These include (i) creating a friendly business environment that fosters experiments; (ii) strengthening government's stewardship; (iii) cultivating a collaborative spirit with the other non-government stakeholders; (iv) building policy capacity for disruptive technology adoption; and (v) combining control-oriented, toleration-oriented and adaptation-oriented governance strategies in the implementation of disruptive technologies. The article concludes with suggestions for future research directions, and cautions other countries on the importance of exploring the implications of unique contextual factors and designing issue-specific risk-coping strategies for the governance of AVs.

2. Background to AVs

According to the Society of Automotive Engineers' (SAEs') levels of automation, AV automation spans six levels from 0 to 5 (SAE, 2018). At level 0, there is no automation in driving functions: only limited automated features, such as warnings, are given to support human drivers. At level 1, function-specific automation that supports human drivers is incorporated, such as braking control or steering. At level 2, combined function automation is enabled to allow two primary control functions, such as steering and acceleration, to work in synchrony. At level 3, partial self-driving automation is enabled, through which most of the safety and critical functional controls of the vehicle are automated, and drivers are expected to assume control only when the system requests it. At level 4, all driving automation functions resemble level 3, but human drivers are not expected to take over driving. Level 5 is full self-driving automation whereby the automated driving features of a vehicle are able to operate under all conditions and without any human intervention (SAE, 2018). In addition, connected AVs are capable of interacting in real time with other vehicles and connected infrastructure, through the exchange of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) information, to better anticipate and manage the uncertainties arising from various road conditions (Nikitas, Kougias, Alyavina, & Tchouamou, 2017).

There are various benefits associated with the deployment of AVs. Much of the support for AVs is driven by their potential to significantly reduce road traffic accidents due to the elimination of human errors. Across the world, road traffic accidents – the most preventable of all leading causes of death – result in 1.2 million deaths each year on average (World Health Organization, 2015). By leveraging the improved precision of GPS, sensors and high-performance computing that enable real-time processing of data, AVs can make much more accurate and timely decisions in appraising and reacting to varying road conditions than their human counterparts (Crayton & Meier, 2017; Fagnant & Kockelman, 2015; Pettigrew, 2016; Thomopoulos & Givoni, 2015). For instance, the AV can activate instant braking with a reaction time that is much faster than that of human drivers (Doecke, Grant, & Anderson, 2015). AVs could minimise collisions, which would translate into substantial cost savings through the reduction of hospitalisation charges (Fagnant & Kockelman, 2015). For instance, in the US, the 2.2 million injuries and over 32,000 fatalities that result from road traffic accidents every year contribute to $277 billion in economic costs (2% of GDP) (Fagnant & Kockelman, 2015). Nonetheless, AVs will not entirely eliminate accident-related casualties and deaths, as suggested by recent high-profile fatal accidents that have occurred, such as an Uber driverless test vehicle's crashing into a pedestrian in Arizona (CNA, 2018a) and a Tesla running on autopilot killing its driver in early 2018 (The Guardian, 2018).

AV deployment could also improve congestion by decreasing human-error accidents and increasing road lane capacity through platooning (Fagnant & Kockelman, 2015; Kane & Whitehead, 2017). Platooning

allows multiple AVs to move as a single entity following a first vehicle, to maximise spatial efficiency (Flamig, 2015), resulting in higher fuel and energy efficiency (Pettigrew, 2016). Environmental benefits could also be accrued by designing AVs to reduce greenhouse gases emissions (Taeihagh & Lim, 2019; Crayton & Meier, 2017; Pettigrew, 2016). Shared AVs could promote other benefits from the sharing economy, including reducing private car ownership, the number of trips required during peak periods, and parking requirements (Taeihagh, 2017b; Li, Taeihagh, & de Jong, 2018; Kane & Whitehead, 2017). Moreover, AVs could improve time efficiency by allowing the human driver to engage in non-driving activities while travelling in the vehicle, such as working or resting (Thomopoulos & Givoni, 2015). Furthermore, when integrated into a broader transport network, AVs could make transport more inclusive and equitable by allowing more seamless first- to last-mile travel for the disabled and elderly (Crayton & Meier, 2017; Pettigrew, 2016).

Amidst optimistic projections of AVs' positive impacts, there are also discussions of the negative implications of AV adoption (Taeihagh & Lim, 2019). First, there are concerns that AVs can induce greater demand for travel resulting from reduced transport pricing, increased frequency of trips made, and the fulfilment of previously unmet needs for transport among specific population groups. Empty rides on shared AVs would also artificially inflate demand. The induced demand could increase vehicle-miles travelled, which could exacerbate congestion and energy use (Crayton & Meier, 2017; Hensher, 2018; Kane & Whitehead, 2017; Milakis, van Arem, & van Wee, 2017; Pettigrew, 2016; Thomopoulos & Givoni, 2015). Some also postulate that shared AVs are unlikely to be a silver bullet for addressing congestion problems or increased transport demand, and would need to be complemented by road user charges and an optimal mix of public transport that integrates with AVs (Hensher, 2018). A second major concern is labour market disruption, as AV deployment would displace the labour force in the transport industry, particularly workers in professional driving occupations (Taeihagh & Lim, 2019; Crayton & Meier, 2017). Framing AV adoption in terms of global competitiveness and economic reasoning (Hopkins & Schwanen, 2018), while preventing AV manufacturers or brokers from dominating the discussion (Hensher, 2018), could potentially help governments create political buy-in from citizens and minimise the adverse public reactions to potential AV-induced labour market disruptions.

3. Analytical framework

In light of the mixed implications associated with AV deployment and the long-term uncertainties involved in its large-scale implementation, it is imperative to examine the inherent and potential technological risks that AV implementation could pose to society at large. Furthermore, it is of both theoretical and pragmatic interest to understand how governments can craft public policies and employ different instruments to address these risks. Guided by the research questions and anchored in the research objectives set out in Section 1, we apply the following analytical frameworks (mechanisms of technology deployment, technological risks and governance strategies) in our inquiry. We apply these frameworks in our case description and analysis to examine the extent to which they can be harnessed to inform policies and governance of novel and disruptive technologies across the world.

3.1. Mechanisms of technology deployment

Technology deployment typically goes through a calibrated policy process from agenda-setting, to formulation, to decision-making, to implementation, and ultimately to the evaluation of the technology. Drawing inspiration from Rogers' (2003) work on the diffusion of innovation and combining this with the technology deployment process model proposed by Baskarada, McKay, and McKenna (2013), a four-stage process (1-knowledge and persuasion, 2-planning and decision-making, 3-implementation and 4-evaluation) was identified as the

mechanism involved in AV deployment in Singapore. According to Rogers (2003), an innovation is shown to go through a five-stage process from knowledge (the awareness of an innovation and operationalisation of an idea), to persuasion (enabling the formation of favourable or unfavourable attitudes through different communication strategies), to decision (engaging in a series of thought processes and activities that leads to the deployment or non-deployment of an innovation), to implementation (putting the innovation into practice), and to confirmation (evaluating the decisions made regarding the deployment or non-deployment of the innovation). Similarly, Baskarada et al. (2013) substantiated this by proposing finer details in the processes of technology deployment. They formulated a four-stage process in technology deployment, comprising 61 activities that span four stages: initiation, planning, execution, and evaluation (see Fig. 1).

3.2. Technological risks

Despite their potential benefits, emerging technologies can bring socio-economic and geopolitical risks that most countries may not be able to mitigate effectively with their current regulatory capacities (Dickinson, 2018). AVs, like many other emerging technologies, possess both uncertain and embedded technological risks, such as risks relating to safety, privacy, cybersecurity, liability, and the effects on the incumbent industry (Taeihagh & Lim, 2019). A technological risk is described as the potential for physical, economic and/or social harm/ loss or other negative consequences stemming from the adoption of a technology over its lifecycle (Li et al., 2018; Renn & Benighaus, 2013). With the adoption of these emerging technologies in the public sector, these technological risks will become inevitable public administration challenges for the government concerned (Agarwal, 2018). There has been a large amount of scholarly work in recent years focusing on the debates, imperatives and frameworks relating to the risk governance of emerging technologies in various fields, such as transport policy (Taeihagh & Lim, 2019), criminology (Hannah-Moffat, 2018), and public service innovation (Brown & Osborne, 2013; Flemig, Osborne, & Kinder, 2016). Table 1 summarises the five different technological risks (safety, privacy, cybersecurity, liability, and effects on the incumbent industry) of AVs.

3.3. Governance strategies for emerging technologies

In this study, we apply an established theoretical framework depicting different types of governance strategies (Li, Taeihagh, de Jong, & Klinke, 2020) which have been applied in previous studies on the governance of disruptive technologies in the transport sector (Li et al., 2018; Taeihagh & Lim, 2019; Rosique, Navarro, Fernández, & Padilla, 2019). In this article we strengthen the original work by further synthesising it with the various approaches adopted in the study of risk regulation and governance (see Table 2):

3.3.1. No-response strategy

This strategy implies the absence of a response, with no provision of explicit rules and regulations by the government to govern the roll-out of technology. This is especially common in the early stage of new technology adoption, which is fraught with information asymmetries (Li et al., 2018). A no-response strategy is also likely to be applied when there remain significant ambiguities in the potential scalability of the service or product, responsiveness from the populace, and financial sustainability of the ventures.

Fig. 1. Policy Processes and Mechanisms of AV Deployment in Singapore.

Table 1
Explanations of major five technological risks of AVs.

Type of risk	Explanation
Safety	Ensuring that human lives are protected from fatal or injurious car accidents through road safety regulations.
Privacy	Compelling the party that controls sensors, high definition maps, and other systems in an AV that contain personal information to preserve the anonymity of that information and ensure the ethical use of data.
Cybersecurity	The ability to prevent software hacking and misuse of vehicles at all levels of automation by shielding the wireless network from hackers' control.
Liability	The apportionment of responsibility for errors among the first party (human driver) or third parties (manufacturers and/or developers involved in the design of the safety system) in the event of vehicle accidents.
Effects on the incumbent industry	Employment implications and labour market effects of widespread AV adoption on existing actors in the incumbent industries (i.e. transport industry, such as taxi drivers, bus drivers, truck drivers, and private car owners).

Adopted from Taeihagh and Lim (2019).

Table 2
A summary of the governance strategies for the adoption of novel and disruptive technologies.

Governance Strategy	Explanation
No-response	This strategy is normally taken in the early stage of the adoption of a new technology when its risks and potentials remain ambiguous and uncertain (e.g. the potential scalability of the service or product, responsiveness from the populace, and financial sustainability of the ventures).
Prevention-oriented	This strategy attempts to avert novel technology adoption, often characterised by strong resistance from the government due to political, social, and cultural factors such as low public acceptance (Egbue & Long, 2012; Taeihagh et al., 2013) and conflicting stakeholder agendas (Quezada et al., 2016). A prevention-oriented strategy is often incentivised by the intention to maintain social stability and minimise interest groups' mobilisations by preserving the status quo.
Control-oriented	This strategy resembles the conventional regulatory-state approach observed in many traditional risk assessments (Moran, 2003) in which various instruments are deployed to regulate their risks (Moran, 2003).
Toleration-oriented	This strategy is highly anticipatory and focuses on risk tolerance. Designing policy alternatives or instituting policy reform to prepare for unanticipated risks as well as to increase response readiness of the various government machineries are some of the hallmarks of toleration-oriented strategies.
Adaptation-oriented	This strategy focuses on building robust structures to increase capacity of the government to withstand volatility and manage policy uncertainty. Policy learning and lesson-drawing are at the core of an adaptation-oriented strategy. Ongoing stakeholder participation, policy experiments, and the ability to engage in long-term thinking and planning are some of the hallmarks of this strategy (Boin & van Eeten, 2013; Li et al., 2018; Janssen & van der Voort, 2016; Duit, 2015).

3.3.2. Prevention-oriented strategy

This strategy attempts to directly prevent risks from occurring and is often reflected in resistance by the government to the immediate adoption of a technology due to political, social and cultural factors. For instance, socio-technical barriers such as low public acceptance (Egbue & Long, 2012; Taeihagh, Givoni, & Bañares-Alcántara, 2013) and conflicting multiple stakeholder agendas (Quezada, Walton, & Sharma, 2016) could result in the government's repudiation of the technology. A prevention-oriented strategy is most notably observed when there are vested interests within government and various interest groups in preserving the status quo, the failure of which could threaten social stability in the event of interest groups' mobilisation. For instance, the halting of the carpooling service offered by Grab across the border between

Singapore and Malaysia was an example of a predominantly prevention-oriented strategy adopted by the government (Li et al., 2018).

3.3.3. Control-oriented strategy

This strategy resembles the conventional regulatory state approach observed in many traditional risk assessments (Moran, 2003) and implies the dominance of the government. A control-oriented strategy is adopted when governments decide to allow novel policies to be rolled out but try to deploy instruments to regulate their risks (Moran, 2003). Some of the most successful urban transport policies, such as congestion pricing introduced in major cities, including the London Congestion Charging Scheme (LCCS) for central London, and Electronic Road Pricing (ERP) for Singapore, are classic examples of a state-directed control-oriented strategy for managing traffic congestion (Santos, 2005).

3.3.4. Toleration-oriented strategy

This strategy focuses on risk tolerance and signals the government's preparedness to handle the calamities or risks associated with the adoption of certain policies. Rather than aiming at risk mitigation, it focuses on risk tolerance. It is strongly anticipatory in nature. Designing policy alternatives or instituting policy reform to increase the response readiness of the various government machineries are some of the common policy responses implemented to prepare for unanticipated risks. A toleration-oriented strategy is applied in emergency management and disaster preparedness as a coping mechanism to improve the robustness and capacity of the government to withstand risks such as those introduced by natural disasters (O'Grady, 2015).

3.3.5. Adaptation-oriented strategy

This strategy focuses on building robust structures within the government that can withstand volatility and policy uncertainty, and is closely associated with the idea of 'adaptive resilience' in the public administration literature (Boin & van Eeten, 2013; Duit, 2015), 'adaptive governance' in the literature on the governance of public service innovation (Janssen & van der Voort, 2016) and 'agile governance' in the literature on the governing or managing of social-technical systems and public organisations (Hong & Lee, 2018; Mergel, Gong, & Bertot, 2018; Soe & Drechsler, 2018; Wang, Megdalia, & Zheng, 2018). In public administration, resilience refers to the ability of an organization to purposefully reform to stay socially and politically relevant (Duit, 2015). Adaptive governance entails the ability to maintain the stability of the governance structure, on the one hand, while being dexterous in adapting to uncertainties through trial and error, on the other (Janssen & van der Voort, 2016). The governance processes are highly malleable and agile in their relation to the changing circumstances, involving the flexibility of regulations and incremental revisions to maintain a functioning bureaucracy (Mergel et al., 2018). An adaptation-oriented strategy is thus a response strategy that has policy learning and lesson drawing at its core. Ongoing stakeholder participation, policy experiments and the ability to engage in long-term thinking and planning are some of the hallmarks of this strategy (Boin & van Eeten, 2013; Li et al., 2018; Janssen & van der Voort, 2016; Duit, 2015; Li et al., 2020).

4. Methods

We employed a single case study approach to analyse the development, risks and governance strategies surrounding AVs in Singapore from 2013 to 2022. The case study is a comprehensive empirical approach that allows an inquiry to be pursued using a flexible research design, various data collection methods and distinctive approaches to data analysis (Yin, 2018). We first applied process tracing to track evolutionary patterns and key developments relating to AVs in Singapore. This process enabled us to map out the entire landscape of AV development comprehensively and chronologically.

Our data sources were derived from both primary and secondary research. Our primary research involved in-depth individual interviews with 20 public and private sector actors in Singapore in the third and fourth quarters of 2018, identified using a combination of purposive sampling and convenience sampling. The respondents are either policymakers or subject-matter experts in various sectors such as transport, technology, urban development, law, media, and social services, and are involved in policy formulation, policy implementation and information dissemination on AVs in Singapore. They include nine public officials, policymakers and practitioners in transport, urban development and technology (Respondents 1, 2, 4, 5, 6, 11, 14, 15 and 19), two AV developers (Respondents 8 and 9), two social-service leaders (Respondents 7 and 16), four academics and subject-matter experts (Respondents 12, 13, 18 and 20), and three transport correspondents (Respondents 3, 10 and 17).

These interviewees were either directly approached by the first author for interview based on their publicly available profiles online (purposive sampling), or through snowball sampling and recommendations obtained from the industrial experts (convenience sampling).

Following Leech (2002) and Brayda and Boyce (2014), we conducted open-ended semi-structured interviews and tailored the questions to different respondents to gauge their perspectives and experiences of the design, intention and implications of policies relating to AVs in Singapore. On average, each interview lasted for an hour and the duration for all 20 interviews ranged from 45 to 90 min. The interview questions were designed by both authors through several rounds of discussion and were informed by the existing literature. The interview guide targeting private sector actors focused on their appraisal and perceptions of the government's policies for AVs to date, how these policies have impacted their commercial strategies, and how they have been engaged by the government in the process of AV deployment. On the other hand, the interview guide targeting public sector actors focused on the actual strategies and policy measures that the government has deployed to address the risks of AVs known at that point in time and that might potentially emerge in the future. Field notes were taken during the interviews, and clarifications were sought via email from some respondents to clarify meanings and information recorded during the interviews.

To cross-validate our primary data and to strengthen our analysis, we supplemented the above interviews with secondary data research. Our secondary research involved collecting news articles, grey literature, policy documents, and laws and statutes of Singapore related to AVs. These secondary data provided more accurate and precise details on the implementation process of AVs, including the detailed clauses and contents of regulatory reforms, the actual timeline of different AV trials, and the composition of the actors involved in different stages of AV implementation. Combining both primary and secondary data also enabled sufficient data triangulation to build compelling narratives and to achieve higher conceptual validity (Creswell & Miller, 2000).

The field notes were analysed thematically through pattern matching and explanation building to derive explanatory and confirmatory insights (Bennett & Checkel, 2015; Yin, 2018). First, line-by-line reading of the field notes and the news articles collected was conducted. Descriptive themes were formed through the categorisation of different texts that conferred the same meaning. Subsequently, analytical themes were formed by re-reading these descriptive themes (Thomas & Harden, 2008). In analysing the data, we focused on different timelines of the policy process, policy intentions of the government, configurations of actors and their interests and dynamics in the policy process, instrument/instrument mixes employed by the government, and how these engendered the exhibition of different governance strategies in AV implementation. Both authors were engaged in ongoing discussions and verification of the factual details of the case throughout the entire research process. Whenever conflicting views or doubts arose, we contacted the respondents again to ensure that the timeline, details and interpretations of the governance strategies were aligned with our analyses.

5. Case description: The policy process and mechanisms of AV deployment in Singapore

This case description describes the policy processes and mechanisms of AV deployment in Singapore, illustrating how the policy cycle evolved from agenda-setting, the formulation of policy ideas, and decision-making to policy implementation (Howlett, Ramesh, & Perl, 2009). Besides articulating what is already known about a particular phenomenon, descriptive case studies contribute significantly to the rigour of case analysis and theory development through the mining of both the factual accounts and the abstract meanings within the data (Mills, Durepos, & Wiebe, 2010). Furthermore, descriptive data analysis in case study analysis plays a narrative role in identifying data patterns, regularities and research hypotheses, filling a gap between exploratory and confirmatory data analyses, and serving as a precursor to confirmatory data analyses (Abt, 1987). Below we describe the four phases of AV deployment in Singapore.

5.1. Phase one (Knowledge and Persuasion): Agenda-setting (June 2013–May 2014)

Singapore is a parliamentary democracy that has been ruled by the People's Action Party (PAP) since the beginning of its nationhood in 1965. The governance structure is divided into three branches: (i) the legislative branch (comprises the President and Parliament), which makes the law; (ii) the executive branch (which comprises all Cabinet Ministers and office-holders, led by the Prime Minister), which administers the law; and (iii) the judicial branch (courts), which interprets the law (Parliament of Singapore, 2019). Inheriting the legacy of the Westminster parliamentary system, regulatory reforms can only be materialised through the legislative process. After a bill is introduced by either Members of Parliament, Cabinet Ministers, or citizens, it will typically go through parliamentary readings and debates, as well as deliberations and inquiries by a Select Committee in the event that it requires special consideration. The bill will then be scrutinised by the Presidential Council of Minority Rights and finally presented to the President before it becomes a law (Beckman, 2005).

In Singapore, the idea of AV implementation first surfaced publicly in June 2013 through a speech given by the former Minister of National Development, Mr. Khaw Boon Wan, in the World Cities Summit Mayors Forum in Spain. The idea of driverless electric cars replacing private cars was envisioned as a likely event in Singapore within a decade. To increase political buy-in, private industry was invited to tap into Singapore's business-friendly environment to implement AVs (The Straits Times, 2013). The following year, the Land Transport Authority (LTA) was actively studying the viability of AVs as a deployable and scalable mode of transport in Singapore (Tan, 2014).

5.2. Phase two (Planning and Decision-Making): Formation of policy advisory group and AV research initiatives (June 2014–December 2014)

The planning and decision-making that led to AV adoption in Singapore took off with the formation of a 17-member Committee on Autonomous Road Transport for Singapore (CARTS), led by the Permanent Secretary from the Ministry of Transport (MOT). Comprising international experts, academics and industry leaders (MOT, 2014), CARTS was the first policy advisory group formed on AVs in Singapore that attempted to lead the policy vision for and lay out the technological possibilities of AV adoption and development in Singapore.

To complement and support CARTS, the Singapore Autonomous Vehicle Initiative (SAVI) was initiated as a technology platform to drive research and development and test-bedding for AVs in Singapore. A memorandum of understanding was signed between the LTA and the Agency for Science, Technology and Research (A*STAR) in relation to this initiative, with the LTA assuming an active regulatory role in implementing AVs for the next five years (LTA, 2014).

5.3. Phase three (Implementation): Active and intensive roll-out of new AV trials (January 2015–January 2017)

Phase Three, spanning about two years, was an intense trial period for AVs in Singapore. The intensity of AV trials rolled out during this period displayed the entrepreneurial and experimental spirit of the Singapore government in the development of a disruptive technology.

During this phase, preliminary discussions of AV safety took place in the media. For instance, preventive measures to minimise security breaches through the careful design of each physical component of the AVs were emphasised. Decisions regarding the extent to which third parties should be allowed to take control of critical systems in AVs to prevent hackers from accessing information systems were also discussed (Duca, 2015).

In October 2016, the first AV collision occurred with a lorry, bringing public attention to the safety and security of AV roll-out in Singapore (CNA, 2016). nuTonomy, the industry player involved in this incident, called for a temporary halt of its AV trial (Lee, 2016). Nevertheless, this incident did not seem to deter the authorities from continuing AV trials. After the first AV accident, Singapore ramped up the installation of infrastructure for AV test-beds and expanded the test routes for AVs (Siong, 2016). Within a month, nuTonomy announced improvements to its software system and resumed its AV trial (Lim, 2016b). Table 3 summarises the AV trials and initiatives launched in Singapore during Phase Three.

5.4. Phase four (Evaluation): Crystallisation of regulatory framework and expansion of AV capacity (February 2017–October 2020)

Phase Four witnessed the crystallisation of a preliminary regulatory framework for AVs and the expansion of AV trials in Singapore. The first step towards regulating AVs in Singapore began in February 2017 when the Road Traffic Act (RTA) was amended (CNA, 2017b). The amended RTA endows the MOT with the power to set new rules that can place time and space limits on AV trials, prescribes the development of standards for the design and use of AV equipment, and stipulates requirements to purchase liability insurance or security deposits before the inception of any approved AV trials. The amended act further imposes requirements for data sharing from all ongoing AV trials with the LTA (The Law Revision Commission, 2018).

By August 2017, road traffic rules were established specifically for AVs. These rules specify application criteria for AV trials, including conditions for the authorisation of AV trials and the obligation to obtain liability insurance or pay a security deposit of at least $1.5 million. Exact penalties are also stipulated and provisions are made for their enforcement should the manufacturers fail to obtain liability insurance or fail to ensure proper maintenance of AVs. The road traffic rules for AVs also require that every AV be installed with a data recorder to collect and store data for three years beyond the expiry date of the authorisation (Pang, 2017).

Furthermore, the rules oblige AV developers to report incidents of malfunction and any accidents involving deaths or injuries (Pang, 2017). These legal amendments were intended to function as regulatory sandboxes that would be effective for five years, after which either an enactment of permanent legislation or an extension of the current regulatory sandboxes will ensue (CNA, 2017b). Regulatory sandboxes in the context of the implementation of AVs in Singapore provide flexibility for the regulators to assess the appropriateness of regulatory responses and to make regulatory amendments, if necessary, five years after February 2017, when the RTA was amended (CNA, 2017b).

From February 2017, capacity for AV trials was further increased by the expansion of trial areas, increasing the number of new trials and the announcement of masterplans for future trials. By July 2018, there was a total of 14 ongoing AV trials in Singapore (Seow, 2018).

In March 2018, the Cybersecurity Act was enacted to strengthen the protection of critical information infrastructure (CII) in 11 sectors,

Table 3
AV trials and initiatives launched in Singapore during phase three.

Date	Type of Trial/ Initiatives	Partnerships/ Actors Involved	Description of Trial/Initiative
January 2015	First AV research hub and test-bed in One-North Business Park in Singapore	LTA and JTC Corporation	This initiative was announced by LTA to test out a 6 km-long test route in phases. To increase vehicle-to-infrastructure communication and to create awareness of this AV trial among the residents in One-North Business Park, four supporting infrastructures: a Closed-Circuit Television Camera System, dedicated short-range communications beacons, a backend system analysing data generated by the test vehicles, and various signage and decals were introduced (LTA, 2015).
June 2015	Request for information	LTA	This initiative was launched to seek proposals for point-to-point mobility-on-demand – a real-time and demand-driven autonomous bus trial in the One-North Business Park (Tan, 2015).
October 2015	First driverless shuttle trial	MOT and Gardens by the Bay	This trial aimed to gather initial implementation insights to help prepare Singapore for the onset of AV adoption in the entire city-state (The Straits Times, 2015).
January 2016	Driverless shuttle trial	MOT, Sentosa Development Corporation and ST Engineering	This trial aimed to test self-driving shuttle services across Sentosa Island, one of the major tourist attractions in Singapore (Duca, 2015).
April 2016	Mobility pods	Singapore Mass Rapid Transit (SMRT) Corporation and 2getthere (a Dutch-based company)	This partnership was formed to bring 24-passenger driverless pods to Singapore as a form of group rapid transit vehicle that will operate in "semi-controlled" designated areas where drivers' behaviours and speed can be better managed. Already proven to work in major cities such as Abu Dhabi and Rotterdam, driverless pods are touted as being safer and more energy efficient. Not only are the pods driverless, but also they operate on-demand, effectively providing first- and last-mile services (Lim, 2016a; Lim, 2016d).
August 2016	Centre of Excellence for Testing and Research of Autonomous Vehicle (CETRAN)	NTU	This initiative signalled Singapore's aspiration to be an early adopter of AV systems, not only in virtual programming and technical operations, but also in setting regulatory and licensing standards that govern safety and cybersecurity (Abdullah, 2016b).
August 2016	First driverless taxi trial in the world	LTA and nuTonomy (a US-based driverless vehicle start-up)	This partnership quickly bore fruit when nuTonomy launched the first on-demand driverless taxi trial in the world, ahead of Uber's driverless taxi trial in Pittsburgh, by the end of August (Abdullah, 2016d, 2016e).
October 2016	Request for information	National Environment Agency (NEA) and MOT	This initiative was intended to seek proposals on the design and development of AVs for street-cleaning (Abdullah, 2016a).
October 2016	First driverless bus trial in Singapore	LTA and NTU	This initiative was launched in Jurong West (Lim, 2016c).
October 2016	Launch of driverless mobility scooters	Singapore-MIT Alliance for Research & Technology	This initiative was tested in several housing estates as well as a university campus (Abdullah, 2016c).
January 2017	First autonomous truck platooning system	Port of Singapore Authority (PSA), MOT and two private companies (Toyota Tusho and Scania)	This initiative aimed to transport containers on driverless trucks within the port terminal in Singapore to increase the efficiency of freight movement (CNA, 2017c).

including land transport. The act accords the Cybersecurity Commissioner the power to set cybersecurity standards and to request owners of CII to share information and manage cybersecurity incidents. The Cybersecurity Act also imposes licensing requirements for cybersecurity service providers (Singapore Statutes Online, 2018).

In addition, the LTA unveiled a new skills framework for the public transport sector through the Industry Transformation Map (ITM), to prepare the transport workforce for the deployment of disruptive technologies that will inevitably transform future job requirements. This framework plans to up-skill or re-skill existing transport workers to enable them to assume roles requiring higher skill sets. Up to 8000 new high-value-added public transport jobs that cross-fertilise expertise from the transport and IT industries will be created by 2030 (Farhan, 2018).

In November 2018, the LTA reinforced the mandatory requirements for AVs. The presence of a safety driver, a black box recorder, a vehicle fault alarm system, insurance against third-party risks and passing an enclosed circuit test will be strictly enforced (Lam, 2018). In January 2019, a provisional national standard, known as Technical Reference 68 (TR68), was launched to guide the development and deployment of AVs in Singapore (LTA, 2019). By the end of 2019, the Singapore government had announced the expansion of AV testing grounds. More than 1000 km of the public roads in the entire western region of the island state were designated to become testing grounds for autonomous vehicles in the near future (Abdullah, 2019). Table 4 summarises the AV trials and initiatives launched in Singapore during Phase Four.

6. Case analysis

In the following paragraphs we analyse five types of technological

risk in AV adoption. For each risk, we examine their implications for different actors and we analyse the approaches that Singapore is currently taking to address the risk.

6.1. Technological risks in AV implementation

6.1.1. Safety
Fatal accidents involving AVs trialled by Uber and Tesla in 2018 have increased the public scrutiny of AV technology (CNA, 2018a; The Guardian, 2018). Critical questions that need to be addressed for safety include the conditions for the issue of licences for AV pilots and the extent of interventions needed by human drivers (Borenstein, Herkert, & Miller, 2017; Holder, Khurana, Harrison, & Jacobs, 2016). Whether pedestrians, cyclists and drivers exploit the safety features of an AV, by being less vigilant in complying with road traffic regulations, will affect the design of safety systems within AVs (Borenstein et al., 2017; Collingwood, 2017). Furthermore, some crashes will remain unavoidable, and in such cases the AV must to decide between crashing into one person or another. Thus, it is unclear whether and how 'crash algorithms' should be programmed into the AV to make these ethical judgements (Taeihagh & Lim, 2019; Nyholm & Smids, 2016; Lim & Taeihagh, 2019).

After the first AV accident was reported in Singapore, an investigation was launched by the LTA and the traffic police. After verifying that there were no major flaws in the AV system, the AV trial was allowed to resume (Respondent 1). Despite the RTA amendment, private developers are anticipating further legislation or concrete guidelines for the development of AV algorithms to prevent crashes on different road systems (Respondents 8 and 9). To assess the safety of AVs, the MOT and

Table 4
AV trials and initiatives launched in Singapore during phase four.

Date	Types of Trials/ Initiatives	Partnerships/ Actors Involved	Descriptions of Trials/Initiatives
April 2017	Driverless bus to be rolled out in Singapore by 2020	LTA announcement (partnerships to be formed between LTA and ST Kinetics)	Cybersecurity of AVs was one of the key agenda items covered in the announcement, and the new partnership promised to strengthen cybersecurity expertise in performing vulnerability analysis and penetration tests to ensure the fidelity of the AV system and safety of the passengers (Loke, 2017).
June 2017	Extension of AV test routes	MOT	Test routes for AV trials in One-North Business Park were extended by 55 km covering the entire campus of National University of Singapore (NUS) and two nearby residential estates – Dover and Bouna Vista (CNA, 2017a).
October 2017	First driverless truck	Belgian logistics company (Katoen Natie)	This trial was piloted on US oil and gas multinational Exxon Mobil's integrated manufacturing hub in Jurong Island. The driverless truck will be used to transport goods and products between the company's packaging stations and storage facilities. This partnership initiative also announced various safety measures that were in place such as demarcated speed zones with inbuilt speed controls in the vehicles, and installation of key signs on the road including a safety bumper that would trigger emergency stop of the vehicle in the event of its physical contact with another object (Tanoto, 2017).
November 2017	Public driverless buses and shuttles to start operating in three towns from 2022 onwards	LTA	Three new towns – Punggol, Tengah, and Jurong Innovation District – would be the first three areas in Singapore with driverless buses and shuttles operating on the public roads at off-peak hours from 2022 onwards. This announcement by LTA is followed by a six-month RFI to seek extensive feedback from industry players and academic institutions on information and facilitators required for successful implementation of AV buses and shuttles in these three new towns (Kwang, 2017).
April 2018	On-campus driverless minibuses by 2019	NTU, SMRT services, 2getthere	A Memorandum of Understanding was signed to set forth the integration of Group Rapid Transit AVs to the existing NTU campus-wide transportation network (Teo, 2018).
June 2018	Public trial for driverless shuttle in Sentosa Island by 2019	LTA	This initiative would allow staff and the visitors to hail driverless shuttles along a total of 5 km route on Sentosa Island using smartphones or kiosks (CNA, 2018b).
July 2018	5G pilot network to be launched in Singapore by Q4 of 2018	SingTel and Ericsson	Two leading telecommunication operators announced partnership to launch 5G pilot network in Singapore to test drones and AVs in One-North by the last quarter of 2018 for the purpose of showcasing network slicing capabilities (Leow, 2018).[a]
November 2018	On-campus driverless shuttle trial by Q1 of 2019	ComfortDelGro	This initiative to carry out a one-year trial of autonomous shuttles in the NUS campus was announced by ComfortDelGro, which is one of the leading taxi transport operators in Singapore (Abdullah, 2018).
November 2018	Reinforcement of mandatory requirements for AVs	LTA	The presence of a safety driver, a black box recorder, a vehicle fault alarm system, insurance against third-party risks and passing an encloser circuit test are among the mandatory requirements for AVs before they can be tested on a large scale.
January 2019	Provisional national standard for AVs	LTA	A provisional national standard, known as Technical Reference 68 (TR 68) was launched to guide the development and deployment of AVs in Singapore.
October 2019	Expansion of AV testing grounds	LTA	An expansion of AV testing grounds which encompasses more than 1000 km of the public roads in the western region was announced.

[a] Network slicing is a process that creates full-functional partitions of network infrastructures that combine multiple virtual and physical networks (Contreras & López, 2018).

LTA are developing a tiered approach for AV trials, with a three-tiered milestone test. Milestone one is a circuit-based test conducted within private test areas (enclosed circuit). It focuses on the ability of safety drivers to intervene and take control during emergencies and when the AV systems malfunction. AVs that have passed this level can be tested in One-North, which is the test-bed for AVs in Singapore. Milestone two, which is in its refinement phase at the time of writing, combines a circuit-based test, a physical road test and a simulation and safety document review to gauge the robustness of the tested AV. Milestone three, which is in its development phase at the time of writing, aims to subject AVs to real-time scenarios on public roads that will require AVs to have more robust safety requirements, including the ability to navigate in mixed traffic conditions containing both AVs and non-AVs (Respondents 4, 7 and 14).

6.1.2. Privacy

Privacy breaches are prevalent in the era of big data as the information that is stored in digital devices risk being exposed and exploited for commercial gain (Hannah-Moffat, 2018). For instance, corporations that run AV services are constantly collecting the personal information of AV passengers (Collingwood, 2017). The extent to which this information is sold to commercial third parties who target individuals for goods and services is unclear. Privacy should also be of social concern

when the algorithmic functions of novel technologies indirectly expose individuals to systemic discrimination that prevents certain segments of the populations from accessing the technology (Taeihagh & Lim, 2019; Hannah-Moffat, 2018).

The Personal Data Protection Act (PDPA), enacted in Parliament in October 2012 and in effect since the middle of 2014, aims to govern privacy issues across all private sector entities in Singapore (Chik, 2013). Unlike other countries that leave the governance of various 'sensitive data' to sector-specific laws, the PDPA in Singapore is over-arching legislation on data privacy that covers all non-government entities and private sectors. Regarding AV privacy, PDPA is currently the prima facie guide for AV implementation in Singapore, but privacy guidelines or measures that are specific to AVs, particularly relating to the protection of data collected by AVs, have not been formulated to date (Lim and Taeihagh, 2018). So far, the primary obligations inscribed in the PDPA are perceived as sufficient to govern data privacy for all business entities (Respondent 18). In June 2018, the Personal Data Protection Commission (PDPC) released a discussion paper explaining best-practice guidelines for personal data protection in artificial intelligence systems (PDPC, 2018). A number of respondents opined that additional safeguards may be needed to prevent the misuse of personal information, which consumers may unknowingly consent to by accepting the long list of terms and conditions enforced by commercial

companies (Respondents 10, 15). While the RTA amendment of February 2017 requires data sharing by all AV developers, information asymmetry driven by commercial interests among AV companies could still affect the extent to which data are shared with the government (Respondents 9 and 15). Hence, further amendments to the PDPA should be explored as AV technology matures over time (Respondent 18).

6.1.3. Cybersecurity

The cybersecurity threat from AVs is most commonly associated with malicious attack by hackers on the information systems of the AV, either to extract the personal information of the driver/passengers, or to manipulate the vehicle (Holder et al., 2016). Multiple cybersecurity threats that could interfere with the functional and design aspects of AVs remain mostly unaddressed by the current legislation on AVs. These include mitigation strategies to prevent the hacking of GPS systems in the AV, ascertaining design features for sensors to minimise the risk of attacks on the vehicle's control systems, determining protocols for human drivers during cyber-attacks, setting standards for AV manufacturers to handle cyber incidents and determining ways to perform forensic investigation that could analyse financially motivated crime (i.e. theft) (Parkinson, Ward, Wilson, & Miller, 2017).

Some respondents opined that the current law in Singapore is not sufficient to address cybersecurity risks specific to AV deployment, which need to be supplemented with additional measures (Respondents 15, 19 and 20). For instance, to minimise the risk of terrorist-initiated cyber-attacks, an AV-specific cybersecurity law could define standard protocols for AV users to intervene when discrepancies between V2V communications are detected in vehicles (Respondent 20). Additional safeguards that regulators and AV developers can consider establishing are multiple decentralisation control points where vehicles and infrastructure communications intersect, to ease communications, on top of a central network that controls the entire operation of AVs (Respondent 20). The Cybersecurity Agency of Singapore (CSA) is currently supporting the LTA to better understand the cybersecurity requirements of AVs and to align local cybersecurity standards with international best practices (Respondent 19). In January 2019, a provisional national standard known as TR 68 was launched to set the fundamental driving behaviours of AVs, to establish safety management process requirements and to prescribe cybersecurity principles and assessment frameworks to support the commercial development of AVs operating at automation levels 4 and 5 (CNA, 2019; LTA, 2019).

6.1.4. Liability

A central issue in the debate over AVs is the allocation of responsibility and, hence, legal liability for damages resulting from vehicle collisions and the circumstances under which insurance claims are justified (Nikitas et al., 2017; Thomopoulos & Givoni, 2015). The automation literature describes two types of liability – civil and criminal. Civil liability deals primarily with the question of who is responsible for damages resulting from accidents. Liable parties could include manufacturers, software developers or drivers monitoring the AV. The difficulty lies in attributing the most significant responsibility for an accident. On the other hand, criminal liability holds manufacturers and operators of AVs liable upon non-compliance with legislature (Holder et al., 2016).

In Singapore, the current liability regime governing AVs is the same framework that is used for conventional vehicles. For the first two milestone tests for AVs, safety drivers will be held responsible for any accidents, which also indicates that the existing motor vehicle legislation (third-party risks and compensation) will apply to AVs during this stage of piloting (Respondents 10, 14, 15 and 17). One expert opined that the current legislation will be untenable as regards resolving liability issues as AV technology becomes more complex over time. For instance, insurance companies and legislators have yet to achieve consensus on which liability framework to adopt for AVs tested at the third milestone assessment (Respondents 15 and 17). Another major

issue stems from the difficulty of quantifying risks in AVs, which contributes to the legal uncertainty in handling insurance claims. As insurance companies are unable to quantify the risks of AVs in real financial terms, the industry lacks sufficient information to calculate insurance premiums (Respondent 15).

6.1.5. Effects on the incumbent industry

The mass adoption of AVs will have profound impacts on labour markets in incumbent transport industries and other adjacent industries (Beede, Powers, & Ingram, 2017; Clements, 2017; Raposo et al., 2018). Demand for services in many subsidiary industries, such as traffic policing and auto-repair, will also be significantly affected (Clements, 2017). While some note that the affected employees can be retrained and upskilled to prevent job loss, others argue that older transport workers, who tend to be less educated, stand a lower chance of being redeployed to other roles that require dynamic learning capabilities to acquire new skills (Beede et al., 2017; Raposo et al., 2018).

In Singapore, AV deployment will inevitably affect workers in the transport industry in the medium to long term. These impacts are likely to be felt more directly among taxi drivers and bus operators compared to other types of transport occupations (i.e. trucking) as more AV public shuttles ply the streets and shared AVs replace existing human driver-centric ride-sharing services (Respondents 1, 2, 4, 5, 10, 11).

Nevertheless, Respondent 5 opined that automation is unlikely to massively displace local public transport workers, as the public transport industry has always relied heavily on foreign bus drivers who are hired on fixed-term contracts. Upon large-scale deployment of AV buses, Singapore may not have to engage these foreign bus drivers once their employment contracts end. Respondent 11 is optimistic that the public transport ITM can transition local transport workers to higher technical roles through job redesign and retraining programmes. In its enthusiasm for staying ahead of the curve in regard to embracing technology, the Singapore government should continue to seek to understand, embrace and address these medium- and long-term trade-offs and impacts (Respondents 2, 4, 6, 10, 11).

6.2. Governance strategies in AV deployment in Singapore

Ongoing policy measures have been taken to prepare the island state for the widespread implementation of AVs. The following analysis evaluates different types of governance strategies adopted by the Singapore government in the agenda-setting, formulation and implementation stages of AV deployment. These governance strategies are also summarised according to the timeline reported in Fig. 2.

6.2.1. No-response strategy

Before 2013, AVs were a distant mobility concept for most Singaporeans, as there were no significant public–private partnerships in the local AV scene. Thus, until 2013, the government adopted a no-response strategy to AV implementation.

6.2.2. Prevention-oriented strategy

As Singapore has made the strategic decision to embrace innovation around AV technology, the Singapore government has not adopted this strategy for AV implementation so far.

6.2.3. Control-oriented strategy

With the MOT given the full authority to set the rules for AV trials and to prescribe the design, construction and use of infrastructure in relation to trials (The Law Revision Commission, 2018), the government has formally assumed full control of setting the rules and standards for AV implementation in Singapore. Other authority-enhancing instruments employed include explicit requirements for AV developers to share data and obtain liability insurance or safety deposits for trials. Furthermore, the three-tiered AV milestone tests and the launch of TR68 to prescribe guidance on safety behaviours and cybersecurity assessment

of AVs also reflect the government's vigilance in controlling AV deployment.

6.2.4. Toleration-oriented strategy

The spirit of promoting entrepreneurship through the launch of multiple AV trials and the risk tolerance approach displayed by the Singapore government towards the policy community of the AV industry, especially developers and scientific communities, is an illustration of the government's toleration-oriented strategy. The launch of the five-year regulatory sandboxes that will lead to permanent regulations governing AVs in Singapore signals that an active role has been taken by the government in AV implementation (Pang, 2017; The Law Revision Commission, 2018). When a collision involving an AV piloted by nuTonomy and a lorry occurred in October 2016, an investigation into the incident was immediately launched. After the safety concerns were addressed, the trial was resumed (Respondent 1). This showcases the Singapore government's commitment to working with the industry constructively to minimise safety risks without stifling innovation.

6.2.5. Adaptation-oriented strategy

An adaptation-oriented strategy is the most dominant strategy applied by the Singapore government in strengthening the city state's readiness for AV deployment in the near future. This strategy is inherent in the political DNA of Singapore, which has always inculcated in its political leaders the need to be visionary, adaptive and flexible in various public policies (Ong, 2010). The intensive roll-out of AV trials throughout 2016 and 2017, coupled with the partnerships forged with various foreign companies and local universities, showcased the strong policy capacity of the Singapore government to strengthen both infrastructure and technical readiness for embracing disruptive technology. The launch of the first driverless taxi trial between the LTA and nuTonomy illustrates the adaptive spirit of Singapore in becoming one of the forerunners in the application of disruptive technologies. The formation of CARTS and the launch of major research initiatives also symbolises an adaptive policy response that seeks to balance both the regulatory and technical development of AVs in Singapore. Moreover, the continuous alignment of AV safety and cybersecurity practices in Singapore with international standards is another policy move taken to keep abreast of ever-changing safety and cybersecurity norms worldwide (Respondent 19), reflecting the government's proactive stance in managing AV safety and cybersecurity risks in tandem with international developments. The launch of the new skills framework under the ITM represents the government's long-term planning for future disruptions to transport labour markets, which epitomises the government's responsiveness and foresight as regards ensuring that existing transport workers adapt to the changing skills requirements imposed by AVs. While the medium- and long-term impacts of AV deployment on incumbent transport industries remain uncertain, the government has engaged with transport unions to ensure that transport workers' skills remain relevant as automation gradually displaces manual labour (Respondents 2, 4 and 5).

7. Discussion

Our analysis, based on key informant interviews, has revealed that there remains ample room for the development of explicit safety guidelines that allow AVs to move seamlessly in various road traffic conditions comprising vehicles with mixed operating modes. To avoid stifling AV development and adoption, Singapore is currently employing a non-binding regulatory framework through AV regulatory sandboxes to govern the risks of AVs (Taeihagh & Lim, 2019; Vellinga, 2017). Existing regulations are expected to evolve as more learning arises from ongoing AV trials.

In governing privacy and cybersecurity, AV-specific legislation and frameworks have yet to be formulated in Singapore. Currently, the PDPA and the Cybersecurity Act are the overarching frameworks that govern

privacy and cybersecurity, respectively, but these provisions apply to all data and systems and are not specific to AVs, indicating room for regulatory improvements in the future. For instance, regulators have yet to define or produce guidelines on the permitted scope of data sharing among AV developers and authorities. It is crucial for data sharing to balance AV developers' interest in safeguarding their commercial intellectual property with the need to not compromise data transparency in order to reveal serious technical faults that could undermine safety. To raise cybersecurity awareness among the public and industry, it is also important for the government to engage in evidence-based message-framing strategies when communicating the relevance and importance of cybersecurity threats and their disastrous impacts on society, in order to increase the visibility and tangibility of cybersecurity issues, considering how intertwined the physical system and the information system have become (de Bruijn & Janssen, 2017).

Intricate liability issues remain, which must be addressed as AV technology matures. Multiple parties that could potentially be liable for various defects in AVs include the vehicle owners, drivers, manufacturers, sensor suppliers, and data controllers (Riehl, 2018). A comparative study on the liability regimes governing AVs in California, the Netherlands and the UK has highlighted different approaches to liability, ranging from a strict liability approach adopted by the Dutch government, to a product liability approach recommended by the California state government, to a tort of negligence approach adopted by the UK government (Vellinga, 2017). Deciding which liability framework to adopt is challenging. For example, if a strict product liability framework was applied to AVs, it could disincentivise AV manufacturers from making further innovations and safety improvements to the technology (Anderson et al., 2016; Beck, 2016). Moreover, some AV manufacturing and design defects may only show up much later in the extensive roll-out period, and not during the trial period (Beck, 2016). Furthermore, as AVs possess deep-learning capabilities that enable them to learn from their own experiences and their interactions with other vehicles, they could potentially alter their behaviours in unpredictable ways, making it challenging to attribute full responsibility to the manufacturers or developers for erroneous behaviours (Čerka, Grigienė, & Sirbikytė, 2015). To date, the UK has developed arguably the most comprehensive regulation to govern liability risks from AVs by enacting the Vehicle Technology and Aviation Bill in February 2017 (HC Bill 143, n.d). Under this new regulation, insurance companies will compensate for the majority of losses from AVs, while manufacturers, developers and human drivers will bear their respective responsibilities for product defects and user negligence (Taeihagh & Lim, 2019). In addition, the new regulation proposes a 'no-fault liability' concept that enables the compensation of victims for losses incurred regardless of which party is at fault; this has the potential to reduce lengthy litigations and lawsuits (Anderson et al., 2016; Čerka et al., 2015).

Despite the technological risks, deploying AVs within the current road system in Singapore could have positive social implications. The deployment of public and shared AVs as the predominant modes of AVs will relieve road congestion, reduce carbon emissions and promote the Singapore government's car-lite strategy (Respondent 4). For instance, the built environment in compact areas, such as the central business district, can be transformed and redesigned to create more green spaces as more carpark spaces designed for conventional vehicles are freed up (Respondents 12 and 13). AVs will also create an additional travel option for older people and the physically disabled, who may be constrained by the existing transport infrastructure (Respondents 7, 13 and 16). As such, additional resources are needed to create an inclusive AV ecosystem and this discussion should be accounted for in the governance of AVs in Singapore. These include reconfiguring street design norms to ensure the safety of AV deployment, improving infrastructure for AV pick-ups and drop-offs, and installing an effective emergency response mechanism in AVs to facilitate help-seeking during medical emergencies (Respondents 7, 12, 13 and 16). Encouraging lifestyle changes is also important to minimise induced demand for travel, such as through
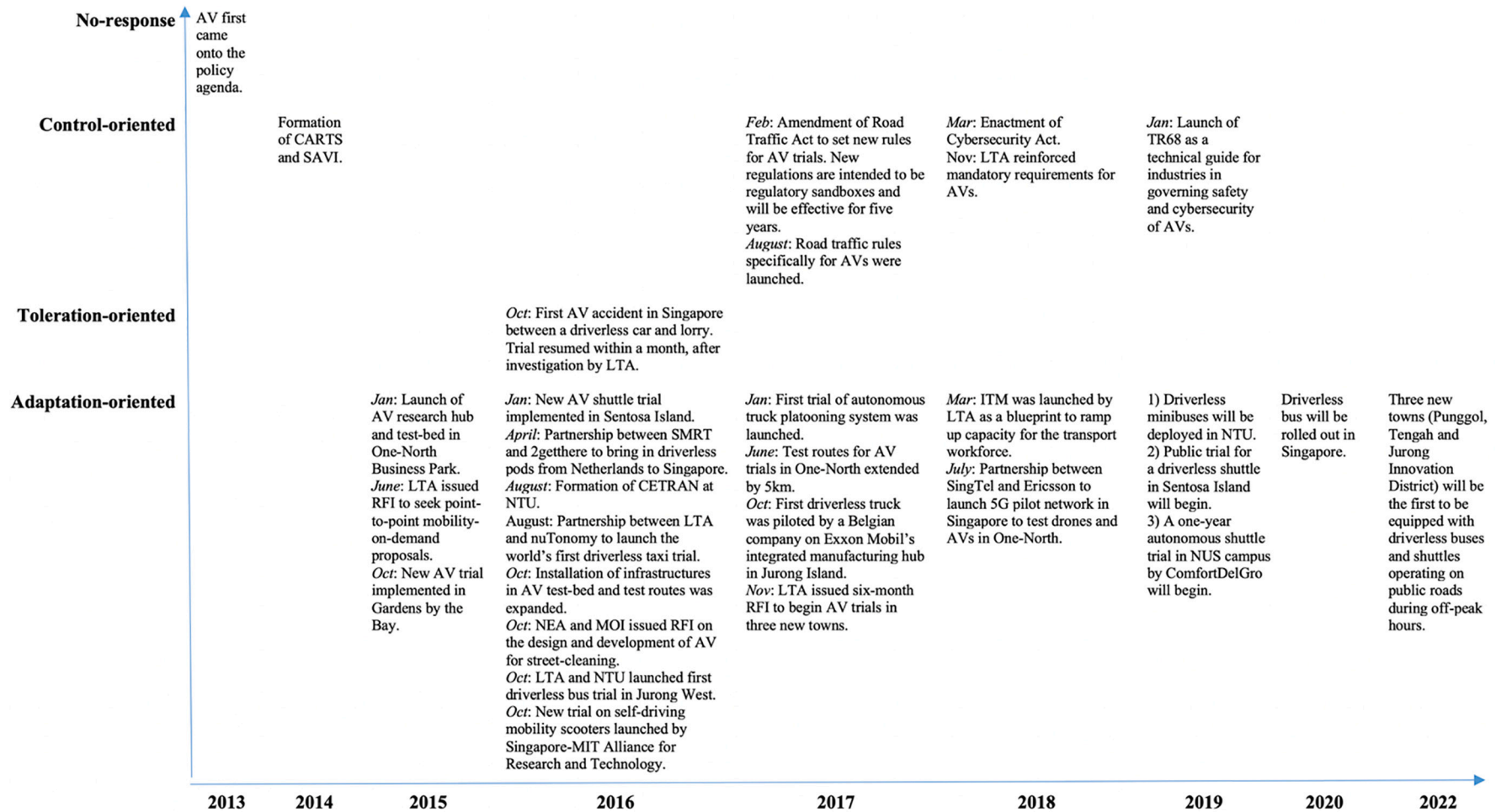
No-response — AV first came onto the policy agenda.

Control-oriented

2014 — Formation of CARTS and SAVI.

2017 — *Feb*: Amendment of Road Traffic Act to set new rules for AV trials. New regulations are intended to be regulatory sandboxes and will be effective for five years.
August: Road traffic rules specifically for AVs were launched.

2018 — *Mar*: Enactment of Cybersecurity Act.
Nov: LTA reinforced mandatory requirements for AVs.

2019 — *Jan*: Launch of TR68 as a technical guide for industries in governing safety and cybersecurity of AVs.

Toleration-oriented

2016 — *Oct*: First AV accident in Singapore between a driverless car and lorry. Trial resumed within a month, after investigation by LTA.

Adaptation-oriented

2015 — *Jan*: Launch of AV research hub and test-bed in One-North Business Park.
June: LTA issued RFI to seek point-to-point mobility-on-demand proposals.
Oct: New AV trial implemented in Gardens by the Bay.

2016 — *Jan*: New AV shuttle trial implemented in Sentosa Island.
April: Partnership between SMRT and 2getthere to bring in driverless pods from Netherlands to Singapore.
August: Formation of CETRAN at NTU.
August: Partnership between LTA and nuTonomy to launch the world's first driverless taxi trial.
Oct: Installation of infrastructures in AV test-bed and test routes was expanded.
Oct: NEA and MOI issued RFI on the design and development of AV for street-cleaning.
Oct: LTA and NTU launched first driverless bus trial in Jurong West.
Oct: New trial on self-driving mobility scooters launched by Singapore-MIT Alliance for Research and Technology.

2017 — *Jan*: First trial of autonomous truck platooning system was launched.
June: Test routes for AV trials in One-North extended by 5km.
Oct: First driverless truck was piloted by a Belgian company on Exxon Mobil's integrated manufacturing hub in Jurong Island.
Nov: LTA issued six-month RFI to begin AV trials in three new towns.

2018 — *Mar*: ITM was launched by LTA as a blueprint to ramp up capacity for the transport workforce.
July: Partnership between SingTel and Ericsson to launch 5G pilot network in Singapore to test drones and AVs in One-North.

2019 — 1) Driverless minibuses will be deployed in NTU.
2) Public trial for a driverless shuttle in Sentosa Island will begin.
3) A one-year autonomous shuttle trial in NUS campus by ComfortDelGro will begin.

2020 — Driverless bus will be rolled out in Singapore.

2022 — Three new towns (Punggol, Tengah and Jurong Innovation District) will be the first to be equipped with driverless buses and shuttles operating on public roads during off-peak hours.

2013 · 2014 · 2015 · 2016 · 2017 · 2018 · 2019 · 2020 · 2022

Fig. 2. Governance Strategies and Development Timeline for AV adoption in Singapore.

reducing private car ownership and creating more opportunities for citizens to work and live in close proximity (Respondent 12). However, the adoption of these lifestyle changes would require value changes among citizens and modifications by the government of the incentives it provides with regard to private car ownership, and these may not be immediately feasible.

Rolling out new technologies in a country requires a substantial level of policy capacity from the government across individual, organisational and systemic levels (Wu, Howlett, & Ramesh, 2015). With a proven track record in accelerating the nation's socio-economic development over the past five decades, the Singapore government possesses high policy capacity for the policy implementation of AVs (Li et al., 2018). It has shown institutional capacity in strategically steering the adoption of AVs as a predominant mode of transport in the next decade, political capacity in controlling the public agenda of AVs to ensure it is aligned with its strategic interests, regulatory capacity in applying a non-binding instrument for its road traffic regulations with the flexibility of future amendments, and financial capacity to invest a significant amount of its financial resources in a disruptive technology that holds uncertain promise in the eyes of many other countries (Saguin, Tan, & Goyal, 2018). The dominant adaptation-oriented strategy adopted by the Singapore government reflects its policy nimbleness and political vision as regards to overcoming challenges in the implementation of novel and disruptive technologies to improve the citizens' lives (Tan and Taeihagh, 2020). This strategy combines an expert-driven technocratic governance style (Littoz-Monnet, 2014), a participatory and collaborative approach in an open policy network through the establishment of CARTs and various working groups and research centres (Brown & Osborne, 2013; Renn, 2008), a 'soft' risk management approach to manage risk and uncertainty through the implementation of the five-year AV regulatory sandboxes (Flemig et al., 2016), and an anticipatory governance approach to build up capacity for future emergency response (O'Grady, 2015). The experimentalist spirit observed in the intense AV trials during Phases Three and Four further reflects Singapore's pragmatism in capitalising on the potential benefits that disruptive technology could bring, despite its uncertainties. In other countries, policy pilots and experiments have been deployed as instruments for problem-solving and dissemination of new technology (Ko & Shin, 2017), capacity building and policy design improvement (Qian, 2017), as well as in contexts with ill-defined policy problems (Nair & Howlett, 2015). Singapore's experience in the governance of AVs contributes additional insights into this growing body of literature, and suggests that pilots and trials can be effective gateways towards accelerated disruptive technology adoption and sustained policy learning.

Nevertheless, as the case study in this article has shown, there remain long-term regulatory uncertainties surrounding privacy, cybersecurity and liability that Singapore has yet to address. The development of statutory laws and policy guidelines that could specifically target AV risks in these areas will be an important area of learning for the government. To enable active learning, obtaining comparative governance insights from other jurisdictions in these areas should be an ongoing endeavour.

8. Policy recommendations for AV adoption and implementation

8.1. Creating a business-friendly ecosystem that promotes trials and pilots for the adoption of novel and disruptive technologies

Trials and pilots are effective tools for policy learning. Singapore's experience in AV implementation shows that the multiple trials and pilots launched in the city state since January 2015 accelerated the successful deployment of AVs. The deployment of AVs is in alignment with smart city visions in many cities, and to achieve this the development of trials and pilots can be encouraged by governments by creating a business-friendly ecosystem with transparent and clear policy guidelines

for both commercial industries and non-commercial parties, including start-ups, that would like to test their AV models (Tan & Taeihagh, 2020). This ecosystem will enable fast-track registration and formalisation of AV start-ups or companies that intend to create a footprint in the local market, promote transparent and fair public–private partnerships in technology deployment, while maintaining flexible rules and regulations that are open to amendment based on changing circumstances. In addition, governments can also facilitate the co-operation between businesses and universities to support the commercialisation of AV technologies.

8.2. Government stewardship in addressing the short-term implications of AV deployment

Governments need to exercise stewardship in balancing the risks of innovation and regulation, especially at the early stage of the technology adoption. For instance, AV safety is one of the most immediate concerns among citizens, who are often seen as target beneficiaries of these technologies by governments. The creation of regulatory sandboxes by the Singapore government at the early stage of AV implementation showcased stewardship in addressing the short-term risks that could be posed by a disruptive technology such as AV. To address safety risks, governments from other countries could draw on the experience of Singapore in steering the development of these regulatory sandboxes, which enable flexibility of amendments and adaptations of the existing transport regulations, to address the unique risks and challenges of AVs. In addition, strengthening the readiness for full deployment, including determining suitable test-bed(s) for AV testing and ramping up the resources needed to subject AVs to rigorous assessment, are pre-requisites for governments intending to roll out this technology.

8.3. Collaborative and participatory approaches in addressing the medium-term and long-term implications of AV deployment

The medium-term and long-term technological risks of AVs remain black boxes. However, some of these risks can already be anticipated and expected, and governance strategies can thus be designed to address these longer-term implications. For instance, in Singapore, the medium-term and long-term employment impacts, which could potentially displace existing transport workers, are issues that could affect the way in which the transport industry operates. In addition, drawing out a comprehensive liability regime that could address the complexity of the liability and ethical issues involved requires collective thinking and long-term deliberations. The complexity of the risks in AV deployment, which involve multiple parties, makes designing an AV liability regime extremely challenging, including in Singapore. As our analysis has shown, governments alone cannot address all of these intricate issues and will need to engage many other non-governmental stakeholders regularly to craft solutions for these issues. Furthermore, citizens can be more actively engaged through participatory approaches, such as public consultations, civic dialogues, crowdsourcing or participation in research studies (Krätzig, Galler, & Warren-Kretzschmar, 2019; Liu, 2017; Taeihagh, 2017a). Engaging these approaches will help governments to gauge citizens' perceptions and preferences, as well as their visions of the government's long-term transport blueprints and other mega-plans, besides tapping into their knowledge and talents to co-create solutions for some of the risks involved in AV deployment.

8.4. Strengthening and developing policy capacity to embrace novel and disruptive technologies

As reflected in the case study, AV implementation requires a high level of policy capacity. Institutional, regulatory and political capacities require strong governance foundations, whereas financial capacity can be strengthened either through increasing a country's fiscal resources or by tapping into foreign direct investments. Developed economies with

high levels of policy capacity could capitalise on their existing advantages to accelerate the adoption of a disruptive technology following the pathway and governance recipe that has already been demonstrated in the Singapore case. In particular, the creation of a five-year regulatory sandbox has attracted the active participation of many foreign AV developers to Singapore, significantly enhancing the capacity of the Singapore government to deploy AVs within a short period of time. Developing economies with capacity deficits could leapfrog this process by tapping into foreign direct investment, bilateral or multilateral agencies, and other innovative financing solutions, such as land monetisation, user charges, and crowdfunding, which have been capitalised in the financing of smart city initiatives in developing countries (Vadgama, Khutwad, Damle, & Patil, 2015). These financing mixes will boost the development of certain basic transport infrastructures that are important pre-conditions for piloting AVs in a city. The strengthening of institutional and regulatory capacities, which are as important, have no obvious shortcuts, and require strong and progressive political leaders that possess the vision and the tenacity to push forward these agendas in the governance process.

8.5. The simultaneous adoption of three different governance strategies (control-oriented, toleration-oriented and adaptation-oriented) is important in rolling out novel and disruptive technologies

The Singapore case study reflects that control-oriented, toleration-oriented and adaptation-oriented strategies can be simultaneously employed by governments to manage the different dimensions of technological risks involved in AV deployment. In the Singapore case, they have overlapped throughout the policy process, and their degree of salience has differed in different circumstances. Control-oriented strategy, for instance, has been prominently employed in the amendment of the road traffic law, as a measure to balance both innovation and regulatory needs. Toleration-oriented strategies were most notably observed in the deployment of AV regulatory sandboxes and the government's handling of the first AV accident in Singapore. Adaptation-oriented strategies, meanwhile, have been reflected in the government's experimentalist spirit in rolling out trials and pilots. While these strategies can be independently deployed in different circumstances, they can produce synergistic effects when they intertwine. A combination of control-oriented, toleration-oriented and adaptation-oriented governance strategies demonstrates a highly engaged, prescriptive and flexible governance approach that is open to revisions and amendments.

9. Conclusion

Singapore is joining the ranks of other leading innovation hubs across the world in regard to actively developing standards for, and regulating the technological risks that are associated with, AV deployment. The dominant adaptation-oriented governing strategy for AVs, which is both prescriptive and experimentalist, is testimony to the Singapore government's determination to leverage autonomous systems in its quest to implement a smart-nation initiative. These aspirations are further bolstered by multiple control-oriented and toleration-oriented strategies that are highly intertwined, aiming to strike a delicate balance between promoting innovation and establishing the necessary regulations to manage AVs' emerging risks. The experiences and lessons derived from AV implementation in Singapore could potentially guide other jurisdictions in their policy processes. Singapore's governance of AVs demonstrates that strong political will, coupled with high levels of policy capacity, can drive the rapid implementation of a disruptive technology, given the presence of public policies that foster policy pilots or trials, dynamic public–private partnerships, an open business environment that favours innovation, as well as inter-agency collaboration that implements deliberative and forward-looking policy decisions. These governance characteristics have propelled Singapore to be the top performer in AV readiness among 30 countries and jurisdictions across

the world in 2020.

To subject policy decisions to more careful deliberation in the future, the Singapore government should actively engage citizens to gauge the public's perception of risks, to determine their preferences in terms of their willingness to pay and modes of deployment, as well as to crowdsource public transport solutions that incorporate AV technologies. Citizen participation could also provide a feedback loop on the governance of disruptive technologies such as AVs. For instance, citizens' concerns regarding safety, privacy, cybersecurity and liability issues revolving around AV deployment can be solicited through formal channels by conducting population-based surveys through future research and setting up accessible mechanisms for feedback gathering via governmental portals. More user-centric and citizen-focused approaches that are able to provide direct feedback to policy decisions can indicate future research directions for public policies surrounding AV deployment. In addition, cross-jurisdictional comparisons with other Asian states with similar or differing characteristics that have started AV implementation would also be an important future research agenda. These proposed research agendas would be pertinent as regards informing policy formulation and the design of subsequent governance strategies.

To date, the Singapore government has addressed most of the short-term risks of AVs. Nevertheless, there are medium-term and longer-term risks, such as behavioural modifications of AVs as a result of their deep learning capabilities, the misuse of AVs to launch cyber-attacks, and the potential of AVs to disrupt many existing low-skilled workers, that need to be addressed, and the strategies for governing these risks remain a work-in-progress. These are some of the limitations of the current study, which should be explored in future research. The exploration of these issues will also align governance and regulations to be on par with AV technology maturation in Singapore.

Singapore's relative success in the implementation of AVs has been realised in large part by its many unique characteristics. Its geography as a confined city state, and its politics, shaped by a majority parliamentarian rule by one political party, as well as its governance structure, which bypasses the complexities inherent in multi-level governance structures in large countries, enable directives and mandates to be executed directly and swiftly. These favourable conditions are coupled with high levels of public acceptance towards the government's policy, which has fuelled the acceleration of AV adoption. This unique sociopolitical climate, which differs from other jurisdictions, is the assumption upon which our findings are based.

The regulatory lessons derived from the governance of AVs in Singapore, albeit driven by some of its unique geographical and political characteristics, could provide illuminating policy guidance, inform policy discussions and facilitate policy learning to manage the risks from AVs as well as other autonomous systems. Decision-makers in different countries should take into account the unique characteristics of the system in which they operate (such as the state of the transportation subsystem, the level of public acceptance of disruptive technologies such as AVs, and the governance structure) and avoid a one-size-fits-all approach for various risks of AVs. While Singapore's experience is exemplary as regards the effective adoption of AVs within a short time span, countries should explore the implications of their unique contexts and design issue-specific risk-coping strategies for the governance of AVs.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this

study.

Author statement

Tan S. and Taeihagh A. have contributed evenly to the design, analysis, writing of the manuscript. Tan S. carried out most of the data collection. Taeihagh A. conceptualized the research and acquired the funding.

Acknowledgments

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