

**Embracing the Future of Land Transportation:
Valuing Flexibility in Design and Technology Options for Autonomous Vehicle
Developments in Singapore**

by

Huiling Eng

B.Eng. Bioengineering, Nanyang Technological University, 2007

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Signature of Author: _____
Huiling Eng
System Design and Management Program
November 15, 2016

Certified by: _____
Richard de Neufville
Professor of Engineering Systems, MIT Institute for Data, Systems, and Society
Thesis Supervisor

Accepted by: _____
Warren Seering
Weber-Shaughness Professor of Mechanical Engineering

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ABSTRACT

This thesis examines the prospects of implementing fully autonomous vehicles in Singapore, and proposes flexible design and development strategies to maximize value creation. This approach recognizes the uncertainties associated with emerging technology domains, and illustrates how an adaptive policy can enable the policymaker to apply policy levers timely to leverage upside opportunities and mitigate downside risks.

A review of the autonomous vehicle developments in the industry shows that there is neither a clear consensus on the technological pathway, nor an agreement on a definitive solution to achieve full autonomy. The thesis evaluates the maturity of the technology enablers for autonomous driving capabilities using the Technology Readiness Level definitions adopted by the United States Department of Defense, and concludes that fully autonomous driving capabilities are not yet ready for the road.

Based on a realistic assessment of the current state of technology, the thesis identifies three areas of uncertainty: rigor in safety validation, transition from prototyping to full-scale development, and effectiveness of autonomous vehicle deployment in improving road congestion. The thesis further discusses the policy implications specific to the context of Singapore, covering: (1) Personal and societal benefits and costs, (2) Balancing regulations with encouraging innovation, (3) Transportation as a service, (4) Pricing, (5) Ethical considerations and social dilemma, (6) Data management and privacy, (7) Social acceptance, (8) Liabilities and insurance, and (9) Infrastructure.

The thesis concludes with actionable recommendations to guide the policymaker to remain capability-defined but technology-agnostic; and application-specific but solution-neutral. The recommendations are based on the following guiding principles: (1) Start small, then grow - prototype and pilot to validate hypotheses before scaling up, (2) Collaborate and leverage, through public-private partnerships, and (3) Do not be in a haste to commit - diversify and keep the options open.

Thesis Supervisor : Richard de Neufville
Title : Professor of Engineering Systems
Institute for Data, Systems, and Society

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Huiling Eng

ehuiling@alum.mit.edu

Cambridge, Massachusetts, USA

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LIST OF ACRONYMS

ACC	Adaptive Cruise Control
AI	Artificial Intelligence
A*STAR	Agency for Science, Technology and Research
CACC	Cooperative Adaptive Cruise Control
CARTS	Committee on Autonomous Road Transport in Singapore
CCAV	Centre for Connected and Autonomous Vehicles, United Kingdom
CETRAN	Centre of Excellence for Testing and Research of Autonomous Vehicles - NTU
DARPA	Defense Advanced Research Projects Agency, United States
DAG	Defense Acquisition Guide
DAU	Defense Acquisition University, United States
DGPS	Differential Global Positioning System
DOD	Department of Defense, United States
DOE	Department of Energy, United States
DOT	Department of Transportation, United States
DSRC	Dedicated Short-range Communications
ERP	Electronic Road Pricing
ERTRAC	European Road Transport Research Advisory Council
ETC	Electronic Toll Collection
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GRT	Group Rapid Transit
GSM	Global System for Mobile Communications
HMI	Human-Machine Interface
HOV	High Occupancy Vehicle
I2R	Institute for Infocomm Research, A*STAR, Singapore
INS	Inertial Navigation System
IPR	Intellectual Property Rights
ITS	Intelligent Transport Systems

JTC	Jurong Town Corporation, Singapore
LDWS	Land Departure Warning System
LIDAR	Light Detection and Ranging
LTA	Land Transport Authority, Singapore
MOF	Ministry of Finance, Singapore
MOU	Memorandum of Understanding
NTU	Nanyang Technological University, Singapore
NUS	National University of Singapore
NASA	National Aeronautics and Space Administration, United States
NHTSA	National Highway Traffic Safety Administration, United States
NTSB	National Transportation Safety Board
OBU	On-Board Unit
PATH	Program on Advanced Transit and Highways
RADAR	Radio Detection and Ranging
RFI	Request for Information
SAE	Society of Automotive Engineers
SARTRE	Safe Road Trains for the Environment
SAVI	Singapore Autonomous Vehicle Initiative
SCOT	Shared Computer Operated Transport
SLAM	Simultaneous Localization and Mapping
SMART	Singapore-MIT Alliance for Research and Technology
SONAR	Sound Navigation and Ranging
TNO	The Netherlands Organization for Applied Scientific Research
TRL	Technology Readiness Levels
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access in the Vehicular Environment
ZEV	Zero Emission Vehicle
4G LTE	4G Long Term Revolution

CHAPTER 1 – INTRODUCTION

1.1 Motivation

If we observe the developments in autonomous vehicle technologies through the lens of the Gartner hype cycle, we would probably agree that the developments are currently at the peak of inflated expectations. The concept of autonomous vehicles can be traced to the *Futurama* exhibit at the World's Fair in 1939, but progress was tepid till the early 2000s when the United States Defense Advanced Research Projects Agency held the Grand Challenges. In the last decade, the explosive growth in investments in the domain of autonomous and connected vehicle technologies, largely driven by the private industries, is testament to the ever-increasing excitement from the market players.

Autonomous vehicle technology represents a major disruptive innovation in the automotive industry and is expected to revolutionize the land transportation of the future, offering prospective benefits of enhanced safety, increased mobility, and reduced reliance on the human driver. Right now, we are at the period of “buzz” where expectations for autonomous vehicle technology are rising, somewhat beyond the current reality of its capabilities.

Introducing driverless technology from concept to entry of a fully autonomous vehicle on the road is a complex systems project. Investing in a transformative technology has its inherent technical risks and uncertainties as the technology progresses through the different stages of development. The journey from Level 2 automation (or driver-assist technology) to Level 3 and beyond (towards fully autonomous) is a huge step change.

In recent years, public and private investments in driverless technology are accelerating, and the technologies to enable autonomous vehicle development are evolving. Many major automotive and technology companies have joined the self-driving vehicle race to pursue autonomous vehicle technologies, and the developments differ in terms of the level of automation, ranging from “driver-assist” to “autopilot”, choice of technologies, and

application (city driving in contrast with highway driving). While some companies have attained promising results with prototype testing on the roads, there still exists uncertainty about how the eventual form and function of an operational autonomous vehicle will arise, and the emergent property of value it will bring to future land mobility.

In addition, we should also be mindful that a successful implementation is driven not only by technology and engineering, but is also anchored in the socio-technical aspects such as driver behavior, public acceptance, regulations and infrastructure. From historical trends of automotive technologies, the introduction of new technologies generally resembles an S-shaped curve. However, uncertainty abounds regarding the rate of diffusion of autonomous vehicle technologies to the market, and one needs to be cautious about defining a timeline for technology deployment.

Turning to the context in Singapore, in 2014, the Land Transport Authority (LTA), Singapore revealed the Intelligent Transport Systems (ITS) strategic plan for Singapore, titled “Smart Mobility 2030”. This plan (Singapore LTA, 2014) outlines the broad strategies it deemed essential for the successful implementation of ITS initiatives and charts the key focal areas to meet transport challenges in a systematic and coordinated manner for a smarter future urban mobility. Under the focal area of “Assistive”, autonomous vehicles are highlighted as a potential solution to reduce traffic congestion, mitigate the impact of road accidents, and address future mobility needs.

The objective of this thesis is to guide the development of a technology strategy using real options and to provide recommendations for effective options that policymakers should plan for, and can utilize depending on how the technology advances and how the market develops.

This work aims to help policymakers and key stakeholders to do the following:

- (1) Appreciate the evolving automotive technology landscape and new business models;
- (2) Understand the technology readiness of enablers to autonomous driving capabilities;
- (3) Recognize the uncertainty in autonomous vehicle technology developments;
- (4) Stay capability-driven and technology-agnostic, instead of solution-centric;
- (5) Consider the extent of flexibility that can be designed in when developing a technology strategy;
- (6) Prioritize investments in selected technologies, aligned with the identified end-goal;
- (7) Be aware of the available options, monitor them, and decide when to exercise or abandon a given option as the technology development picture, and demand become more evident.

1.2 Organization of Thesis

Chapter 2 provides a background on the autonomous vehicle development landscape and introduces the reader to the following areas:

- (1) The definition for each level of automation as stated by: (a) the U.S. National Highway Traffic Safety Administration, and (b) Society of Automotive Engineers (SAE) International;
- (2) A brief history of the evolution of autonomous vehicles;
- (3) Private industry-driven investments in autonomous vehicle developments;
- (4) Public agencies-driven investments in autonomous vehicle developments;
- (5) The vision of Singapore's transportation landscape;
- (6) Potential benefits and challenges associated with implementation.

Chapters 3 and 4 cover the methodologies that will be applied for the analyses and discussions in Chapters 5 and 6.

Chapter 3 describes the technology readiness level, which is a schema used to assess the maturity of technologies. The corresponding scale provides a measure of technology maturity with a view towards an operational use of the technology in a system.

Chapter 4 presents the literature on the concepts of uncertainty and flexibility, with a focus on real options. An adapted form of Real Options Analysis will be applied in this thesis to qualitatively assess the value of flexibility in technology options.

Chapters 5 and 6 cover the analyses, discussions, and recommendations to policymakers on implementing autonomous vehicle technologies.

Chapter 5 provides a detailed explanation of the technology enablers for autonomous vehicles, and applies the technology readiness level scale to evaluate the maturity of the autonomous vehicle capabilities.

Chapter 6 discusses the analyses derived from Chapter 5, and highlights the different technological pathways. The chapter also examines the uncertainties associated with the technology development, analyzes the policy implications, and provides actionable recommendations in the context of policy, regulatory, and socio-technical considerations. The application of real options to address uncertainty is also illustrated using a case study on autonomous vehicle deployment in Singapore.

Chapter 7 summarizes the key findings from this study and proposes potential avenues for future research.

CHAPTER 2 – LITERATURE REVIEW

2.1 Definition of Automation Levels

The term “autonomous vehicle” is generally used to describe a vehicle that is capable of sensing its environment and navigating without human input. From literature review, one can readily notice that there are various terms used synonymously to describe autonomous vehicle technologies. For example, “driverless vehicle technology”, “self-driving vehicle technology” and “automated vehicle technology” are some of the common terms that are often associated with this domain.

Presently, there are two formal classification systems for vehicle automation. In the United States, the National Highway Traffic Safety Administration (NHTSA), under the US Department of Transportation, defines automated vehicles as those in which at least some aspects of a safety-critical control function (e.g., steering, acceleration, or braking) occur without direct driver input. The NHTSA is responsible for reducing deaths, injuries, and economic losses resulting from motor vehicle crashes. This is accomplished by setting and enforcing safety performance standards for motor vehicles and motor vehicle equipment, and through grants to state and local governments to enable them to conduct effective local highway safety programs.

In May 2013, the NHTSA issued a preliminary policy on automated vehicle development, where it defined a five-level hierarchy of automation (US NHTSA, 2013). Since then, the NHTSA has been working on proposing best practices and guidance to the industry on establishing principles of safe operation for fully autonomous vehicles (e.g., vehicles at Level 4 on the scale defined by NHTSA), and the policy was published in September 2016.

Table 2.1: NHTSA's Levels of Automation
 (Adapted from: US, National Highway Traffic Safety Administration, 2013)

Level of Automation	Definition	Role of Driver	Role of Vehicle System
0	No Automation	Is in complete and sole control of the primary vehicle controls at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls.	Does not have control authority over steering, braking or throttle. May include systems that provide warnings only as well as automated secondary controls (e.g., wipers, headlights and turn signals).
1	Function-specific Automation	Has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (e.g., adaptive cruise control, lane-keeping or automatic braking).	Can assist or augment driver in operating one of the primary controls – either steering or braking/throttle, but not both. Vehicle can automatically assume limited authority over a primary control (e.g., electronic stability control), or the automated system can provide added control to aid the driver in certain normal driving or crash imminent situations.
2	Combined Function Automation	Can share authority over primary control with vehicle in certain limited driving situations. but is still responsible for monitoring the roadway and safe operation, and is expected to be available for control at all times and on short notice.	At least two primary control functions in the vehicle are designed to work in unison to relieve driver of control functions. However, vehicle can relinquish control with no advance warning. E.g., adaptive cruise control in combination with lane centering.
3	Limited Self-Driving Automation	Can cede full control of all safety critical functions under certain traffic or environmental conditions to the vehicle. Driver relies heavily on vehicle to monitor for changes in conditions that may require transition back to driver control. Driver is expected to be available for occasional control, but with sufficiently comfortable transition time.	Designed to ensure safe operation during the automated driving mode, such that the driver is not expected to constantly monitor the roadway while driving.
4	Full Self-Driving Automation	Provides destination or navigation inputs, but is not expected to be available for control at any time during the trip.	Designed to perform all safety critical driving functions and monitor roadway conditions for the entire trip. By design, safe operation rests solely on the automated vehicle system.

Besides NHTSA, the SAE International, which is the largest global automotive and aerospace standards-setting body, also developed a new standard called J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, in January 2014 (SAE, 2014). SAE's technical standards are consensus-based, developed by the collective efforts of SAE technical committee members, and are used widely by the international engineering community and global regulatory agencies. The focus of SAE standards is on safety, quality, and effectiveness of products and services in the mobility engineering industry.

J3016 identifies six levels of driving automation, as compared to NHTSA's five-level hierarchy. Some literature attempts to map the NHTSA's levels to the SAE levels, and correlates SAE 4 and 5 levels with NHTSA Level 4.

In the context of this thesis, we use the terms "autonomous vehicle", "self-driving", and "driverless" to refer to the autonomous vehicle technologies that allow for safe navigation between two locations without human intervention. At this stage of vehicle development, we are not truly autonomous yet, and would still require a human driver to take manual control when necessary. However, we view fully autonomous vehicles as the end state where the technologies transform driving from *adaptable* automation (where the human driver is the decision authority) to *adaptive* automation (where the automation is the decision authority).

Table 2.2: SAE's Definition of Six Levels of Driving Automation
(Adapted from: SAE International, J3016 Standard, 2014)

Level of Automation	Definition	Role of Driver	Role of Vehicle System
0	No Automation	Responsible for all aspects of the dynamic driving tasks, including execution of steering and acceleration/ deceleration, as well as monitoring of the driving environment.	Does not have control authority over steering, braking or throttle.
1	Driver Assistance	Has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (e.g., steering <u>or</u> acceleration/deceleration) in some driving modes.	Can assist or augment driver in operating one of the primary controls – either steering or acceleration/deceleration, using information about the driving environment, but not both. Vehicle expects human driver to perform all remaining aspects of the dynamic driving task.
2	Partial Automation	Can share authority over primary control with vehicle for both steering and acceleration/deceleration in some driving modes. Driver is still responsible for monitoring the driving environment and performing the remaining aspects of the dynamic driving task.	Can perform execution of both steering and acceleration/ deceleration. Vehicle expects human driver to perform all remaining aspects of the dynamic driving task.
3	Conditional Automation	Can cede full control of the dynamic driving task to the vehicle in some driving modes. Driver is expected to respond appropriately to the vehicle's request to intervene.	Is responsible for all aspects of the dynamic driving task, with the expectation that the human driver will respond appropriately to a request to intervene.
4	High Automation	Can cede full control of the dynamic driving task to the vehicle in some driving modes. Driver is not expected to respond to the vehicle's request to intervene.	Is responsible for all aspects of the dynamic driving task and safe operation, even if the human driver does not respond appropriately to a request to intervene.
5	Full Automation	Can cede full control of the dynamic driving task to the vehicle in all driving modes.	Is responsible for all aspects of the dynamic driving task and safe operation under all roadway and environmental conditions.

2.2 Evolution of Autonomous Vehicle Technology

There is no literature that specifically traces the evolution of autonomous vehicle technology, but many have attributed the dream of pursuing the vision of greater mobility to the *Futurama* exhibit at the 1939 World's Fair in New York. The General Motors *Futurama* exhibit featured a vision of technologically advanced superhighways where cars would navigate curves at speeds up to 50 miles per hour using "automatic radio control" to maintain safe distances (Anderson, J.M. et al, 2016).

From 1972 to 1973, the European ARAMIS project demonstrated platooning of 25 small transit vehicles running a foot apart at 50 miles per hour on a French test track. The vehicles were using ultrasonic and optical range sensors¹.

In 1987, the Eureka Program for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS) Pan-European project was launched by then Daimler-Benz in cooperation with several European car manufacturers, electronics producers, suppliers, institutes, and universities. This project was then the largest research and development program in history associated with autonomous driving and related technologies, and involved an estimated total cost of EUR 749 million². The project was completed in 1995, and culminated with a re-engineered Mercedes-Benz W140 S-Class that technically drove almost entirely by itself over 1,678 kilometers (or 1,043 miles) on the Autobahn from Munich to Copenhagen. According to Mercedes-Benz, this technology demonstration was the precursor to modern day technologies found on their car models, such as Pre-Safe, DISTRONIC Plus with Steering Assist, Stop&Go Pilot and Magic Body Control³.

In North America, the first research program on Intelligent Transportation Systems was established in 1986 under the Program on Advanced Technology for the Highway (PATH)

¹ <https://trucks.cardekho.com/en/news/detail/truck-platooning-history-benefits-future-945.html>

² <http://www.eurekanetwork.org/project/id/45>

³ <http://www.autoevolution.com/news/a-short-history-of-mercedes-benz-autonomous-driving-technology-68148.html#>

at the University of California, Berkeley, with substantial funding from the California Department of Transportation. PATH was subsequently renamed to Program on Advanced Transit and Highways in 1992 to include scope on multi-modal transportation. The initial years of PATH were focused on research in Advanced Transportation Management and Information Systems, Advanced Vehicle Control and Safety Systems, and roadway electrification. In 1989, Ford provided PATH with four vehicles as experimental platforms for automatic longitudinal control in a closed formation platoon. This capability was successfully demonstrated on the I-15 HOV lanes in San Diego in 1994. By 1997, PATH was able to prove the platooning of eight vehicles, guided by magnets embedded in the highway and coordinated with vehicle-to-vehicle communications, as part of the National Automated Highway Systems Consortium with General Motors (Shladover, S. E, 2006). During the same time period, research on the development of semi-autonomous and autonomous vehicles also commenced, as seen in the NavLab series of vehicles developed by Carnegie Mellon University.

Besides the US and Europe, Japan also begun research in intelligent transport systems in the 1960s to 1970s, leading to projects such as the Road Automobile Communication System, and Advanced Mobile Traffic Information and Communication System (Shladover, S. E, 2006).

In 1998, Mercedes, Toyota, and Mitsubishi began offering adaptive cruise control in selected car models. From 1999 to 2001, a pilot project was established to implement ParkShuttle services between the subway station Kralingse Zoom and business park Rivium in the city of Capelle aan den IJssel, Netherlands. The trajectory started with a 1,300-meter single lane and was extended to an 1,800-meter dual lane (with the exception of tunnel and bridge) with a total of five stops over a dedicated road infrastructure installed at grade⁴.

From 2003 to 2007, the U.S. Defense Advanced Research Projects Agency (DARPA) held three “Grand Challenges” that stimulated the acceleration in research and

⁴ <http://www.2getthere.eu/projects/rivium-grt/>

advancement in autonomous vehicle technologies. The Grand Challenges were believed to have spearheaded innovations in sensor systems and computing algorithms to detect and react to the behavior of other autonomous vehicles and human-driven vehicles, to navigate marked roads, and to obey traffic rules and signals. The DARPA Challenges brought together the academia and the automotive industries, to collaborate and advance autonomous vehicle research and development.

In 2008, the National Natural Science Foundation of China started a major research plan called the “Cognitive Computing of Visual and Auditory Information”, where the unmanned intelligent vehicle was chosen as the physical verification platform of scientific issues. Furthermore, inspired by the DARPA Challenge and to advance perceptions of the natural environment and decision-making for unmanned vehicle platforms, a competition known as the “Intelligent Vehicle Future Challenge” has been held annually in China since 2009⁵.

From around 2005, more automobile manufacturers are jumping onto the bandwagon to commit research and development investments in self-driving cars and autonomous vehicle technologies. In addition, the economic attractiveness of revolutionizing land transportation also enticed non-traditional private companies such as Google, Uber, Baidu, and Apple, to enter the automotive space and commit resources in future mobility technologies. Google began developing its self-driving car in 2009 and passed the driving test conducted by Nevada Department of Motor Vehicles in May 2012 on a pre-determined test route, but was not tested at roundabouts, railroad crossings, and school zones⁶. Details of private industry investments in autonomous vehicle developments are presented in **Appendix A**.

Development in platooning technology also continues to advance in the last decade. From 2010 to 2012, the Safe Road Trains for the Environment (SARTRE) project was conducted by the European Commission in partnership with Ricardo UK and Volvo. The

⁵ <http://www.prweb.com/releases/2015/11/prweb13101566.htm>

⁶ <http://spectrum.ieee.org/transportation/advanced-cars/how-googles-autonomous-car-passed-the-first-us-state-selfdriving-test>

project focused on designing intelligent systems for truck platooning and for the first time in platooning technology, automated controls in lateral positions were used in addition to the longitudinal positions⁷.

More recently, in 2016, the Dutch Ministry of Infrastructure and the Environment, along with the Directorate General Rijkswaterstaat, the Netherlands Vehicle Authority, and the Conference of European Directors of Roads held the first European Truck Platooning Challenge, where trucks from six manufacturers: DAF Trucks, Daimler Trucks, Iveco, MAN Truck & Bus, Scania, and Volvo Group, drove in platoons from three different locations to arrive at Rotterdam, Netherlands⁸. A driver in the lead vehicle of each convoy set the speed and the route, while the other trucks followed automatically, with a Wi-Fi connection keeping their braking and acceleration (but not steering) in-sync. The trucks did not travel in platoon for the entire journey; rather only on motorways when traffic conditions were considered "normal", and each vehicle, even those following the lead truck, had a human driver⁹.

Notably, a spinoff effect from the huge direct investments in autonomous vehicle developments by automotive manufacturers, technology developers, and parts suppliers is the surge in the number of technical publications and research discussions through conferences and symposiums. The topics being discussed range from ethical considerations, public perception and acceptance, legal issues, technology challenges, safety assurance, shared mobility, urban planning, and cybersecurity. In 2016 itself, there are at least 30 different conferences and symposiums having at least a discussion track on autonomous vehicles or connected vehicle technologies, as shown in **Table 2.3**.

⁷ <https://trucks.cardekho.com/en/news/detail/truck-platooning-history-benefits-future-945.html>

⁸ <http://www.technewsworld.com/story/83345.html>

⁹ <http://www.theverge.com/2016/4/7/11383392/self-driving-truck-platooning-europe>

Table 2.3: List of Conferences and Symposiums related to
Autonomous Vehicle Developments in 2016

Event	Organizer	Date
2016 International Consumer Electronics Show http://www.cesweb.org/	Consumer Electronics Association	Jan 6-9
Autonomous Cars Silicon Valley 2016 http://www.autonomousevent.com/	IQPC	Feb 24-26
TU-Automotive Cybersecurity USA 2016 http://www.tu-auto.com/cyber-security/	TU-Automotive	Mar 29-30
GPU Technology Conference http://www.gputechconf.com/	NVIDIA	Apr 4-7
Automated Vehicles: Planning the Next Disruptive Technology http://www.conferenceboard.ca/conf/16-0133/default.aspx	Conference Board of Canada	Apr 19-20
Future Connected Cars USA https://usa.connectedcarsworld.com/	Informa	May 10-12
Autonomous Trucks http://www.autonomoustrucksevent.com/	International Quality and Productivity Center	May 16-18
2016 Connected and Charged Symposium http://www.connectedandcharged.com/	Prospect Silicon Valley	May 25
Driverless Technologies Insurance North America 2016 http://www.driverless-technologies-insurance-north-america.com/	American Business Conferences	May 26
Autonomous Vehicle Test & Development Symposium 2016 http://www.autonomousvehiclesymposium.com/index.php	UKIP Media and Events	May 31 - Jun 2
ITS World Congress http://glasgow2016.itsineurope.com/home/	ERTICO - ITS Europe	Jun 6-9
TU-Automotive Detroit 2016 http://www.tu-auto.com/detroit/	TU-Automotive	Jun 8-9
ITS America 2016 http://itsamerica2016.org/	Intelligent Transportation Society of America	Jun 12-15
2016 IEEE Intelligent Vehicles Symposium http://iv2016.org/	IEEE Intelligent Transportation Systems Society	Jun 19-22
9th IFAC Symposium on Intelligent Autonomous Vehicles http://iav2016.inf.h-brs.de/	International Federation of Automatic Control	Jun 29 - Jul 1
2016 Sustainable Transportation Summit http://energy.gov/eere/2016-sustainable-transportation-summit	US Department of Energy – Office of Energy Efficiency	Jul 11-12
Automated Vehicles Symposium http://www.automatedvehiclessymposium.org/home	Association for Unmanned Vehicle Systems International	Jul 18-22

Event	Organizer	Date
Autonomous Vehicles Summit http://www.autonomousvehiclegroup.com/	IQPC	Aug 22-24
5 th International Symposium on Naturalistic Driving Research http://www.vtti.vt.edu/ndrs/	Virginia Tech Transportation Institute	Aug 30 - Sep 1
International Conference on Connected Vehicles and Expo http://www.iccve.org/	IEEE	Sep 12-16
Podcar City & Advanced Transit http://podcarcity.org/antwerp/	Advanced Transit Association, International Institute of Sustainable Transportation	Sep 19-21
AutoSens Conference 2016 http://www.auto-sens.com/	Sense Media	Sep 20-22
Telematics India 2016 http://telematicswire.net/conf/2016/blr/index.html	Telematics Wire	Sep 21-22
SAE 2016 Commercial Vehicle Engineering Congress http://www.sae.org/events/cve/	SAE International	Oct 4-6
23 rd World Congress on Intelligent Transport Systems http://www.itsworldcongress2016.com/	ITS Australia	Oct 10-14
National Shared Mobility Summit http://sharedusemobilitycenter.org/summits/	Shared Use Mobility Center	Oct 17-19
Autonomous Vehicle Safety Regulation World Congress 2016 http://www.autonomousregulationscongress.com/	UKIP Media & Events Ltd	Oct 25-26
Driverless Cities http://infocastinc.com/event/driverless-cities/#section-attend	Infocast	Oct 26-28
Connected Fleets USA http://www.tu-auto.com/fleet/	TU-Automotive	Nov 15-16
Driverless Technology Conference http://www.driverlesstechevent.com/	Charles Maxwell Limited	Nov 22

2.3 Land Transportation in Singapore

2.3.1 Overview

As of June 2016, the total population in Singapore was 5.61 million¹⁰, with a land area of 719 square kilometers. Singapore is the world's third most densely populated country. Land use for roads accounts for approximately 12% of Singapore's total land area. In comparison, housing takes up 14% of the total land area. With the total population projected to reach 6.9 million by 2030, demand for housing infrastructure and amenities is expected to rise. Therefore, the impetus to optimize land use for roads, housing, healthcare, and other societal needs is becoming stronger in the recent years.

Currently, 45% of the households in Singapore owned a car. With the constraint of limited land use available for new road infrastructure to accommodate more vehicles on the road, various tools such the Vehicle Quota System to control vehicle growth, and the Electronic Road Pricing system to manage congestion were introduced since the 1990s to alleviate the road congestion situations and strain on the road infrastructure. While these strategies have proven effective thus far, it is anticipated that they will enter a period of diminishing returns in the near future (Singapore LTA, 2013).

In the long term, public transportation is viewed as the more sustainable approach to tackle the competing needs of the population (hence transportation needs) growth and land use. The modes of public land transportation in Singapore include buses, taxis, Mass Rapid Transit, and the Light Rapid Transit.

2.3.2 Electronic Road Pricing System in Singapore

The Electronic Road Pricing (ERP) system is a usage-based electronic toll collection scheme used to manage Central city road congestion. The ERP system complements the purchase-based Certificate of Entitlement system for car ownership. Based on a pay-as-you-use principle, motorists are charged when they use priced roads during the peak hours. Singapore was the first city in the world to implement ERP to manage road

¹⁰ <http://www.nptd.gov.sg/Portals/0/Homepage/Highlights/population-in-brief-2016.pdf>

congestion in September 1998, when it replaced the manual road pricing scheme that had been in operation since 1975. The ERP system costs S\$200 million (or approximately US\$121 million¹¹) in 1998, and uses open road tolling, where vehicles do not need to stop or slow down to pay tolls.

The current ERP system uses dedicated short-range radio communications in the 2.54 GHz band, and comprises the following components: (1) an in-vehicle unit with a smart card called CashCard inserted, (2) overhead ERP gantries located at the control points across the roads, and (3) a control center.

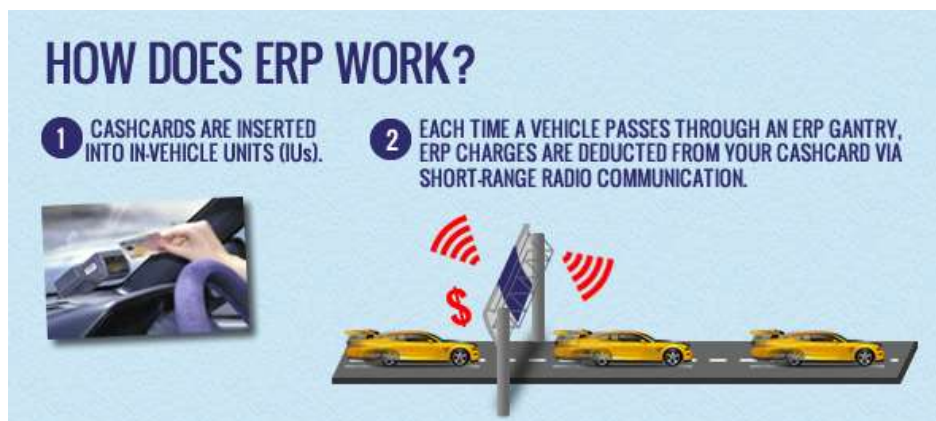


Figure 2.1: Current Electronic Road Pricing System
(Source: Land Transport Authority, Singapore, 2016)

As of 2016, the ERP system has been in operation for 18 years. With the advancement in technology, the LTA is currently developing the next generation ERP system that is based on Global Navigation Satellite System (GNSS) technology. GNSS uses satellites to pinpoint a user's geographic location.

¹¹ Computed based on exchange rate of USD 1.00 = SGD 1.65, in December 1998. Source: https://www.federalreserve.gov/releases/h10/Hist/dat96_si.htm

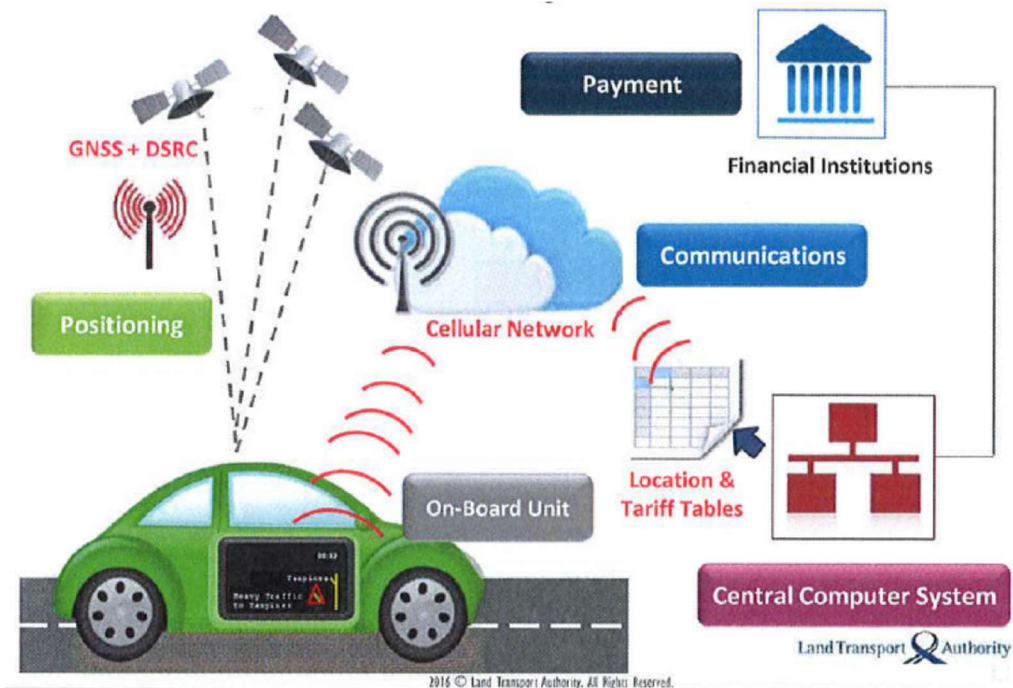


Figure 2.2: Next Generation Electronic Road Pricing System
 (Source: Land Transport Authority, Singapore, 2016)

Three consortia were shortlisted by LTA to participate in the tender in October 2014 for the next generation ERP system, following an 18-month system evaluation test that concluded in December 2012. The contract was awarded to the consortium from NCS Private Limited and Mitsubishi Heavy Industries Engine System Asia Private Limited, at a cost of S\$556 million (or approximately US\$397 million¹²) in February 2016. The next generation ERP system is expected to be implemented progressively from 2020.

According to the LTA, the next generation ERP system allows for more flexibility in managing traffic congestion through a distance-based road pricing, where motorists are charged according to the distance travelled on congested roads, which it claimed would be fairer to the motorists. The GNSS-based system will also be able to overcome the constraints of physical gantries, which are costly, and take up land space.

¹² Computed based on exchange rate of USD 1.00 = SGD 1.40, in February 2016. Source: https://www.federalreserve.gov/releases/h10/Hist/dat00_si.htm

In addition, new policies may be introduced to allow off-peak car users to pay only for vehicle usage for short periods rather than for the whole day, or for using them only on uncongested roads. A new On-Board Unit (OBU) will replace the existing In-Vehicle Unit, which can also be used by LTA to deliver additional services such as traffic advisories to motorists. The OBU can also be used to pay for parking, checkpoint tolls, and usage of off-peak cars electronically.

2.3.3 Smart Mobility 2030

The Land Transport Authority is a statutory board under the Ministry of Transport (MOT) that spearheads land transport developments in Singapore. The LTA is responsible for planning, operating, and maintaining Singapore's land transport infrastructure and systems.

Intelligent Transport Systems have played a pivotal role in enhancing the commuters' travelling experiences on land transportation, and are expected to contribute even more significantly as new transportation technologies and solutions are being exploited. Smart Mobility 2030 is an Intelligent Transport Systems Masterplan jointly developed by LTA and the Intelligent Transportation Society Singapore in 2014. This plan built on the first ITS masterplan that was developed in 2006, which guided the realization of advanced incident management and parking guidance systems, as well as, the enhanced transport information delivery to the end-users (Singapore LTA, 2014).

With the advancement of smart data collection and analytics technologies, Smart Mobility 2030 aims to continue to exploit these emerging technologies. The plan outlined the strategies that it deemed essential to enable a successful implementation of intelligent transport systems initiatives, and charted the key focal areas to address transportation-related challenges in the coming years. The four key focal areas were: (1) Informative, (2) Interactive, (3) Assistive, and (4) Green Mobility. Of specific relevance to the context of this thesis is "Assistive", which planned to explore the applications of vehicle telematics, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) intelligent communications, and autonomous vehicles to provide a more harmonized and safe transport ecosystem.

2.3.4 Autonomous Vehicles - Turning Vision into Reality

To chart the strategic direction for self-driving vehicle-enabled land mobility concepts and moving Singapore towards a more sustainable and liveable city, the Committee on Autonomous Road Transport in Singapore (CARTS) was established in August 2014. The CARTS is chaired by the Permanent Secretary from MOT, and comprises members from the public and private sectors. The committee is supported by two workgroups, focusing on: (1) visioning autonomous vehicle deployment, and (2) regulations and implementation respectively (Chin, K. K., 2014). Four potential areas for autonomous vehicle applications were identified:

- (1) Fixed and Scheduled services to enable efficient mass transport for intra and inter -town travel on a fixed route and scheduled basis (e.g., autonomous public buses);
- (2) Point-to-Point or Mobility-on-Demand services which refer to shared services with dynamic routing for point-to-point, first and last-mile travel (e.g., autonomous taxis or car pods);
- (3) Freight for carriage of goods for long distance delivery (e.g., autonomous truck platoon);
- (4) Utility operations (e.g., autonomous road sweepers and container transporters).

The autonomous vehicle is a complex system. Prior to implementation, one must understand the technology and its limitations, and how it interacts with the physical environment as well as other users and systems on the road. To achieve this understanding, various collaboration initiatives have been established between the government, research, academic, and industry communities.

In August 2014, the LTA signed a Memorandum of Understanding (MOU) with the Agency for Science, Technology and Research (A*STAR), a public sector agency that spearheads economic-oriented research, to jointly set up the Singapore Autonomous Vehicle Initiative (SAVI). The SAVI serves as a platform to oversee and manage research

and development, and test-bedding of autonomous vehicle technologies, applications and solutions for industry partners and stakeholders.

In January 2015, the LTA announced that the one-north district¹³ in Singapore as the first test site for autonomous vehicle technologies and mobility concepts. The test route was doubled from the original 6km to a 12km network in September 2016. As of October 2016, there were four distinct entities conducting autonomous vehicle proof-of-concept tests at the test site¹⁴.

In June 2015, LTA issued a Request for Information (RFI) to seek proposals on how autonomous vehicle technology could be harnessed as part of other land transport mobility concepts, such as mobility-on-demand and autonomous buses. The RFI also sought to understand the requirements, such as road and communications infrastructure, that are necessary to enable implementation of autonomous vehicle enabled mobility concepts in Singapore. Eight proposals were received in response to the RFI and the evaluation outcomes are progressively being released.

In October 2015, a MOU was signed between the MOT and the Port of Singapore Authority to jointly develop autonomous truck platooning technology for transporting cargo between port terminals. The MOT also signed another MOU with Sentosa Development Corporation and Singapore Technologies Engineering Ltd to trial self-driving shuttle services across Sentosa.

The key research and test-bedding efforts in the field of autonomous vehicle developments in Singapore are summarized as follows:

(1) The Shared Computer Operated Transport (SCOT) was launched in January 2014. SCOT is a collaboration project between the Singapore-MIT Alliance for Research and

¹³ <http://www.channelnewsasia.com/news/singapore/lta-seeks-ideas-on/1894620.html>

¹⁴ <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=9fc4a578-094c-4e70-84f2-d598784a3058>

Technology (SMART) and the National University of Singapore (NUS)¹⁵. SCOT leverages Commercial-Off-The-Shelf sensors such as Light Detection and Ranging (LIDAR) to equip a Mitsubishi i-MiEV electric vehicle with autonomous capabilities, with the primary objective of complementing the public transportation network by addressing first and last-mile challenges in built-up cities. SCOT has been operating driverlessly within the NUS campus since 2011, and is currently being tested in the designed test site in one-north.



Figure 2.3: Shared Computer Operated Transport by SMART and NUS
(Source: Singapore-MIT Alliance for Research and Technology, 2016)

(2) Since August 2013, the Nanyang Technological University (NTU) in partnership with the Jurong Town Corporation (JTC) and Induct Technologies have commenced trials on Singapore's first driverless electric shuttle transportation system named NAVIA, on a pre-programmed route between NTU and JTC's CleanTech Park¹⁶. NAVIA can carry eight passengers, with a maximum speed of 12.5 miles per hour. In April 2015, NTU also announced collaboration with Dutch firm NXP Semiconductors to equip up to 100 vehicles and roadside units with Vehicle-to-Everything (V2X) technologies such that they can communicate wirelessly with traffic light and road sign infrastructure in real-time. At the Singapore International Transport Congress and Exhibition in October 2016, LTA announced partnership with the Energy Research Institute @ NTU, to develop

¹⁵ <http://www.straitstimes.com/singapore/singapore-made-driverless-car-to-ply-nus-roads>

¹⁶ <http://media.ntu.edu.sg/NewsReleases/Pages/newsdetail.aspx?news=635afd55-4f9b-484a-a658-2187e2bb788d>

autonomous bus technologies, which included a self-driving bus trial¹⁷ for fixed and scheduled services for intra and inter-town travel.



Figure 2.4: NAVIA by NTU (Source: Nanyang Technological University, 2016)

(3) ST Kinetics, the land systems and specialty vehicles arm of Singapore Technologies Engineering Ltd., that provides engineering solutions for the commercial, defense, and homeland security markets, has also developed an autonomous unmanned ground vehicle that is based on a Ford Everest Sport Utility Vehicle. The vehicle, known as TERRAV, aims to achieve autonomous navigation in urban traffic environment safely. Operated by drive-by-wire technology, TERRAV is also integrated with radar, laser scanners, and cameras to assist in the detection of static and dynamic obstacles from different directions and distances. As of August 2014, the performance of TERRAV has been validated in a confined urban circuit in behaviors such as lane-keeping, distance keeping, lane switching, junction negotiation, and U-turn execution. A potential application for TERRAV is in driverless patrol and surveillance operations in an urban environment¹⁸.

¹⁷ <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=2bc42aac-6b74-4e58-bca3-e2e819c66d20>

¹⁸ https://www.lta.gov.sg/data/apps/news/press/2014/20140827_AV-Annex.pdf



Figure 2.5: TERRAV by ST Kinetics (Source: Land Transport Authority, Singapore, 2016)

(4) In December 2015, a two-week public trial for the Auto Rider self-driving vehicle took place at the Gardens by the Bay in Singapore, on a virtual pre-encoded route¹⁹. Claimed to be the first operational self-driving vehicle in Asia, the Auto Rider was manufactured in Europe, and configured in Singapore to adapt to the local environmental conditions. The outdoor visual navigation algorithm works in tandem with the LIDAR simultaneous localization and mapping algorithm to enable situational awareness of the surrounding environment, including interferences such as moderate rain conditions up to 10 millimeters per hour. A transponder-based technique using Radio Frequency Identification also allows the Auto Rider to continue operations in heavy rainfall²⁰.



Figure 2.6: Auto Rider at Gardens by the Bay (Source: Gardens by the Bay, Singapore, 2016)

¹⁹ <http://www.mot.gov.sg/News-Centre/News/2015/Joint-News-Release-by-Gardens-by-the-Bay-and-MOT----First-Fully-Operational-Self-Driving-Vehicle-in-Asia-Set-to-Ply-Gardens-by-the-Bay-in-Mid-2016/>

²⁰ <http://www.gardensbythebay.com.sg/content/dam/gbb/documents/media-room/2015/autorider-annex-a.pdf>

(5) The A*STAR autonomous vehicle program from the Institute for Infocomm Research (I²R) is also developing its own autonomous vehicle (AuVeS) and has been conducting trials at the one-north test site²¹. In July 2014, I²R also signed a joint laboratory agreement with BYD Co. Ltd., one of China's largest companies specializing in battery technologies to develop electric vehicles with autonomous vehicle sensors²².



Figure 2.7: A*STAR Autonomous Vehicle (Source: Institute for Infocomm Research, 2016)

(6) In May 2016, a MIT spinout, nuTonomy announced that they have raised US\$16 million in its latest funding round, through investors including Highland Capital Partners, Fontinalis Partners, Signal Ventures, EDBI - the dedicated corporate investment arm of the Singapore Economic Development Board, and Samsung Ventures²³. nuTonomy is currently conducting trials at one-north and aims to be the first company in the world to deliver an autonomous taxi solution in Singapore, which includes software for autonomous vehicle navigation in urban environments and smartphone-based ride-hailing, fleet routing, and management. In August 2016, LTA established a partnership with nuTonomy to test their shared, on-demand, door-to-door, first and-last-mile, and intra-town self-driving transportation concepts in one-north. In addition, nuTonomy also partnered Grab, a leading ride-hailing app in Southeast Asia in September 2016.

²¹ <http://www.i2r.a-star.edu.sg/autonomousvehicle/projects/astar-autonomous-vehicle-alphard>

²² <http://byd.com/news/news-206.html>

²³ <http://www.nutonomy.com/press.html>



Figure 2.8: Self-driving Car from nuTonomy (Source: nuTonomy Inc., 2016)

(7) In June 2016, SMRT International Pte. Ltd., Singapore (SMRT International) and United Technical Services announced their investments in 2 Getthere Holding B.V. (2getthere), a Netherlands-based company that designs and makes a family of automated vehicles. SMRT International is acquiring a 20% stake in 2getthere. Earlier in April 2016, SMRT Services Pte. Ltd., Singapore and 2getthere also formed a joint venture called 2getthere Asia Pte. Ltd., and has been awarded its first consultancy project to assess the feasibility of implementing the Group Rapid Transit (GRT) system within a client's premises in Singapore. In addition, 2getthere Asia plans to trial the first 3rd Generation GRT vehicle in Singapore by the end 2016²⁴.



Figure 2.9: 3rd Generation Group Rapid Transit from 2 Getthere (Source: 2 Getthere Holding B.V., 2016)

²⁴ <http://www.2getthere.eu/smrt-and-uts-investment/>

(8) In addition, the LTA also established a partnership agreement with Delphi Automotive Systems in August 2016. Delphi is one of the major Tier 1 supplier of vehicle technologies, and they will develop and test a fleet of fully autonomous vehicles including a cloud-based mobility-on-demand software suite at one-north²⁵.

(9) The LTA and JTC also partnered with NTU to launch the Centre of Excellence for Testing and Research of Autonomous Vehicles - NTU (CETRAN) and test circuit at CleanTech Park in the Jurong Innovation District in August 2016. CETRAN will spearhead the development of testing requirements for self-driving vehicles, and the test circuit will provide a simulated road environment for testing of the vehicles prior to deployment on public roads. As part of the five-year agreement with LTA, NTU will lead the research activities at CETRAN, collaborate with international testing, inspection and certification bodies, research institutions and industry, operate the test circuit, and evaluate the self-driving vehicle prototypes that are tested. The test circuit is expected to be operational by the second half of 2017²⁶.

2.5 Global Investments in Autonomous Vehicle Developments

Since the mid-2000s, private investments in autonomous vehicle development have grown, and continue to accelerate. **Appendix A** provides a detailed list of the various players involved in autonomous vehicle technology developments, their plans and current progress, accurate as of September 2016. The list includes: (1) Automotive manufacturers, (2) Technology developers, (3) Technology start-ups, (4) Major Tier 1 and Tier 2 companies, (5) Ride-sharing service providers, (6) Testing and proving service providers, (7) Map and mapping service providers, and (8) Driverless shuttle developers.

While some analysts have attempted to assess the strategies and execution of the key players in the autonomous vehicle market, such as that shown in **Figure 2.10**, it is still not clear at this point which player will emerge as the ultimate winner, nor is it apparent on which particular technology pathway is the winning concept. With strong inter-

²⁵ <http://www.autonews.com/article/20160801/OEM10/160739998/delphi-plans-to-test-self-driving-cars-in-singapore>

²⁶ <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=e950a4c8-dd8b-4434-90dd-30cc6cace662>

dependencies among technologies, developing an autonomous vehicle requires diverse technical expertise and significant cost, such that it is almost impossible or too risky for a single entity to develop it alone.

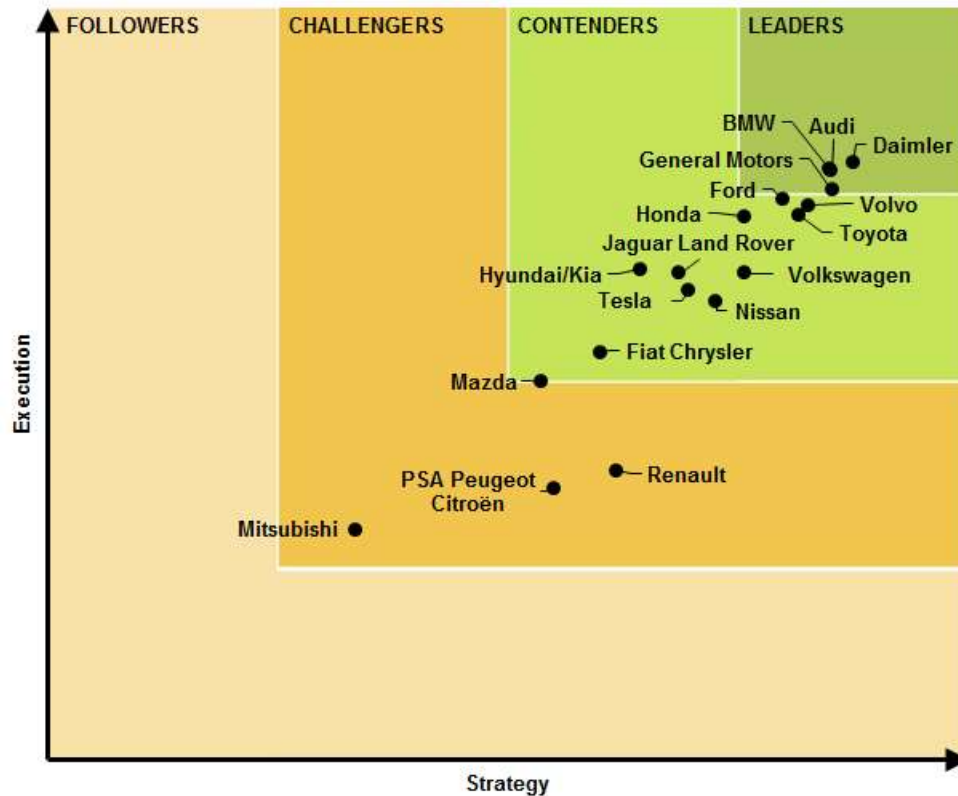


Figure 2.10: Navigant Research’s Analysis of Leading Players in Autonomous Vehicle Development (Source: Navigant Research Leaderboard Report, 2015)

From the Intellectual Property Rights (IPR) point-of-view, no single entity holds all the patented technologies to put a self-driving car into production. Various forms of IPR are applicable to the autonomous vehicle, ranging from patents to copyrights, trade secrets, and trademarks. A typical example of the various types of patents pertaining to an autonomous vehicle is shown in **Figure 2.11**. Patent ownership is one of the indicators to measure the extent of R&D investment and inventive creativity. Value capture in a high-tech industry is also deemed to be heavily reliant on IPR. According to ClearViewIP (2016)²⁷, Google has filed the largest number of autonomous-vehicle-related patents to-date, followed by Volkswagen and Ford.

²⁷ <http://www.clearviewip.com/autonomous-vehicles-an-ip-perspective/>

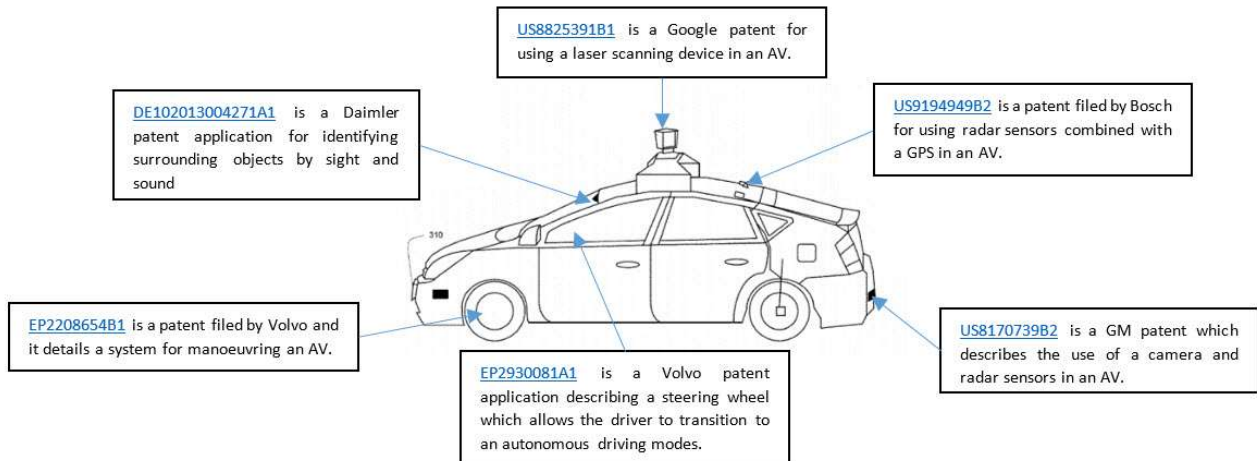


Figure 2.11: An Example of Key Patents Associated with an Autonomous Vehicle
(Source: ClearViewIP, 2016)

In terms of deployment timeline, several market players have indicated the desire to launch a highly automated or fully autonomous vehicle by 2020. **Figure 2.12** shows the companies that have made official announcements on an expected release of a product.

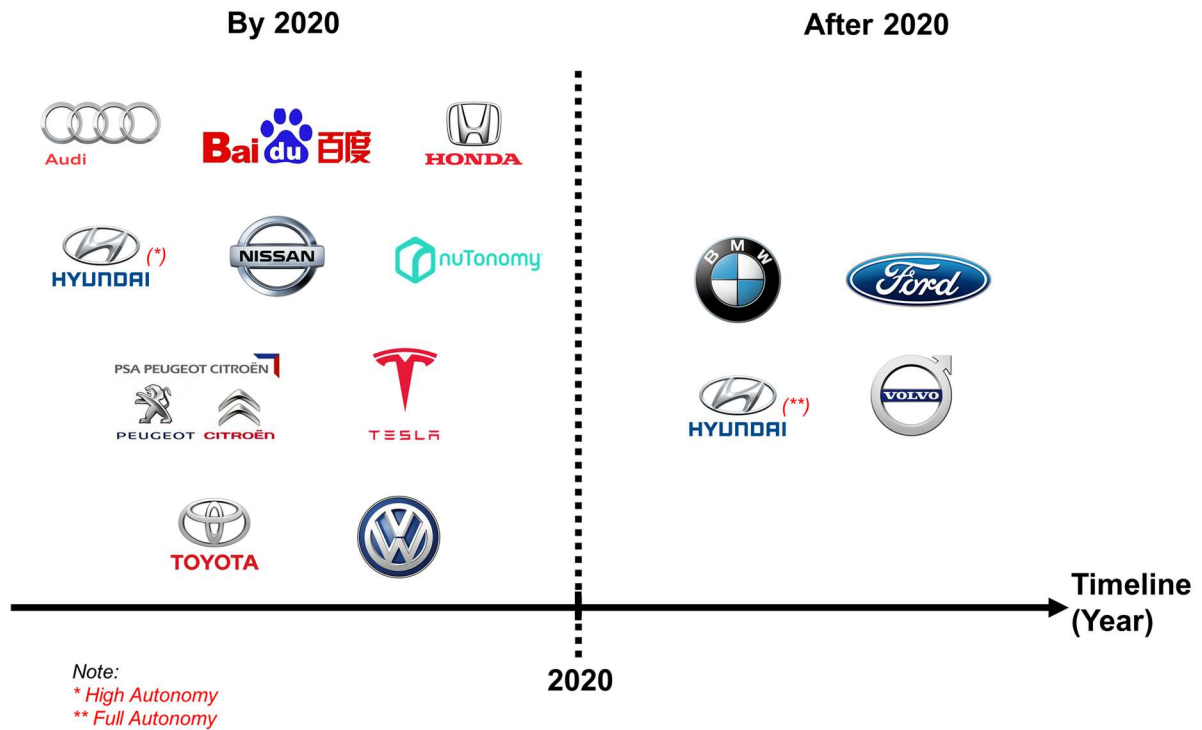


Figure 2.12 Expected Timeline for Launch of a Highly automated or Fully autonomous Vehicle

It is also evident from the market survey that numerous collaborations, partnerships, and acquisitions are involved between the companies and among the industry players to collectively harness the knowledge and experience to accelerate the technology developments. The attractiveness of the potential benefits to be reaped from autonomous vehicle market pie has also influenced the entry of new players and prompted existing players to move into new business areas. An example would be traditional carmakers venturing into the ride-sharing business, and vice-versa.

2.6 Government Involvement in Autonomous Vehicle Developments Globally

This section highlights the current and future plans undertaken by countries and major cities around the world to embrace the future mobility landscape enabled by the prospects of autonomous vehicles. These plans focus on the policy and regulatory perspectives for testing and deployment of autonomous vehicles on public roads to ensure safety and address liability considerations.

United States

The NHTSA published a Preliminary Statement of Policy concerning Automated Vehicles in 2013 that defined the levels of automation, gave an overview of NHTSA's automated research program and recommended principles that the States may wish to apply as part of their considerations for driverless vehicle operation, specifically in testing and licensing. An update was provided in January 2016 (US NHTSA, 2016).

In January 2016, at the North America International Auto Show in Detroit, the US Transportation Secretary, Anthony Foxx revealed a 10-year, \$4 billion investment to accelerate the development and adoption of safe vehicle automation through real world pilot projects. In 2016, NHTSA plans to embark on the following initiatives: (1) Work with industry and other stakeholders to develop guidance on the safe deployment and operation of autonomous vehicles, provide a common understanding of the performance characteristics necessary for fully autonomous vehicles, as well as the testing and analysis methods needed to assess them, and (2) Work with state partners, the American

Association of Motor Vehicle Administrators, and other stakeholders to develop a model state policy on automated vehicles that offers a path to consistent national policy.

Nevada was the first state in the United States to authorize the operation of autonomous vehicles in 2011. As of July 2016, seven other states - California, Florida, Louisiana, Michigan, North Dakota, Tennessee, Utah, and Washington D.C. have passed legislation related to autonomous vehicles. Arizona issued an executive order related to autonomous vehicles²⁸.

On a related note, in December 2015, the US Department of Transportation organized the Smart City Challenge, which was a national competition to implement bold, data-driven ideas that make transportation safer, easier, and more reliable in the city. A total of 78 applications was received and the seven finalists were shortlisted in March 2016, and they were: Austin, TX; Columbus, OH; Denver, CO; Kansas City, MO; Pittsburgh, PA; Portland, OR; and San Francisco, CA. In June 2016, Columbus, OH was selected as the eventual winner of the Challenge, and will receive up to \$40 million from the US DOT and up to \$10 million from Paul G. Allen's Vulcan Inc. to supplement the \$90 million that the city had raised from other private partners to reshape its transportation system²⁹.

In September 2016, California passed a new legislation that allowed testing of self-driving vehicles with no steering wheels, brake pedals or accelerators on public roads. A human driver as backup was not required, but the vehicles would be limited to speeds of less than 35 miles per hour. Previous state regulations in California mandated the presence of a human driver in the self-driving car during testing on public roads. For the initial phase, this new legislation applied only to a pilot project by the Contra Costa Transportation Authority at GoMentum Station, an autonomous-vehicle testing facility at the former Concord Naval Weapons Station, and test deployment of EasyMile driverless shuttles at the Bishop Ranch business park in San Ramon³⁰.

²⁸ <http://www.ncsl.org/research/transportation/autonomous-vehicles-legislation.aspx>

²⁹ <https://www.transportation.gov/briefing-room/us-department-transportation-announces-columbus-winner-unprecedented-40-million-smart>

³⁰ <https://www.engadget.com/2016/09/30/cali-unmanned-autonomous-trials/>

The NHTSA also published a Federal Automated Vehicles Policy in September 2016, with the intent to guide manufacturers and technology developers in the safe design, development, testing, and deployment of highly automated vehicles (the equivalent of SAE Levels 3 to 5), where the automated vehicle systems were responsible for monitoring the driving environment. As part of the policy, the NHTSA also requested for the voluntary submission of a safety assessment by the agencies developing the highly automated vehicle systems. The safety assessment covered 15 areas, ranging from privacy, cybersecurity, human-machine interface to ethical considerations and minimal risk conditions (NHTSA, 2016).

Europe

Europe has a very strong industrial base in automotive technologies and systems. The automotive industry is the largest private investor of research and development in Europe. In 2014, the European Road Transport Research Advisory Council (ERTRAC) established a task force with the stakeholders and experts from member associations and individual members to define a joint roadmap for Automated Driving, with the aim of ensuring a harmonized approach towards implementation of higher levels of automated driving functionalities. In the final version of the roadmap published in July 2015, the ERTRAC provided examples of the different automation systems pegged to the SAE definitions, and stated the expected timelines for their possible deployment. For example, the “Highway Pilot” was pegged at Level 4 SAE, with possible deployment from 2020 to 2024, where automated driving up to 130 kilometers per hour on motorways was allowed, and the driver did not need to monitor the driving constantly but had the option to override the automated driving (ERTRAC, 2015).

With the exception of UK and Spain who have not ratified it, all the European Union member states are signatories of the 1968 Vienna Convention on Road Traffic, which is an international treaty designed to facilitate international road traffic and to increase road safety by establishing standard traffic rules among the contracting parties. Under this Convention, one of the fundamental principles is the concept that a driver is always fully in control and responsible for the behavior of a vehicle in traffic. To-date, the driver is

always defined as a person. It may be noteworthy to highlight that the United States is a signatory of the 1949 Convention, but not the 1968 Convention, where the earlier Convention contains “less extensive obligations” regarding the driver, hence making it easier to allow for autonomous vehicles.

Carmakers in Germany, Italy, and France have rallied for amendments to be made to the Convention. Amendment work was already done to address systems in the context of the driver still being present enough in the situation to take over driving of the vehicle when required. The proposed amendments to allow for semi-autonomous driving as the driver was still in control and would be able to take over driving the vehicle as required at any time, was accepted into law in March 2016³¹.

Another potential amendment currently under discussion is the introduction of technical provisions for self-steering systems, which refers to systems that, under specific driving circumstances, will take over the control of the vehicle under the permanent supervision of the driver, such as lane-keeping assist systems, self-parking functions, and highway autopilots. Evaluation of the technical requirements is in progress to assess the feasibility of removing the current limitation of automatic steering functions to driving conditions below 10 kilometers per hour contained in the UN Regulation No. 79 and could potentially be adopted by the World Forum for harmonization of vehicle regulations in 2017³².

As for the regulatory environment, the areas of focus are related to cybersecurity, data privacy, and liability issues associated with the development of automated vehicles. In the international setting, in September 2015, the transport ministers of the G7 States and the European Commissioner for Transport agreed on a declaration on automated and connected driving. The declaration underlined the need to establish a harmonized regulatory framework to enable safe deployment of autonomous vehicle technologies across national borders. Within the European Union, enabling intelligent transport

³¹ <https://www.sbdautomotive.com/en/unece-updates-vienna-convention>

³² <http://www.unece.org/info/media/presscurrent-press-h/transport/2016/unece-paves-the-way-for-automated-driving-by-updating-un-international-convention/doc.html>

systems, automated and connected vehicles is a task that spans across transport and economic policies, particularly in the framework of the Digital Agenda for Europe. This involves investments in broadband networks and transport infrastructure, which are necessary for an effective Cooperative-Intelligent Transport System.

United Kingdom (UK)

As part of the 2013 National Infrastructure Plan, the UK government pledged a review of the legislative and regulatory framework to enable the trialing of driverless cars on UK roads. In July 2014, the UK government launched a “driverless cars” competition to invite UK cities to collaborate with businesses and research organizations to host vehicle trials in their cities. The results were announced in December 2014, and £19 million was provided by the UK government to allow testing of automated vehicle technology in Greenwich, Milton Keynes, Coventry, and Bristol (UK Department for Transport, 2015).

In February 2015, the UK Department for Transport published a policy paper on “Driverless Cars in the UK: A Regulatory Review”. This paper reviewed the present regulations and identified issues that need to be addressed to enable automated vehicle technology testing on UK roads whilst maintaining high levels of road safety. The key issues raised in the paper included: (1) Clarification of criminal and civil liabilities in the event of an automated vehicle being involved in a collision, (2) Amending regulations on vehicle use without a test driver and (3) Promoting safety, both physical as well as against cyber threats. The UK government is working with the administrations and plans to amend the domestic regulations by summer 2017 to accommodate driverless vehicle technology, and aims to liaise and amend international regulations by the end of 2018. A new joint policy unit, the Centre for Connected and Autonomous Vehicles (CCAV) was also established to help ensure that the UK remains a world leader in developing and testing connected and autonomous vehicles by leading innovating policy development in this sector, and being the single contact point for stakeholder engagement.

Meanwhile, in July 2015, the Department for Transport issued a Code of Practice to provide guidance to anyone who wishes to conduct testing of automated vehicle

technologies on public roads or in other public places in the UK. The code applied to the testing of a wide range of vehicles, from small automated pods and shuttles, to cars, vans, and heavy duty vehicles.

KPMG (2015) also projected a strong growth in the UK automotive industry and postulated that all vehicles produced in the UK will have at least NHTSA's Level 3 automated technologies embedded in them by 2027, with a 25% penetration of fully autonomous vehicles by 2030.

Japan

The Advanced Safety Vehicle project initiated by the Japanese government in 1991 marked the early considerations for automated driving in Japan, with focus on communications-based systems. In 2011, road-to-vehicle communication service was established on the expressways to provide two-way communication at high speed and high capacity between on-board units and the ITS spots. In addition to the usual toll collection, the installed ITS spots and on-board units are also used to provide driving assistance such as Congestion Avoidance Support, Safe Driving Support, and Post Disaster Information Support (Naono, T., 2014).



Figure 2.13: Electronic Toll Collection 2.0
 (Source: White Paper on Land, Infrastructure, Transport and Tourism in Japan, 2015)

Besides, an automated driving system research program as part of the Cross-Ministerial Strategic Innovation Promotion Program was also introduced in May 2014. The program recognized the development and verification of automated driving systems, development of technologies that will contribute to the reduction of traffic fatalities and congestion, international cooperation, and deployment for the next generation urban transport. Symbolically, the Tokyo 2020 Olympic and Paralympic Summer Games have been chosen as the central milestone for demonstrating autonomous driving in Japan.

To help realize this goal, a consortium of nine carmakers and six car navigation systems-related companies, including Mitsubishi Electric Corporation, Toyota, and map publisher Zenrin, established a new company called Dynamic Map Planning in June 2016³³. This new company plans to develop a high-precision, multilayered, “One Stop” 3D map that contains both static and dynamic information³⁴, with measuring errors of as little as 10 centimeters (approximately 20 times more precise than current commercial maps), to facilitate safe navigation of autonomous vehicles³⁵.

In the domain of truck platooning, a semi-governmental organization, New Energy and Industrial Technology Development Organization, demonstrated the platooning of four trucks in an oval test track in Tsukuba City, Japan in 2014. During the trial, the speed of the lead vehicle was communicated wirelessly to the train of vehicles once every 20 milliseconds to ensure an optimum and safe driving distance. Each vehicle was also equipped with millimeter-wave Radar and infra-red laser Radar to detect obstacles and recognize lane markings, coupled with a series of algorithms and fail-safe controls to manage the platoon³⁶.

In terms of policy and regulations, the automated driving technologies are largely concentrated on “Driver-Assist”, where there is a human driver in the control loop. At this

³³ <http://www.japantimes.co.jp/news/2016/08/19/business/japan-firms-developing-3-d-maps-autonomous-driving/#.WByVqvkrI2x>

³⁴ <http://www.forbes.com/sites/janetwburns/2016/09/08/japanese-leaders-aim-to-make-tokyo-a-self-driving-city-for-2020-olympics/#2c38c9df7845>

³⁵ <http://www.sip-adus.jp/workshop/program/speaker/profile/dm/koyama.pdf>

³⁶ <http://www.bbc.com/future/story/20130409-robot-truck-platoons-roll-forward>

point, there are no special procedures or amendments required to the current legislation for driving on public roads. For full self-driving, where the human driver is out of the loop, the Japanese government has not had a prospect of a practical use of the technology and shares NHTSA's view that "it is too soon to reach conclusions about the feasibility of producing a vehicle that can safely operate in a fully automated mode". Moreover, the Japanese car manufacturers are working on advanced driver assistance technologies and have not developed tangible research plans for full self-driving. The Japanese government plans to monitor the public acceptance of driver assistance technologies and will review existing legislation and policies concerning road transport, as well as the new car assessment program as the technologies evolve.

Australia

In Australia, automated driving started with the mining industry. In October 2015, the Australian mining giant, Rio Tinto completed its rollout of 69 units of driverless trucks to transport iron ore around its Pilbara sites. The trucks were controlled by employees in a control center in Perth, about 750 miles away. Besides Rio Tinto, two other mining companies, BHP Billiton and Fortescue were also testing autonomous truck technologies.

In February 2016, the Australian Transport Minister announced that a staged trial of a driverless and fully electric shuttle bus will take place at the Royal Automobile Club's driving center, with plans to expand to the Perth roads in late 2016. The shuttle bus, developed by Navya SAS, a French company specializing in intelligent transport systems, can carry up to 15 passengers and has a maximum speed of 28 miles per hour.

Besides Perth, Australia's capital, Canberra, has also expressed interest to test and legalize self-driving cars.

2.7 Benefits and Challenges for Autonomous Vehicle Implementation

This section provides a general summary of the expected long-term benefits through implementation of high automated or fully autonomous vehicles, as well as highlights the

barriers to a successful transformation of urban mobility (KPMG, 2012, Anderson, J.M., 2016, Litman, T, 2016). The expected benefits and challenges specific to Singapore's context are discussed in **Chapter 6**.

2.7.1 Benefits

Urban Mobility

In major cities where land space for road infrastructure is scarce and traffic congestion is hindering economic progress and degrading the travelling experience, leveraging autonomous vehicles coupled with connected vehicle technologies may be a stop-gap interim solution to accommodate more vehicles on the roads by reducing the distance between autonomous vehicles, hence increasing the road capacity.

The adoption of autonomous vehicles can also serve as an alternative form of public transportation, or as a car or ride-sharing concept, with the expected benefits of better time optimization for the human to engage in other tasks instead of holding on to the steering wheel during the travel journey. This would mean that drivers give up car ownership and switch to public transportation instead, and this will help alleviate the deteriorating traffic conditions on arterial roads and expressways, and relieve parking woes in urban cities. However, the sustainability of this approach remains to be studied, especially on the impact of car or ride-sharing on the travel behavior shifts, as one possible scenario could be car or ride-sharing results in commuters who do not own cars previously, to have accessibility to a new mode of transportation, and hence move away from public transit modes.

Social Inclusion

Autonomous vehicles with the human driver out of the loop will increase the mobility of the society as a whole, by enabling the elderly population, people with disabilities, or persons without a driving license or unfit for driving, to have more independent access to essential services, and hence potentially improving their quality of life. The advent of automated driving can complement the current mass transit and para-transit services.

Road Safety

On average, more than 90% of road accidents are attributed to human error, such as misjudgment of other road users' movements, and inability to react in time to an impending collision. Some current vehicles are already installed with driver-assist technologies such as collision and lane departure warning systems, automatic emergency braking, blind spot assist, and adaptive headlights. These technologies may improve driving safety by compensating for the flaws in human judgement and errors. Progression of these technologies to highly reliable automation is expected to bring about enhanced safety to the human driver and other road users.

Energy Efficiency

Vehicle control systems that automatically accelerate and brake with the traffic flow can conserve fuel more efficiently than the average human driver. Reduction in fuel consumption can yield positive reduction in greenhouse gas emissions. This outcome is premised on the assumption that the vehicle miles travelled still remains largely unchanged even with the increased ease of mobility.

Relief of Labor Shortage

In some developed cities such as Singapore, the shortage of drivers in the trucking and public transportation industries is a prevalent challenge. The use of autonomous vehicles as public buses or for truck platooning at ports could reduce the reliance on manpower, increase productivity, and alleviate the driver shortage problem. However, in other parts of the world where a significant percentage of the country's working population drives trucks or buses for a living, the advent of fully autonomous vehicles may threaten their livelihood.

2.7.2 Challenges

Safety and Technology Robustness

While automated and autonomous driving claims to reduce the number of road traffic casualties and fatalities, a significant concern is the safety and reliability of the

autonomous driving technologies. Public confidence in the technology readiness and fail-safe architecture of autonomous driving systems under dynamic road conditions is key to social acceptance and adoption of self-driving cars.

In addition, before fully autonomous driving becomes a reality, a “shared driving” concept of operation is likely to pervade for at least the next five to ten years. This concept of shared decision authority depending on the situation introduces another set of challenges, such as: (1) When should the human be in charge of the vehicle, and when should the automated driving be in charge, (2) What can the human be permitted to do when he/she is not in control of the driving, and (3) What is a realistic transition time to transfer control of vehicle from automated driving to a human driver. Coordination between the human driver and automated driving system requires understanding of the human mental models and human-automation interactions.

Legal and Regulatory Framework

Re-assessment of the current legal and regulatory framework has to be performed before market introduction of autonomous vehicles on public roads. The responsibilities and liabilities of all involved stakeholders, including the vehicle manufacturers, vehicle owners, other road users, motor insurance companies, and land transport authorities need to be reviewed and defined, and the extent of standardization of technical requirements and performance characteristics also need to be studied.

Social Acceptance and Adoption

Uncertainty exists in the extent of social acceptance and adoption of autonomous vehicles over time. Besides gaining trust in the safety and reliability of the vehicle, data privacy and security concerns also need to be addressed and the benefits of automated driving need to be weighed against the potential security vulnerabilities associated with pervasive connectivity. In addition, affordability may pose an initial barrier to adoption, but the cost of the added sensor suite to enable automated driving is expected to go down due to economies of scale if the technology gradually becomes a standard feature for new cars.

Infrastructure Requirements

The implications and requirements for higher levels of automated driving on the physical infrastructure are not well-defined yet. It is important to recognize that the inherent relationship between the infrastructure performance and the autonomous vehicle dynamics is the key factor for a safe and reliable automated driving, and yet, it is also the weakest link due to cybersecurity concerns and resiliency of the network infrastructure against malicious intent.

Mixed Fleet of Human-Driven Vehicles and Autonomous Vehicles on the Road

The transition from human-driven vehicles to vehicles with different levels of autonomy will span decades, and it is unlikely that there will be 100% adoption of autonomous vehicles on the road. A possible solution would be to have separate lanes for human-driven vehicles and autonomous vehicles respectively, but that is likely to incur additional land and infrastructure cost, which is not sustainable for deployment in land-scarce environments. Moreover, another technical challenge to be overcome will be the interactions between human-driven vehicles and the autonomous vehicles, due to the significant differences in driving behavior.

CHAPTER 3 – TECHNOLOGY READINESS AND DIFFUSION

From the technology perspective, two key attributes drive the extent and rate of adoption of new technologies in the market, and they are: (1) Technology Readiness, and (2) Technology Diffusion.

3.1 Concept of Technology Readiness

Technology Readiness Levels (TRL)s is a method that supports the assessment of technology maturity of critical technology elements of a program. The TRLs are typically determined during a process called Technology Readiness Assessment that examines program concepts, technology requirements, and demonstrated technology capabilities. TRLs are measured based on a scale from 1 to 9 with 9 being the most mature technology. The corresponding TRL scale provides a measure of technology maturity with a view towards operational use of the technology concerned in a system context. It also serves as a scale to compare maturity levels across different types of technologies. Decision authorities will consider the recommended TRL when assessing program risk.

It is important to note that TRLs are not a measure of design validity, and they do not indicate the difficulty to achieve the next TRL. A TRL number is obtained once the definition prescribed for that TRL has been achieved, and the technology remains at that TRL until it meets the requirements to move on to the next TRL. For example, successfully achieving TRL 4 (lab environment) does not move the technology to TRL 5. TRL 5 is achieved only when there is component/breadboard validation in a relevant environment.

In addition, while a critical technology element may appear to be mature in isolation, the assessment may change when this technology element is integrated as part of a larger system, due to the interactions with other elements in the system.

3.2 Origin of Technology Readiness Level

The concept of TRL originated from the US National Aeronautics and Space Administration (NASA). A NASA researcher, Stan Sadin, conceived the first TRL scale in 1974. It had seven levels which were not formally defined until 1989. In the 1990s, NASA adopted a scale with nine levels which gained widespread acceptance across industry and remains in use today (Mankins, 1995 and DAG, 2013).

Since its inception, many government organizations and industries including the automotive industry have adapted and tailored the TRL definitions to their unique needs (e.g., hardware versus software), to serve as a planning tool for management of research and development investments, as a classification tool to demarcate technologies in different phases of technology development, or as a common yardstick to measure across different technologies.

3.3 Technology Readiness Level Scale

Table 3.1 summarizes the definition of TRLs used by NASA, which are specific to the nature of research done at NASA, while Table 3.2 provides a more generic description of TRL that is currently adopted by the US Department of Defense (US DoD). In this thesis, we will use the US DoD TRL definitions to evaluate the technology maturity of the autonomous vehicle technologies, and this will be discussed in **Chapter 5**.

Table 3.1: NASA TRL Definitions (Source: National Aeronautics and Space Administration)

TRL	NASA's Definition
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.
4	Component and/or breadboard validation in laboratory environment.
5	Component and/or breadboard validation in relevant environment.
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space).
7	System prototype demonstration in a space environment.
8	Actual system completed and "flight qualified" through test and demonstration (ground or space).
9	Actual system "flight proven" through successful mission operations.

Table 3.2: TRL Definitions used by US DoD (Source: US Defense Acquisition Guidebook, 2013)

TRL	US DoD's Definition	Description
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad-hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

3.4 Technology Hype Cycle

Another approach to look at technology maturity or readiness is to use the Gartner hype cycle, which is a graphical depiction of a common pattern that arises with each new technology or innovation. Some organizations use the hype cycle to track technology maturity and future potential, to aid technology planners in decisions on which technologies to adopt at what time. According to Gartner, a technology passes through several stages on its path to productivity and this is typically characterized by the hype cycle, as shown in **Figure 3.1** (Fenn, J., Raskino, M., and Burton, B., 2015)

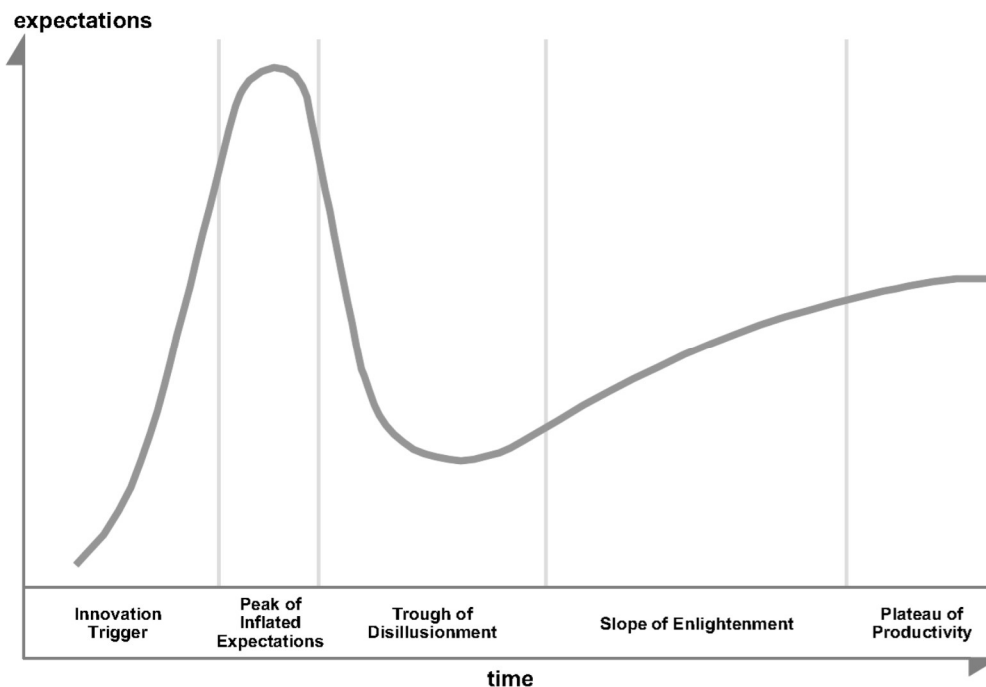


Figure 3.1: Gartner Hype Cycle (Source: Gartner, Inc., 2015)

The terms used to describe the different stages of the hype cycle are explained as follows:

(1) **Innovation Trigger:** The hype cycle starts when a breakthrough, public demonstration, product launch, or some other event generates press and industry interest in a technology innovation. In the case of the autonomous vehicle, the General Motors *Futurama* exhibit on a vision of technologically advanced superhighways at the 1939 World's Fair in New York may well have been the innovation trigger.

(2) **Peak of Inflated Expectations:** A wave of “buzz” builds and the expectations for this new technology rise above the current reality of its capabilities. Gartner’s assessment in 2015 reflected that autonomous vehicle technologies are currently at this phase of the hype cycle, and that seems to be representative from current market observations.

(3) **Trough of Disillusionment:** Inevitably, impatience for results begins to replace the original excitement about potential value. Problems with performance, slower than expected adoption, or failure to deliver financial returns in the time anticipated all lead to missed expectations, and hence disillusionment sets in. Some of these comments have been observed during the development of zero emission vehicles, with further discussion in **Chapter 4** on uncertainty. Given the current hype yet significant uncertainty on the performance, safety, reliability, cost, and adoption rate for autonomous vehicles at this point, there is a risk that this technology may fall into the trough of disillusionment in the years to come.

(4) **Slope of Enlightenment:** Some early adopters overcome the initial hurdles, begin to experience benefits and recommit efforts to move forward. Drawing on the experience of the early adopters, understanding grows about where and how the technology can be used to good effect and, just as importantly, where it brings little or no value. Using the example on zero emission vehicles again, we have seen an increasing adoption rate of plug-in hybrid electric vehicles in the recent years, as more people start to appreciate the value of the technology, coupled with the decreasing cost barrier to entry. Similarly, for autonomous vehicles, it may take a while for people to overcome the psychological barrier of being in a self-driving car, as well as to trust the technology and be assured of safety.

(5) **Plateau of Productivity:** With the real world benefits of the technology demonstrated and accepted, growing numbers of organizations feel comfortable with the now greatly reduced levels of risk. A sharp uptick in adoption begins, and penetration accelerates rapidly as a result of productive and useful value. It is premature at this point to speculate when and if this phase will be reached for autonomous vehicles, but looking

at past deployment of automotive-related technologies, it will probably take at least 50 years or even longer.

3.5 Concept of Technology Diffusion

From literature, we recognize that there is no common language in the definition of market adoption of new technologies. Market adoption is a process, of which initial market entry is just a single milestone in the overall timeline of market penetration. Moreover, the point of likely market entry is dependent on numerous factors, such as: (1) The technology attaining maturity in the laboratory and relevant environment, (2) Successful integration of the technology with the system, and (3) Satisfying regulatory requirements prior to introduction into the market, and each of these factors has its inherent uncertainty. Therefore, one needs to be mindful when interpreting proposed timelines for market entry and mainstream adoption of new technologies (US DOE, 2013).

It is also important to distinguish between incremental technologies whose introduction may be virtually transparent to the consumer, as compared to disruptive new technologies that can potentially change the vehicle characteristics and/or driver behavior. Autonomous vehicle technologies fall under the latter category.

The process of technology diffusion has been depicted in many ways, of which, the diffusion of innovation theory originated by Dr. Everett M. Rogers, has been significantly cited by academics and analysts. This is presented in **Figure 3.2**.

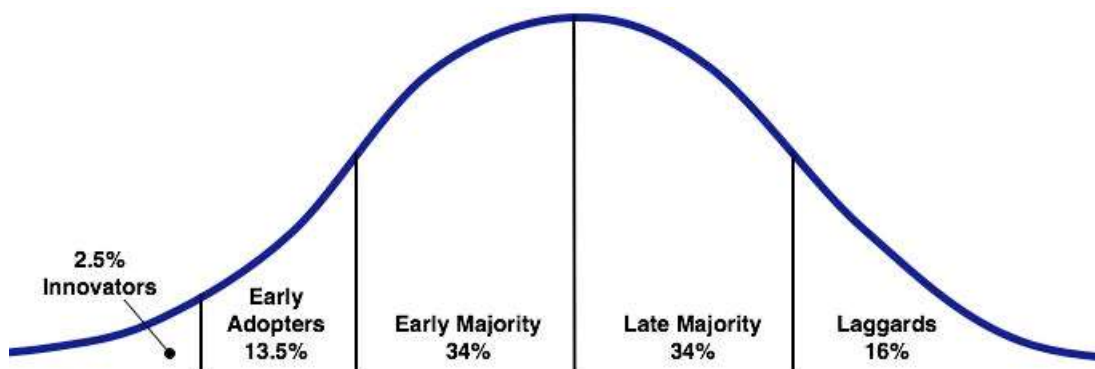


Figure 3.2: Diffusion of Innovation Model
(Source: Everett M. Rogers, Diffusion of Innovations, 5th Edition, 2003)

Alternative representations of the technology diffusion model have since emerged, that attempted to correlate the cumulative diffusion of technologies over a timeline. While the theoretical model presents a smooth growth or transition from one group of users to another, and assumes that the technology will eventually reach market saturation, this is not reflective of the actual implementation of automotive-related technologies gathered from past records.

For example, automatic transmission was developed in the 1930s but took about 50 years before it became reliable and affordable in the 1980s. Even then, automatic transmission is still not pervasive in new vehicle markets worldwide. It is estimated that about 90% of new vehicles in North America have automatic transmission, while only about half of the new vehicles in Europe and Asia are equipped with this technology.

Another example is the deployment of hybrid vehicles. The first modern production hybrid, the Prius, was introduced by Toyota in Japan in 1997. According to a technical brief published by the International Council on Clean Transportation in 2015, hybrid vehicles accounted for a mere 3% of the overall passenger vehicle market in the United States, and about 20% market share in Japan. It remains uncertain if and when the traditional hybrid vehicle technology will achieve a substantial market share or will be rendered obsolete by emerging technologies such as electric powertrains.

Notwithstanding, we also note that there are a minority of automotive related technologies that attained 100% market share in a comparatively shorter time. An example is the airbag technology, which was introduced in 1973 and became available in all vehicles by 1998. However, this was in the context of federal regulations that mandated the installation of airbags as a standard feature in all vehicle models, due to safety considerations.

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CHAPTER 4 – CONCEPT OF UNCERTAINTY, FLEXIBILITY, AND REAL OPTIONS

4.1 The Future is Uncertain

The future demand and maturity of a new technology is uncertain. In 1990, the Zero-Emission Vehicle (ZEV) regulation was enacted, which required two percent of all vehicles for sale in California in 1998 be zero-emission vehicles. A ZEV is defined as a vehicle which produces no emissions from the onboard source of power, and is determined by the tailpipe emissions. The amount of emissions generated by the production of the fuel that the vehicles use is not considered. There was also a further requirement that 10 percent of the vehicles sold in California must be zero-emission vehicles (e.g., hydrogen fuel and battery electric vehicles) by 2003. In 1996, the California Air Resources Board eliminated the intermediate 1998 requirement, due to pressure from the automotive companies and concerns about the state of the technology. However, the 2003 target of 10 percent ZEVs remained. By 2001, the regulation was further revised to allow automotive companies to meet the ten percent requirement through three new vehicle categories: (1) Pure Zero-Emission e.g., hydrogen fuel cell vehicles or battery electric vehicles, (2) Advanced Technology Partial Zero-Emission e.g., hybrid electric vehicles, and (3) Partial Zero-Emission e.g., ultra-clean gasoline vehicles, with defined proportion limits for each category. Towards the end of 2003, many automotive companies ended their battery electric vehicle programs citing limited demand and slow battery technology development.

Since then, an evolving trend of hybrid and fuel cell vehicles started to emerge and further changes to the ZEV regulations in 2008 promoted the development of plug-in hybrids. A plug-in hybrid runs as an electric vehicle, but has an internal combustion engine as a backup. The latest amendment to the regulations was in 2012, which increased the requirements for Zero-Emission Vehicles and Plug-in Hybrid Electric Vehicles to over 15 percent of new vehicle sales by 2025. This is less than 10 years from now, and as a reality check, electric vehicles accounted for a mere 3.1% market share in new vehicles in California in 2015. Will the target of 15 percent be achieved by 2025?

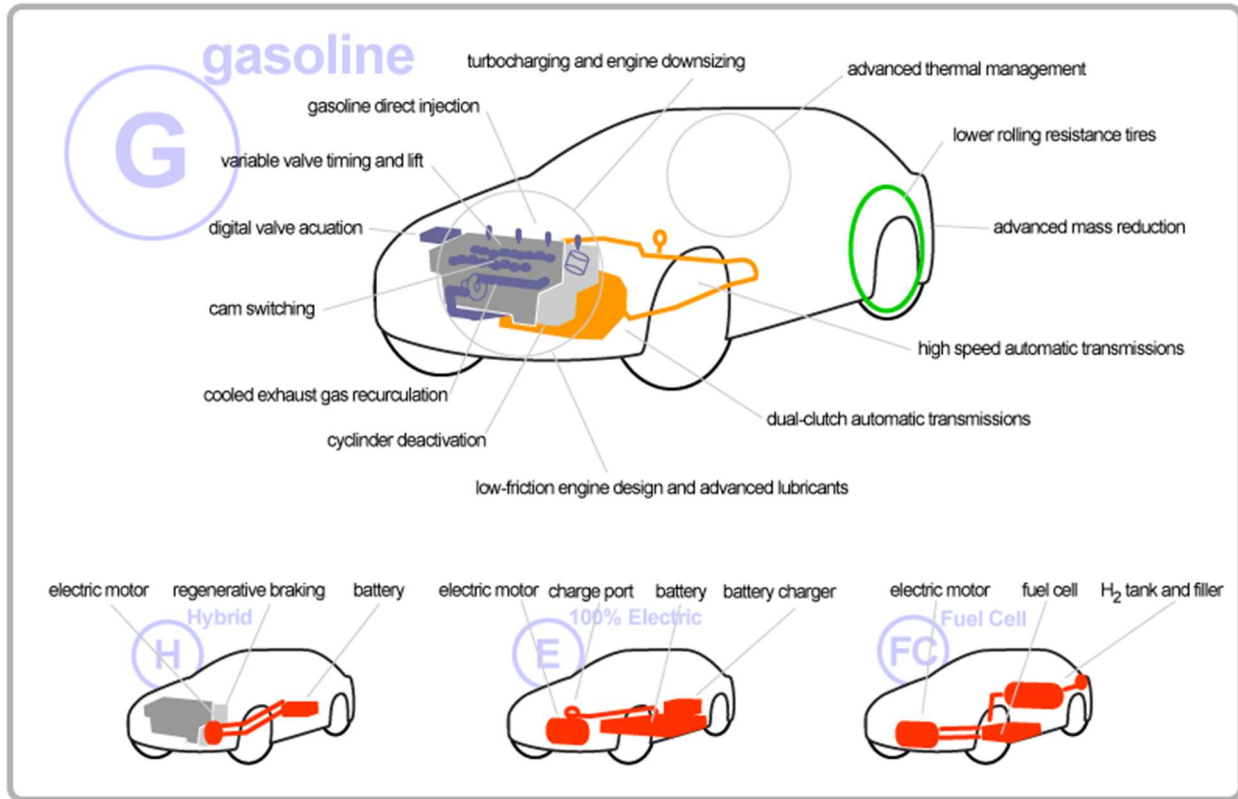


Figure 4.1: Pictorial Illustration of Gasoline, Hybrid, Electric, and Fuel Cell Technologies
 (Source: California Air Resources Board, 2016³⁷)

Besides indeterminate technical factors inherent to the introduction of any new technology, the future is further cluttered by external market factors. During the State of the Union speech in 2011, US President Barack Obama announced the goal of putting one million electric cars on the road by 2015. Since then, the US had introduced various federal policies and initiatives during the Obama Administration to advance the developments in production of fuel efficient vehicles and battery technologies. However, 2015 has passed and currently the United States has about 400,000 electric vehicles on the road, which is a significant increase since 2010, but fell short of the one million vehicle goal, which is now shifted to 2020 instead. In a recent interview³⁸ with The Science Times, Secretary Ernest Moniz from the US Department of Energy cited the unforeseen

³⁷ http://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/consumer_acc_technology.htm

³⁸ <http://www.sciencetimes.com/articles/8255/20160122/1m-electric-cars-target-moved-2020.htm>

continuing drop in fossil fuel prices as one of the reasons resulting in the slower than expected sales of electric vehicles in the past few years.

These examples illustrate that it is almost impossible to accurately forecast the long-term trends and patterns of demand of a new technology. While there could be historical behaviors observed for similar technologies in a related domain for comparison, these cannot be assumed as the definitive baseline to benchmark the next technology, as the expected future value of each technology is unique, highly complex, and uncertain.

4.2 Flexibility Can Add Value

The International Council on Systems Engineering defines systems engineering as “an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem”. A common graphical representation of the systems engineering life cycle is the V-model, as shown in **Figure 4.2**. The left side of the V represents concept development and decomposition of requirements into functions and physical entities that can be architected, designed and developed; while the right side of the V symbolizes integration and testing of these entities and their transition into the field, where they are operated and maintained.

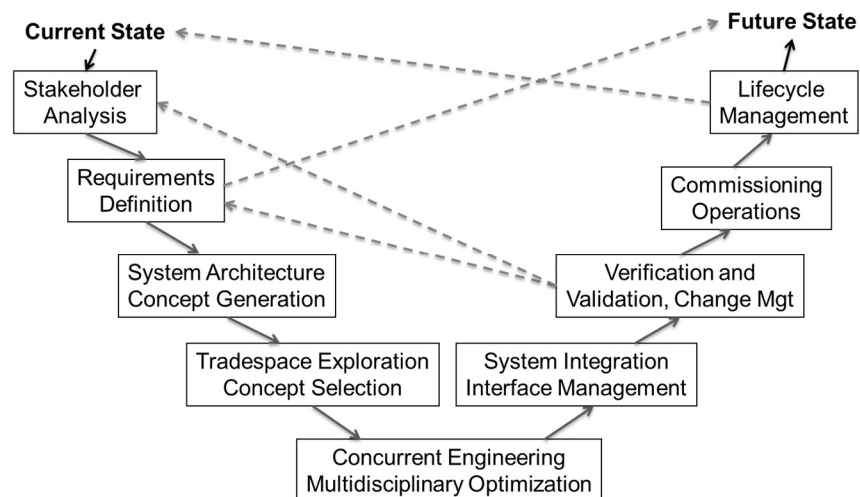


Figure 4.2: Systems Engineering V-model (Source: MIT ESD.413 Lecture Notes, 2016)

In reality, the system life cycle is rarely as linear and sequential as presented in the V-model. The classical systems engineering approach is ideal for situations where all the relevant systems engineering factors are under control and well understood. This usually applies for technologies that are relatively mature and the requirements are well established (MITRE, 2014). For new and emerging technologies, it is almost impossible to define a comprehensive set of requirements upfront, and even if such a document exists, it is unlikely to stay accurate through the implementation phase. Furthermore, with increased emphasis on networked capabilities and complex systems, new challenges in the engineering of Systems of Systems arise.

According to de Neufville, R., and Scholtes, S., (2006, 2011), project managers should first recognize the fact the future is uncertain, and thus can and should maximize value by making sure that flexibility, also known as real options are embedded in the design, plan or strategy, amidst the inevitable uncertainties. This is expected to enable the project to react to changing circumstances, take advantages of upside opportunities and insure itself from downside risks. It is also believed that flexibility is most valuable when uncertainty is the greatest. Instead of a single plan, one should consider a “family of plans” designed to respond and adapt to different outcomes of the project development over time.

In general, there are two types of flexibilities in engineering systems, known as: (1) Flexibility “in” projects, and (2) Flexibility “on” projects (de Neufville, R., 2016). Flexibility “in” exploits the design features to enable the system to evolve easily as circumstances change. For example, in the case of an autonomous vehicle, the firmware and software architecture can be designed to be modular in nature to allow plug-and-play of new features and technologies as and when they are ready, without having to re-design the entire system. On the other hand, flexibility “on” is design independent and is more associated with project management decisions to accelerate, delay, or abandon a project, depending on the endogenous factors such as technology maturity and readiness, and/or exogenous factors such as market fluctuations. In the context of an autonomous vehicle, flexibility “on” can be to perform test and evaluation on a pilot scale, and gradually scale

it up if the technical performance is favorable, or to revise or terminate the scope if the results are unsatisfactory.

4.3 Real Options

In systems analysis, dynamic strategic planning is believed to be an effective method for designing and implementing new technology or large-scale engineering projects. This method incorporates in projects, the flexibility to adjust easily over time to the actual situations and conditions as they arise, either to avoid bad situations or to take advantage of new opportunities. It leads systems planners and managers to recognize the great value of flexibility in the design of technological projects, and thus resulting in demonstrable, substantial improvements in technology policy (de Neufville, R., 2000).

This method is analogous to what is known as “real options” in the financial world. An option is defined as the right, but not the obligation, to take an action sometime in the future, usually for a pre-determined price and a given period. A “call” option allows one to take advantage of an opportunity to buy into a good situation, while a “put” option allows for an exit from a bad situation by not exercising the option.

To develop a dynamic strategic plan, the following seven activities are considered:

- (1) Modeling – this activity should result in one or more models of the technical system and its performance.
- (2) Optimization – this activity should result in an overview of different cost-effective means for achieving specified levels of results.
- (3) Estimation of probabilities – since the performance of a system in the future cannot be forecasted, it is necessary to estimate a range of values for key system parameters and the likely probability distributions for these parameters.
- (4) Decision analysis – by combining the results from (1) to (3), a decision analysis for the set of choices can be carried out.
- (5) Sensitivity analysis – this activity ensures that the outcome of the decision analysis is robust with regard to changes in parameter values.

- (6) Evaluation of real options – this activity focuses on identifying cost-effective real options that increase the flexibility of the plan. They can then be included in the decision analysis.
- (7) Analysis of implicit negotiation – the implementation of a plan to a large extent is dependent on the support of relevant stakeholders. The final proposal for an effective technology policy will result from a combination of the analysis of implicit negotiation and the plausible plans identified through (1) to (6).

4.4 Application to Technology Options

So how do the concepts and methods discussed in the earlier sections apply to technology options in managing an autonomous vehicle technology project?

Firstly, we must recognize that the future of autonomous vehicles is promising but uncertain, and is affected by both endogenous and exogenous factors. From the technical perspective, uncertainty lies in: (1) The technology readiness level of the technologies being integrated onto the vehicle, (2) Performance of the autonomous vehicle as an integrated system of systems, and (3) Safety, reliability, and maintainability of the autonomous vehicle over its life cycle. In addition, external factors such as regulations, insurance and liability effects, rate of adoption, and cost can also influence the end outcome.

Secondly, having acknowledged that uncertainties in deployment of new technologies are inevitable, one should design in flexibilities when developing plans and technology strategies so as to create real options for the policymakers when the future outlook becomes more apparent over time. For the autonomous vehicle, flexibility can be considered in the design by adopting a scalable and modular architecture, to allow incorporation and update of new features as and when they become technologically ready. Furthermore, flexibility “on” the system can be designed by prioritizing the issues that these technologies are expected to address, followed by a staged-gate approach to

enable abandonment, switching of options, or scaling up, depending on how the future environment evolves.

4.5 Application to Policymaking

With respect to policymaking, uncertainty refers to the gap between available knowledge and the knowledge policymakers would need in order to make the best policy choice. According to Marchau, V.A.W.J. et al. (2010), a “predict and act” approach, or otherwise known as a static policy is often used in most policymaking, which works well if the future can be predicted well enough to develop a policy that will produce acceptable outcomes in most plausible future worlds. However, the limited attention to uncertainty in static policies can lead to policy failures.

A dynamic adaptive approach considers an integrated view of the system domain and its interactions with the environment, such as external influences and policies. The notion of adaptive policies allows policymakers to cope with uncertainty by creating policies that respond to changes over time, that make explicit provisions for learning, and that leverage the self-organizing potential of actors and the decentralization of governance to detect emerging issues and craft necessary adaptive responses. Such policies combine actions that are time-sensitive with those that make important commitments to shape the future, and those that preserve the needed flexibility for future (Marchau, V.A.W.J. et al., (2010)).

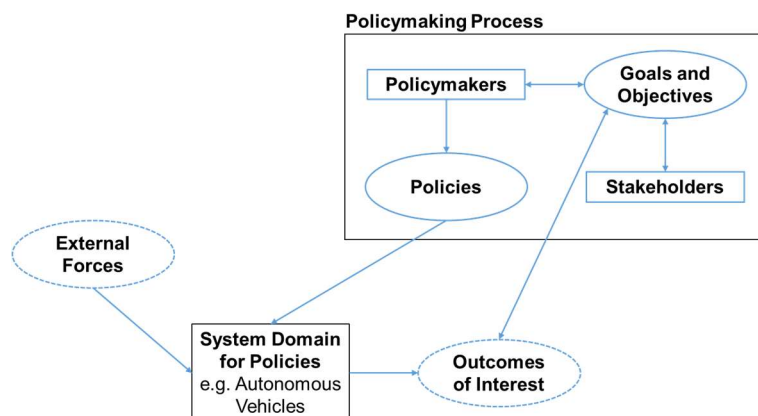


Figure 4.3: An Integrated View of Policymaking
(Adapted from Source: Marchau, V.A.W.J. et al. (2010))

Besides dynamic strategic planning, two other approaches have also been suggested – adaptive policymaking and flexible strategic planning. The three approaches are common in that they all consider a systems view and are based on the concepts of flexibility and adaptability.

Kwakkel, J. H., et al. (2010) attempted to synthesize the three adaptive planning approaches into a framework to guide the development of adaptive policies, as shown in **Figure 4.4**.

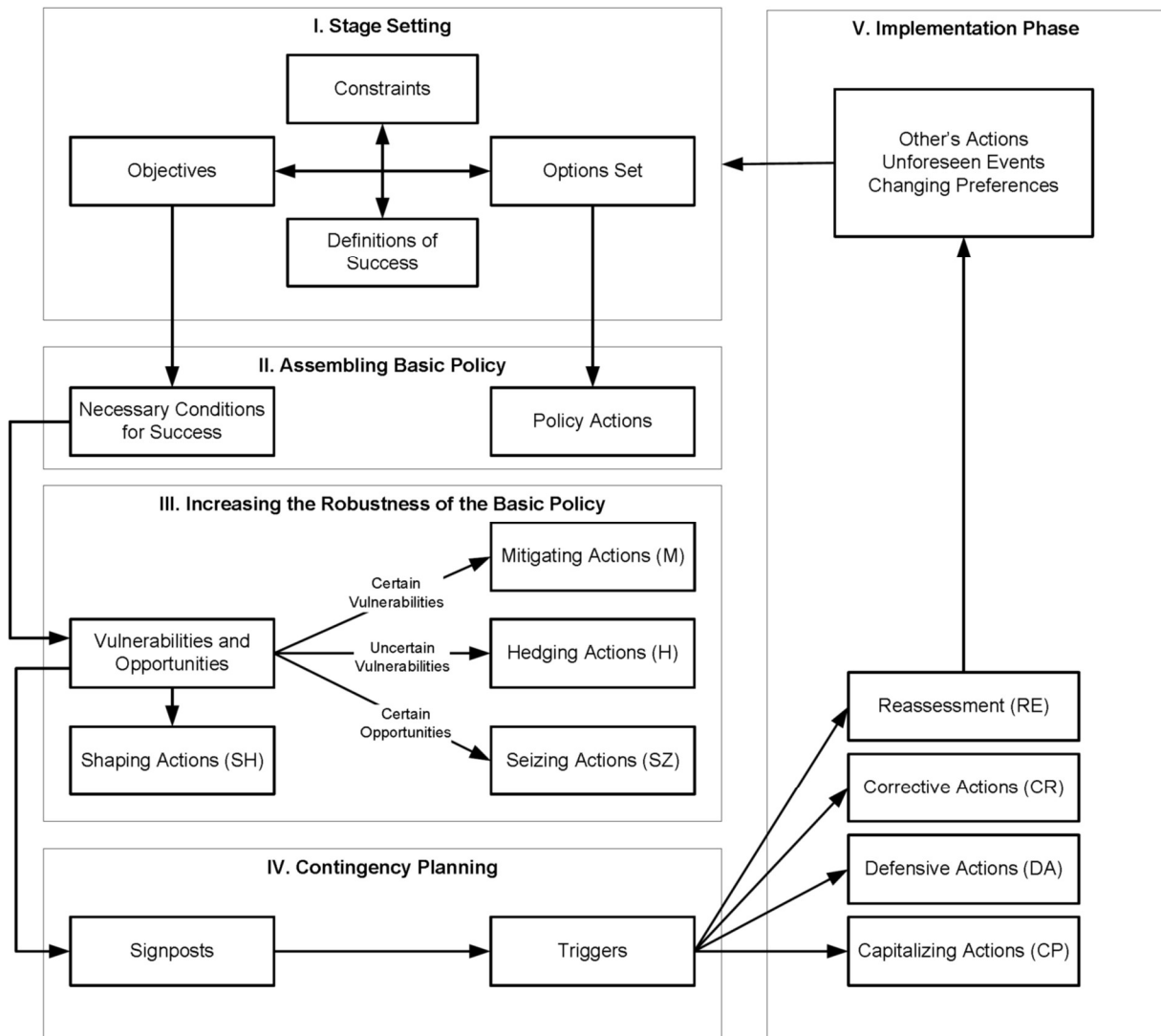


Figure 4.4: Adaptive Policymaking Process
(Source: Kwakkel, J. H., et al. (2010))

CHAPTER 5 – TECHNOLOGY READINESS ASSESSMENT OF AUTONOMOUS VEHICLE CAPABILITIES

5.1 Overview

The terms “autonomous vehicle” or “autopilot” have been so frequently used that it causes one to wonder if it is true that the era of autonomous vehicles has indeed arrived. One may associate the Google car with a fully autonomous vehicle, but it is important to note that the Google car fleet is experimental and throughout the road trials, the Google car is in a fully autonomous mode only 57% of the time, according to a study by the University of Michigan Transportation Research Institute in 2015 (Schoettle, B., and Sivak. M, 2015).

In May 2016, we learned about the first fatal car accident involving a tractor trailer and the Tesla Model S. The official statement issued by Tesla stated that the Model S was engaged in Autopilot mode at the time of accident, but neither the Autopilot nor the driver noticed the white side of the tractor trailer against a brightly lit sky. As such, the brakes were not applied. The Tesla car accident triggered public concerns and prompted investigations by the US National Highway Traffic Safety Administration (NHTSA) and National Transportation Safety Board (NTSB). Preliminary NTSB investigations revealed that the vehicle was travelling above the speed limit, with driver assistance features - Traffic-Aware Cruise Control and Autosteer Lane-keeping Assistance in operation.

The fatal car accident involving the Tesla Model S in Autopilot mode was unfortunate. From the technology perspective, it is also an indication of perhaps, the limitations of the current technologies in autonomous driving, as well as the lack of understanding of human driver behavior (e.g., over-expectations) when operating vehicles with limited autonomy.

In this chapter, we will discuss the key technologies used to develop driver-assist and autonomous driving capabilities. We will also attempt to provide an assessment of the technology readiness level of these capabilities. In this context, we define “Technology”

as the study and knowledge of the practical use of scientific discoveries³⁹, and “Capability” as the ability to perform or achieve a certain action or outcome.

5.2 System Decomposition

As discussed in Chapter 2, autonomous driving is the emergent property of a vehicle system, arising from a confluence and integration of technologies in perception, navigation and localization, telematics, and communications. To understand how the different technologies interact and interoperate in a complex system such as the autonomous vehicle, we performed a form and functional decomposition of the key features that enable autonomous driving.

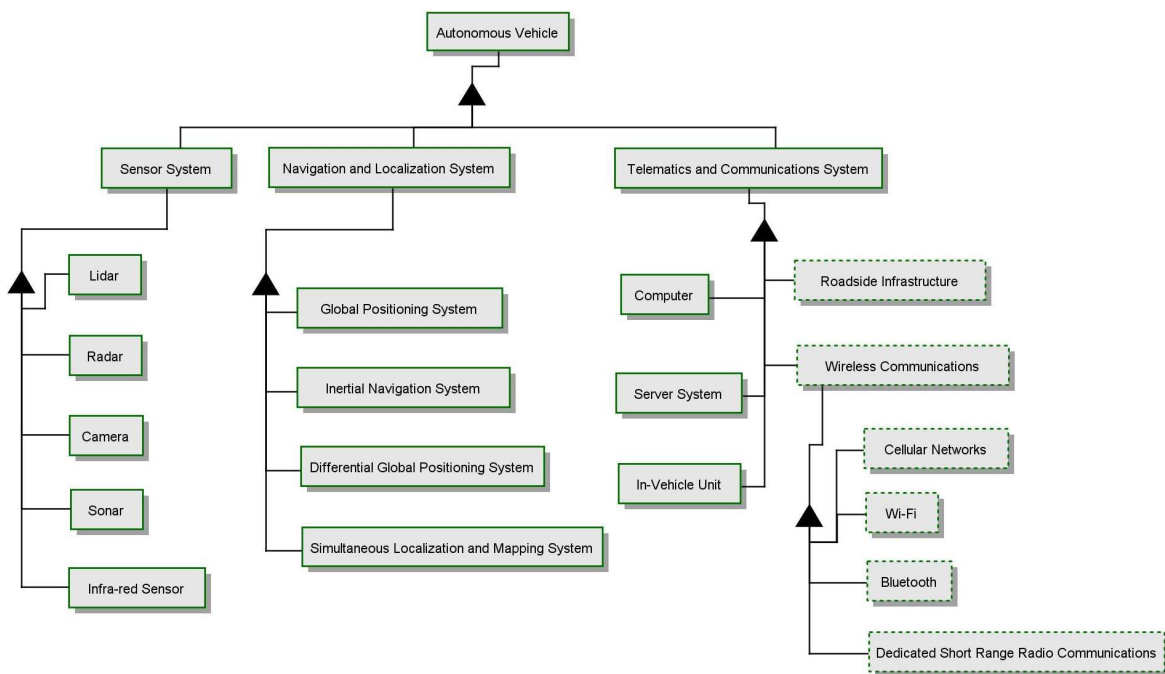


Figure 5.1: Form Decomposition of an Autonomous Vehicle

Figure 5.1 and **Figure 5.2** illustrate a simplified form and functional decomposition of the key features of an autonomous vehicle respectively. To achieve an operational fully autonomous vehicle, we postulate that most, if not all of the functions highlighted in **Figure 5.2** must be technologically mature and present in the system.

³⁹ <http://dictionary.cambridge.org/dictionary/english/technology>

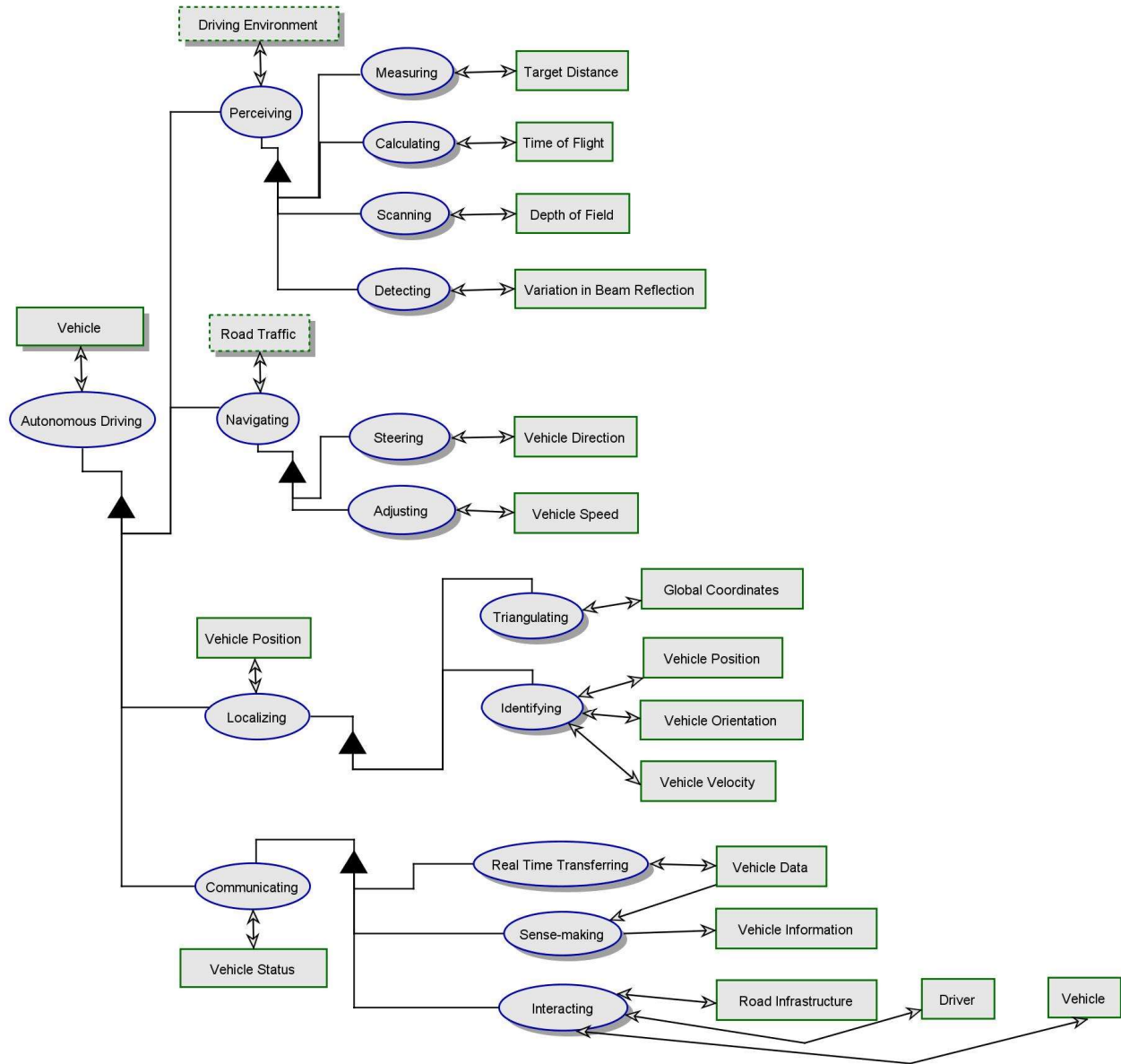


Figure 5.2: Functional Decomposition of the Key Features in an Autonomous Vehicle

5.3 Technology Enablers for Autonomous Vehicle Capabilities

A convergence of sensor technologies and connected vehicle communications is a key enabler for realization of fully autonomous vehicles. This section discusses the technologies involved to allow the autonomous vehicle to perceive, navigate and localize itself, and how it interacts with other vehicles and road infrastructure through telematics and data communications. At this juncture of development, it appears that there are many

possible technological pathways, and the ideal combination of sensor and communications technologies is still unclear. It is largely dependent on the type of environment, intended capabilities of the autonomous vehicle, and redundancies required to be designed in the system. Cost is also a practical constraint, and is driven by the physical and computational complexity necessitated by the automated driving features.

5.3.1 Perception

Perception refers to the ability of the autonomous vehicle to sense the complex and dynamic driving environment which can include elements such as: (1) Other vehicles on the road, (2) Other road users or road obstacles, (3) Varying weather conditions, (4) Varying terrain conditions, and (5) Traffic events including congestion and accidents. Each sensor technology has its strengths and limitations, hence an autonomous vehicle is typically installed with a suite of different types of sensors to complement each sensor's performance, coupled with a sensor fusion software to enable the vehicle to see and sense-make in different environments. According to an analysis by Yole Développement⁴⁰ in 2015, a vehicle may have up to 32 units of nine different types of sensors, depending on the level of autonomy.

Light Detection and Ranging (Lidar)

Lidar is an optical remote sensing technology that measures the distance to a target by using a laser range finder that emits electromagnetic energy (in the visible or near infrared wavelengths), and calculates the time of flight until a reflection is returned by the objects in the environment. Lidar was traditionally used as an airborne system for terrain mapping and surveying due to its superior performance in accurately mapping surroundings. Since then, vehicular-borne units have been developed and used for the adaptive cruise control system in automobiles. Lidar applications have also expanded to include autonomous vehicles to detect the presence of objects in the surroundings and determine its location in the path of travel.

⁴⁰ http://www.yole.fr/AutonomousVehicles_TechnologyFocus.aspx#.V6PCBLgri2w

An example is the Velodyne HDL-64E Lidar that was developed during the DARPA Grand Challenges and is also used in the Google Car. By mounting the Lidar unit on the roof of the car, the 64 lasers provide an unobstructed 360-degree view of the surroundings. To produce complete point clouds, each laser emits as many as 100,000 laser pulses per second. In large Lidar systems such as the HDL-64E, the 64 lasers (or channels) enable the system to generate more than a million data points per second. While 64 stationary channels can produce very clear resolution in focused areas, they are still insufficient to map an entire environment. More channels can be added, but that will escalate the cost almost exponentially. Therefore, another strategy is to place the sensors on rotating assemblies to sweep around the environment, coupled with appropriate angling of each emitter and receiver to maximize the field-of-view. In the case of the HDL-64E, the Lidar can see the top of an object that is 12 meters tall, from 50 meters away⁴¹.

Lidar has a moderate range of 80 to 100 meters and given that the wavelength of light is 100,000 times smaller than radio wavelengths, it can have a much higher resolution as compared to Radar. Lidar is claimed to be superior among the perception sensors in terms of generating a 360-degree horizontal field-of-view depth map of the environment and reflecting non-metallic surfaces such as pedestrians. Additional object information, such as the velocity or material composition, can also be determined by measuring the induced Doppler shift in the reflected signal.

However, Lidar technology is limited by its reflectivity against certain kinds of materials (detects black asphalt up to a range of 50 meters). In the case of highly reflective surfaces, the light is reflected coherently away from the sensor, resulting in an incomplete point cloud for that area. Vertical resolution remains a challenge, and in order to achieve adequate vertical pixel density, the vertical field-of-view is limited to about 26 degrees, hence preventing the system from detecting objects directly in front of the vehicle⁴². Current mechanical Lidar units also have a large physical footprint, high reliance on

⁴¹ http://www.robotictrends.com/article/what_is_lidar_and_how_does_it_help_robots_see

⁴² <http://www.sensorsmag.com/automotive/automotive-fusion-combining-legacy-and-emerging-sensors-19687>

moving parts and a high cost (approximately \$80,000 for a Velodyne HDL-64E). Lidar technology may also underperform in less ideal environments such as rain, snow, and fog.

The high capital and maintenance cost of mechanical Lidar could potentially inhibit mass adoption. To overcome this, a newer technology based on solid-state sensors is being developed. A solid-state Lidar is essentially a Lidar on a microchip. At the recent International Consumer Electronics Show 2016, Delphi Automotive and Quanergy - an automotive start-up based in California announced that they are developing a solid-state Lidar system that does not have any moving parts and is expected to cost \$250 or less at production volume level. The leading player in the Lidar market, Velodyne has also introduced a solid-state Lidar known as the Ultra Puck Auto⁴³ that is expected to cost about \$500 in mass production.



Figure 5.3: Examples of (a) Mechanical Lidar and (b) Solid-State Lidar Sensor (Sources: Velodyne for (a) and Quanergy for (b))

Radio Detection and Ranging (Radar)

Another key sensor used in autonomous vehicles is Radar. Radar uses a transmitter that radiates radio waves, and a receiver that collects the waves reflected off an object. By detecting changes in the reflected wavelengths, Radar leverages the Doppler Effect to accurately calculate the velocity of objects. The detection ability of Radar is largely

⁴³ <http://www.connectorsupplier.com/driverless-cars-shrink-lidar-technology/>

dependent on the strength of the reflection, influenced by the size of the object, distance and absorption characteristics, the reflection angle, and the strength of the original transmission. Radars can be broadly categorized according to their operating range⁴⁴:

(1) Short-range Radars operate in the 24 GHz range and usually require a large bandwidth of 3-5 GHz. They typically operate in a pulsed mode and have a maximum range of detection of up to 30 meters and a wide angular coverage of $\pm 65^\circ$ to $\pm 80^\circ$. Short-range Radars are commonly used for driver-assist applications such as collision warning and blind spot monitoring.

(2) Mid-range Radars also operate in the 24 GHz range but use a narrower bandwidth of around 200 MHz. They typically operate in a continuous wave mode and have a maximum range of detection of about 70 meters and an angular coverage of $\pm 40^\circ$ to $\pm 50^\circ$. Due to its low bandwidth, mid-range Radars have a low range resolution and are primarily used for lane-change assist applications.

(3) Long-range Radars operate in the 76-77 GHz range, in a continuous wave mode, and are usually used in adaptive cruise control systems because of their long range of detection up to about 200 meters.

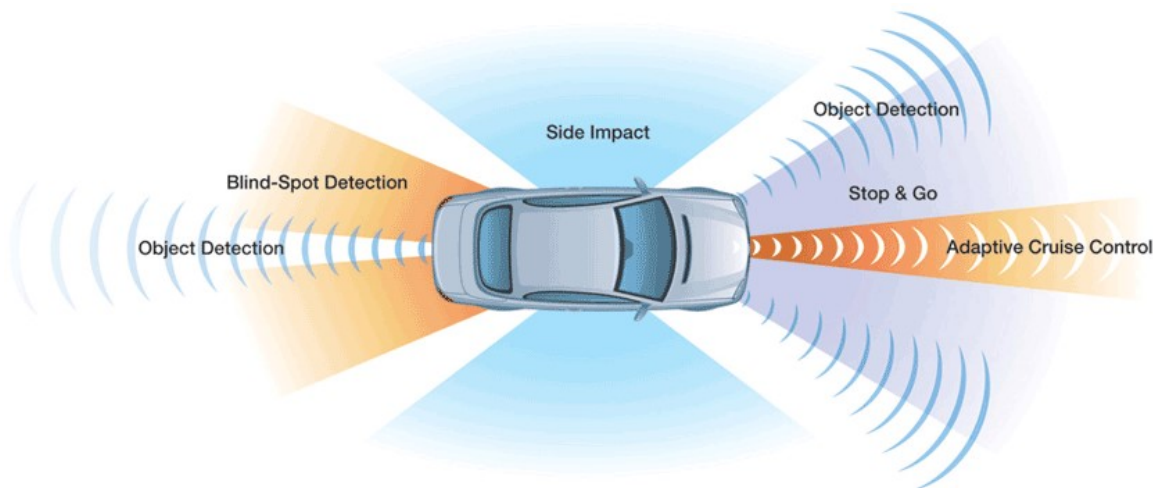


Figure 5.4: Applications of Automotive Radar

(Source: <http://www.nxp.com/pages/automotive-radar-millimeter-wave-technology:AUTRMWT>)

⁴⁴ <http://physastro.pomona.edu/wp-content/uploads/2016/07/Jerry-Martinez-Thesis-FINAL.pdf>

Unlike Lidar, Radar is largely immune to the challenging environmental conditions such as fog, rain, wind, darkness, and glaring sun, as it uses microwave energy. Radar works well on metallic objects such as vehicles, and is able to accurately monitor the speed of surrounding vehicles in real time. Together with the on-board inertial measurement system, the autonomous vehicle is able to timely and accurately accelerate or apply braking in response to the surrounding driving environment.

However, Radar alone is unable to detect non-metallic objects, such as pedestrians. Moreover, due to physical constraints on the size of the transmitter and receiver so as to fit into a vehicle, automotive Radars are limited by their angular resolution, field-of-view, and range. The limited angular resolution means that it is unable to resolve small details of objects to aid in object identification e.g., distinguishing between a lamp post and a human. There is also trade-off in terms of range and the field-of-view. In high-speed highway traffic, a long range is necessary to detect objects about 200 meters away in the surroundings; however, this results in a narrower beam width that looks at objects directly in front of the car, and may miss the vehicles or objects in the adjacent lanes. Therefore, in an automotive application, a suite of short and long range Radars is typically used to provide both early detection and close-range detection.

In the past, Radars are based on multiple gallium-arsenide chips to generate, amplify, and detect the microwave signals. With advancement in semiconductor technologies, silicon-germanium chips enable Radars to be manufactured at a lower cost, with smaller footprint, operate at a higher frequency, with a lower power consumption⁴⁵. The first commercial silicon-germanium automotive Radar chips which ran at 77 GHz was produced by Infineon. To accommodate the increasing automotive safety applications, there has also been plans to move away from the 24 GHz band, towards an ultra-wide band Radar system operating at 79 GHz, with wider bandwidth for automotive Radars⁴⁶. Developments are also underway to improve the ability of the Radar to distinguish a human from a lamp post by: (1) Increasing the Doppler sensitivity of the Radar such that

⁴⁵ <http://spectrum.ieee.org/transportation/advanced-cars/longdistance-car-radar>

⁴⁶ <https://itunews.itu.int/en/3935-Future-trends-for-automotive-radars-Towards-the-79GHz-band.note.aspx>

it can determine which of the object is advancing (human) and which is stationary (lamp post), and (2) Improving the Kalman filtering method⁴⁷.

Cameras

The first generation of automotive vision safety systems is largely based on a single camera, also known as monocular vision systems. The monocular system is effective in mitigating front collisions and inadvertent lane departures, and is relatively inexpensive as compared to Lidar and Radar sensors. However, monocular systems are limited by their ability to provide range perception.

Stereoscopic vision systems are advantageous over monocular vision systems in that they are able to provide depth information. Analogous to the human binocular vision, a stereo camera has two or more lenses to obtain three-dimensional information from two or more views of the environment. The location of the objects and their distances in the environment can then be estimated. Detailed depth maps derived from stereoscopic vision enable terrain mapping, generic obstacle, and debris detection⁴⁸. However, a stereo camera is more expensive than a monocular vision system.

Cameras allow for color vision (e.g., traffic lights) and can detect visible messages such as street signs and road markings. Like all vision-based systems, the performance of monocular and stereoscopic vision systems is limited by low or no lighting, glare, dirt, and adverse environmental conditions.

Nonetheless, cameras are an important component enabling the development of driver safety applications such as the automatic emergency braking system⁴⁹, and proactive pedestrian protection system. In driver-assist scenarios, cameras can also be installed

⁴⁷ <http://spectrum.ieee.org/transportation/self-driving/how-we-gave-sight-to-the-mercedes-robotic-car>

⁴⁸ <http://www.sensorsmag.com/automotive/automotive-fusion-combining-legacy-and-emerging-sensors-19687>

⁴⁹

http://www.boschmediaservice.hu/sajtokozelemenye/Bosch_vezsekezes_videoszenzorral_2015_majus_HU
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within the vehicle as part of face detection system to monitor signs of attention diversion or fatigue in the driver.



Figure 5.5: Examples of (a) Monocular Vision System and (b) Stereoscopic Vision System
(Source: Bosch, 2016)

Sound Navigation and Ranging (Sonar)

At very short ranges (1 to 10 meters), ultrasonic sensors or Sonar outperform the other perception technologies. They have been used in back-up safety systems on trucks for decades, and are now used in parking-assist systems. Ultrasound is an acoustic wave with a high frequency (above 20 kHz) beyond human hearing. By calculating the distance and/or direction of an object from the time it takes for a sound wave to travel to the target and back, Sonar sensors are useful for detecting obstacles in the proximity when parking. For automotive applications, these sensors typically operate at 48 kHz or 58 kHz and provide relatively reliable measurements for distances between 15 centimeters to six meters⁵⁰, supported by adequate signal processing techniques.

However, as Sonars can only operate in a medium, unlike electromagnetic waves, the sensing capabilities are more susceptible to changes in the environment such as temperature and humidity. With the development of the vehicle towards higher levels of autonomy, research is in progress to extend the range of the ultrasonic sensor to about eight meters, for applications in automatic emergency braking system against forward obstacles⁵¹.

⁵⁰ <https://www.pddnet.com/article/2014/10/ultrasonic-sensors-push-limits-automotive-applications>

⁵¹ <http://www.mitsubishielectric.com/bu/automotive/products/ultrasonic-sensor/index.html>

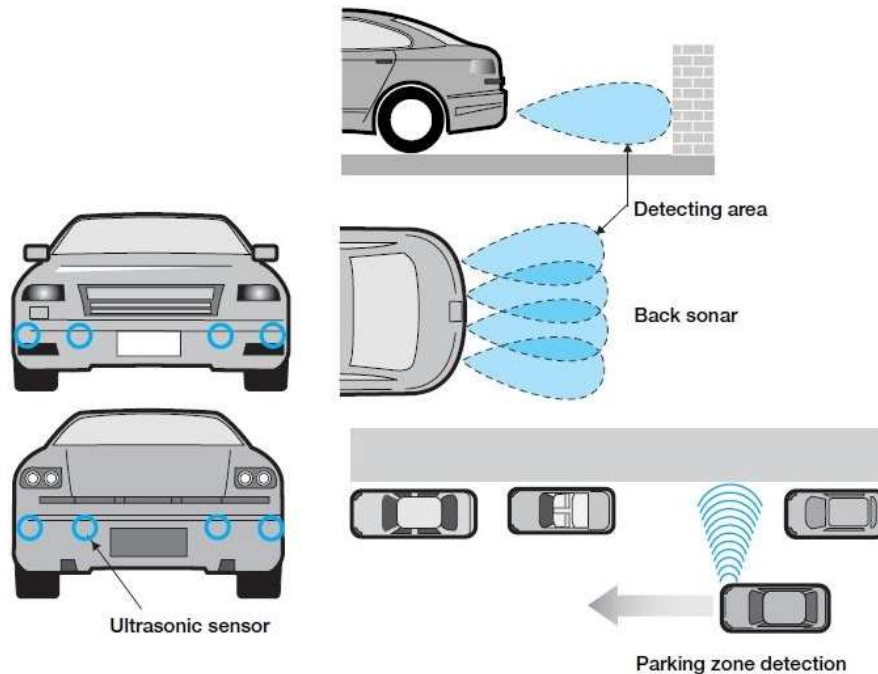


Figure 5.6: Applications of Ultrasonic Sensor or Sonar

(Source: <http://www.newelectronics.co.uk/electronics-technology/an-introduction-to-ultrasonic-sensors-for-vehicle-parking/24966/>)

Infrared Sensor System

Night vision systems have been available in some vehicles since the early 2000s. These systems use either infrared or thermographic cameras to scan the road ahead in poor visibility conditions, for people or animals, and alert the human driver. By integrating far-infrared sensors onto the vehicle, a heat map of the surroundings can be generated. In environments where a person is significantly warmer than the ambient night air, the far-infrared sensors can highlight the individual and enable pedestrian detection algorithms to easily detect him or her.

However, far-infrared sensing has its limitations. In warm climates and summer months, the difference in temperature between the person and the environment is often too small to be detected by these sensors. Similarly, if an individual has been outside for a long period of time, the difference in temperature may be less apparent. Bulky clothing and gloves can also distort the shape of an individual or hide the thermal disparity between

the person and the ambient air. These challenges, coupled with the low resolution of far-infrared sensors, complicate the effectiveness of pedestrian detection algorithms.

Current lane departure warning systems in some vehicles use infrared sensors to enable detection of lane departures. The infrared sensors are mounted under the front bumper of the vehicle to identify the lane markings on the roadway. Each sensor contains an infrared light-emitting diode and a detection cell. The sensors detect the variations in the reflections from the infrared beams emitted by the diode onto the road. When the vehicle moves over a lane marking, the system detects a change and alerts the driver if the indicator signal has not been used⁵².

In addition, infrared cameras are also used within the vehicle for drowsy driver sensing, which monitors the driver's eyelids to tell whether they are blinking rapidly, indicating that the driver is alert; or blinking slowly or even closing. The vehicle then sends an audible warning to the driver or a vibratory signal to the driver's seat⁵³.

5.3.2 Navigation and Localization

Navigation and localization work in tandem but there is a distinction between them. Navigational accuracy refers to the precision with which the autonomous vehicle can guide itself from one point to another, whereas localization accuracy is a measure of how well the vehicle localizes itself within a map.

Global Navigation Satellite System (GNSS) is an umbrella term that encompasses all global satellite positioning systems, that includes constellations of satellites orbiting over the Earth's surface and continuously transmitting signals that enables users to determine their position. A GNSS consists of three major segments: (1) Space segment, which are the satellites, (2) Ground segment, which are the ground control stations, and (3) User segment, which refers to the GNSS receivers.

⁵² <http://www.extremetech.com/extreme/165320-what-is-lane-departure-warning-and-how-does-it-work>

⁵³ <http://www.edn.com/design/automotive/4368069/Automobile-sensors-may-usher-in-self-driving-cars>

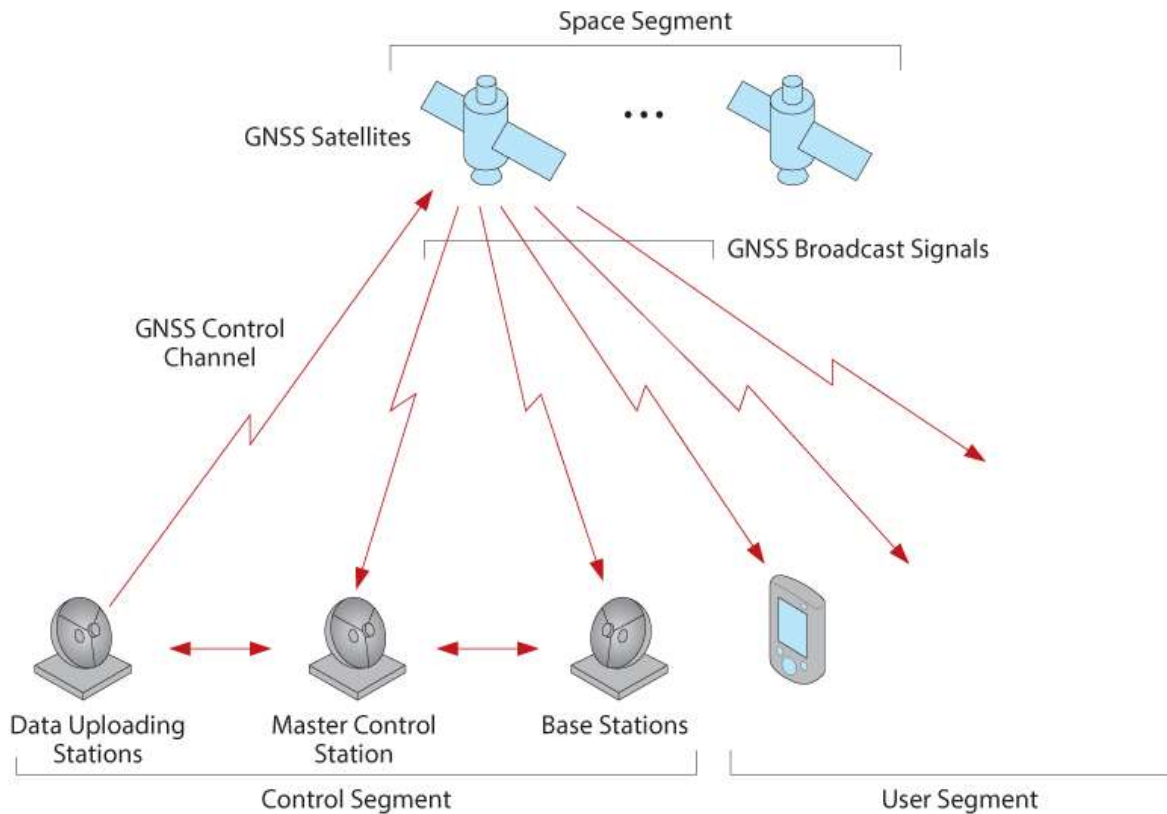


Figure 5.7: Global Satellite Navigation System Architecture
 (Source: Novatel⁵⁴, 2016)

The operating principle of a GNSS is described as follows: (1) The satellites broadcast a signal that contains orbital data and the exact time the signal is transmitted, (2) The orbital data is transmitted in a data message that is superimposed on a code that serves as a timing reference, (3) The satellite uses an atomic clock to maintain synchronization of all the satellites in the constellation, (4) The receiver compares the time of broadcast encoded in the transmission with the time of reception measured by an internal clock, thereby measuring the time of flight to the satellite. The receiver measures the signals from several satellites at the same time and uses a method called triangulation to determine its location by measuring the angles to it from two known points. Four parameters are being computed by the receiver: latitude, longitude, altitude, and time. In general, the receiver needs at least four satellites to calculate the four parameters, although estimation will be used in scenarios where there are fewer satellites⁵⁵.

⁵⁴ http://www.novatel.com/assets/Intro-to-GNSS/Figs/_resampled/ResizedImage300225-Figure-2.png

⁵⁵ <https://linxtechnologies.com/blog/beginners-guide-satellite-navigation-systems/>

As of June 2016, there are two operational GNSS: (1) NAVSTAR Global Positioning System (GPS), the world's first GNSS that was launched in the late 1970s by the US Department of Defense, using a constellation of 31 operational satellites⁵⁶ to provide global coverage, and (2) GLONASS, using a constellation of 24 satellites and is operated by the Russian government. There are two other GNSS that are under development: (1) Galileo, a civil GNSS operated by the European Global Navigation Satellite Systems Agency, with a full constellation of 27 satellites planned to be deployed by 2020, and (2) Compass, a second generation of the regional BeiDou satellite navigation system, expected to be completed by 2020 with a full constellation of 35 satellites⁵⁷.

In addition, there are also three regional systems: (1) BeiDou-1, a Chinese navigation satellite system consisting of three satellites providing regional service since December 2012, (2) IRNSS, the Indian Regional Navigation Satellite System that provides service to India, using a constellation of seven satellites, expected to be operational by late 2016⁵⁸, and (3) QZSS, the Quasi-Zenith Satellite System that provides service to Japan and the Asia-Oceania region, expected to be operational by 2018.

The current accuracy of a GNSS system is about 10 meters, and the error increases with obstacle or terrain occlusion. In urban areas with high-rise buildings, the skyscrapers often create "urban canyons" that severely limit the GNSS' availability. To mitigate against intermittent GPS signal outages and disruption in signal transmission path when the satellite is not in line-of-sight, the GNSS is typically coupled with the Inertial Navigation System (INS) for vehicle navigation. The INS comprises gyroscopes and accelerometers to provide continuous computation of the vehicle's position, orientation, and velocity without the need for external references. However, a shortfall in INS is the drift, which can result in significant differences between the calculated position and the true position.

⁵⁶ <http://www.gps.gov/systems/gps/space/>

⁵⁷ <http://www.novatel.com/an-introduction-to-gnss/chapter-1-gnss-overview/section-1/>

⁵⁸ <http://tech.firstpost.com/news-analysis/isro-puts-seventh-and-final-irns-navigation-satellite-into-orbit-311968.html>

An enhancement to the GNSS is the Differential GNSS (DGNSS). The DGNSS is derived from the principle that any two GNSS receivers that are relatively close together will experience similar atmospheric errors. Therefore, DGNSS requires for a GNSS receiver be set up on a precisely known location, and this GNSS receiver will serve as the base or reference station. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is then applied to the GNSS data recorded by the second GNSS receiver, which is known as the roving receiver. The corrected information can then be applied to data from the roving receiver in real time in the field using radio signals or through post processing after data capture. DGNSS claims to be able to improve location accuracy from 10 *meters* to about 10 *centimeters*. It is believed that decimeter accuracy in high-definition maps is required for the safe navigation and localization of autonomous vehicles⁵⁹.

Currently, before a self-driving car is tested, a regular car is driven along the route to map out the route and road conditions including poles, road markers, and road signs. This map is fed into the car's software to help the car identify the "regular" parts of the road. Subsequently as the self-driving car moves, the on-board Lidar scans and generates a detailed three-dimensional map of the environment, based on a process known as Simultaneous Localization and Mapping (SLAM). The car then compares this map with the pre-existing map to figure out the non-standard aspects on the road, such as pedestrians and other cars, and responds by avoiding them.

While SLAM has proven to be the current state-of-the-art technology for generating three-dimensional maps, a key challenge is the resources and cost required to map the entire city or country, to provide the level of map details that autonomous vehicles need for safe operation. As of February 2015, Google has mapped approximately 2,000 miles of road, but there are more than 170,000 miles of road in California alone, or more than four million miles of public roads in the United States.

⁵⁹ <http://www.wired.com/2014/12/nokia-here-autonomous-car-maps/>

5.3.3 Communications and Sense-Making

With the voluminous data collected through perception, navigation, and localization technologies, autonomous vehicles need to sense, plan, and react accordingly with little or no intervention from the human as the level of autonomy increases. Artificial intelligence plays a key role in the sense-making and learning from the amassed data to generate useful information to guide decision-making on the next course of action that the vehicle should take. In the case of a highly automated or fully autonomous vehicle, there will be scenarios where there is no steering wheel available for the human, or there will not even be a human in the vehicle in some parts of the journey. Besides intra-vehicle communications and human-machine interactions between the human with the vehicle, the vehicle also needs to interact with the external infrastructure and surrounding driving environment.

Artificial Intelligence

The term “Artificial Intelligence” or AI in short, was coined at the Dartmouth conference on artificial intelligence by computer scientist, John McCarthy in 1956. According to literature, AI started with a dream of constructing complex machines enabled by emerging computer technologies that possess the same characteristics of human intelligence⁶⁰. Since the inception of AI, new terminologies associated with subsets of artificial intelligence have emerged over the years, from machine learning to deep learning.

In simplified terms, machine learning refers to the practice of using algorithms to parse data, learn from it, and then make a determination or prediction about something. Generally, machine learning algorithms are classified into three main groups, namely:

(1) Supervised Learning – which are algorithms that learned by example, trying to approximate a specific function. The training dataset usually includes labels (i.e., the required output) and the model will try to converge to the required functionality. Pattern recognition is an example of supervised machine learning.

⁶⁰ <https://blogs.nvidia.com/blog/2016/07/29/whats-difference-artificial-intelligence-machine-learning-deep-learning-ai/>

(2) Unsupervised Learning – in contrast to supervised learning, the desired output is not provided to the model hence increasing the difficulty level of the task of differentiation. These algorithms are typically used in clustering tasks to sort and separate huge unlabeled datasets. Combinations of labeled and unlabeled data have also been used to enhance the classification accuracy.

(3) Reinforcement Learning – this set of machine learning methods deals with training agents, which are algorithms designed to take specific actions in various environments. The agent's behavior is optimized through feedback given to the system after each action, and through exploration of the possible scenarios, it is expected that the agent will converge to an optimal behavior that maximizes future benefit.

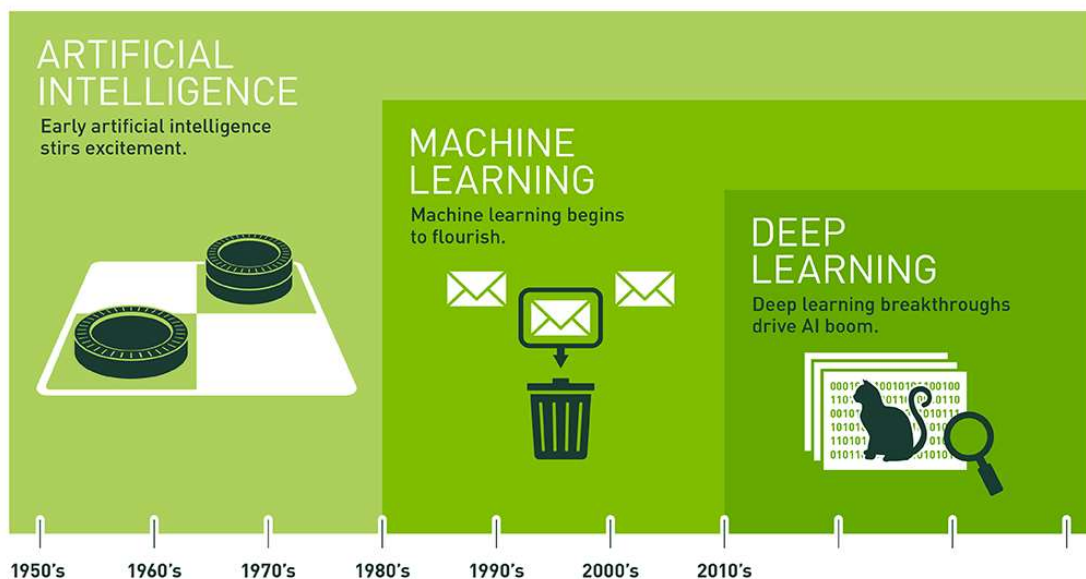


Figure 5.8: Artificial Intelligence, Machine Learning, and Deep Learning (Source: Nvidia, 2016)

Since the 1980s, various algorithmic approaches in machine learning have been developed, and include decision tree learning, inductive logic programming, clustering, reinforcement learning, and Bayesian networks. These approaches have been instrumental in various applications such as computer vision developments.

One of the challenges associated with traditional machine learning models is the need for the programmer to tell the computer exactly what kinds of things it should be looking for

that will be informative in decision-making, also known as feature extraction⁶¹. As such, the algorithm is only as effective as how it has been programmed. Deep learning offers a possibility to circumvent this as they are capable of learning by themselves with little guidance from the programmer.

Deep learning is inspired from neural networks, and the basic unit of a neural network is the neuron. A perceptron can be considered as a simplified version of a biological neuron. The perceptron will take several inputs and weigh them according to the importance to the output decision and produce a single output. A neural network learns by training, using an algorithm known as backpropagation, and the margin of error between the input and the ideal output is reduced over time by repeating this process. There are several neural architectures in deep learning, and the more common ones include: (1) Convolutional Neural Network which utilizes numerous identical replicas of the same neuron, and has found useful applications in object recognition and image tagging, (2) Recurrent Neural Network that assumes all inputs and outputs are independent of one another and are reliant on preceding computations, and (3) Recursive Neural Network that is generated by applying a fixed and consistent set of weights recursively and has been used in natural language processing for sentiment analysis⁶².

Telematics

Telematics is generally used to describe the transfer of data to and from a moving vehicle in real-time, and forms the foundation for autonomous vehicles to continually update the state of the environment that the vehicle is in. Connected vehicles refer to vehicles that use a number of different communication technologies to communicate with the driver, other cars on the road (also known as Vehicle-to-Vehicle, V2V), roadside infrastructure (also known as Vehicle-to-Infrastructure, V2I), and the “Cloud”. Most sensing, navigation, and localization technologies require line-of-sight connectivity, therefore telematics and Vehicle-to-Everything (V2X) communications can be used to augment these services to

⁶¹ <http://www.kdnuggets.com/2015/01/deep-learning-explanation-what-how-why.html>

⁶² <http://blog.aylien.com/10-deep-learning-terms-explained-in-simple-english/>

provide always available positioning⁶³. This section highlights the communications technologies that could potentially be used for autonomous vehicle applications.

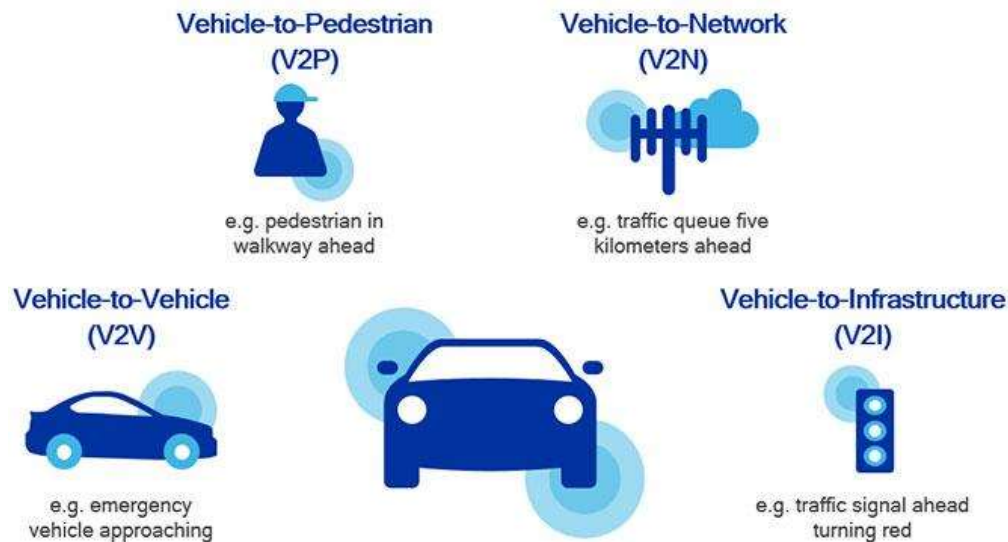


Figure 5.9: Vehicle-to-Everything (V2X)
(Source: Qualcomm, 2016⁶⁴)

Cellular Networks

Most people are familiar with 3G and 4G. The “G” actually refers to the generation of wireless technology. 1G was analog cellular while 2G was the first generation of digital cellular technologies that includes Global System for Mobile Communications (GSM), Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA). 3G technologies then increased the speed from 200 kilobits per second to a few megabits per second, and 4G technologies further scaled up the speed to hundreds of megabits per second with lower latency⁶⁵.

Specifically, the high bandwidth and low latency of 4G Long Term Evolution (LTE) are expected to enable high-definition audio and video streaming, allow for real-time video diagnostics, and provide more accurate real-time traffic information. 4G LTE also opens

⁶³ http://www.auto-talks.com/wp-content/uploads/2016/06/V2X_Communication_for_Autonomous_Driving_Technical_Brief.pdf

⁶⁴ <https://www.qualcomm.com/news/onq/2016/06/07/path-5g-paving-road-tomorrows-autonomous-vehicles>

⁶⁵ <http://www.pcmag.com/article/345387/what-is-5g>

up the possibility of proximity communication with nearby devices, where in the short term, drivers can pick up information about road conditions and share content with other drivers. In the longer term, 4G LTE appears to be an attractive candidate to enable the development of V2V communications, which can improve road safety and contribute to the development of the autonomous vehicle.

For example, in January 2016, Ford announced that it is planning to connect more than 10 million customers to SYNC Connect with AT&T's high-speed 4G/LTE connectivity. The AT&T network service has been a standard feature in all Ford plug-in electric vehicles, including Ford Focus Electric, Fusion Energi and C-MAX Energi. SYNC Connect plays a key role in Ford's connectivity strategy as part of Ford Smart Mobility, a plan to attain the next level in connectivity, mobility, autonomous vehicles, customer experience, and data analytics.

With the surge in demand for greater connectivity arising from Machine-to-Machine services and the Internet of Things, it is postulated that the next generation of cellular technologies, 5G, will allow for higher coverage and availability, and higher network density in terms of devices. Specifically, for autonomous vehicle applications, it is claimed that if all the vehicles on the road are connected to a network incorporating a traffic management system, they could potentially travel at a higher speed with greater proximity of each other without risk of an accident. While high bandwidth is not required, providing data with a response time close to instantaneous would be crucial for safe operations. Therefore, it is envisaged that reliability and low latencies (a reduction in delay down to milliseconds) are key requirements for a viable proposition for 5G as an enabler of connected autonomous driving (Warren, D., and Dewar, C., 2014).

Short-range Communications

In the United States, Dedicated Short-Range Communications (DSRC) is used as a synonym for Wireless Access in the Vehicular Environment (WAVE). DSRC operates on a 5.9 GHz frequency, using standards such as SAE J2735 and IEEE 1609 suite that define the message protocols and structures. DSRC is reliable with a fast network

acquisition and low latency, and appears to be one of the most promising communications technology for autonomous vehicle applications. The US Federal Communications Commission has allocated a dedicated 75 MHz spectrum band around 5.9 GHz for automotive use, as well as to support vehicle safety applications that require nearly instantaneous communications (Anderson, J.M., et al, 2016). In the European context, DSRC refers to the 5.8 GHz system developed by the European Committee for Standardisation’s Technical Committee TC278 Working Group 9 and used for tolling systems worldwide.

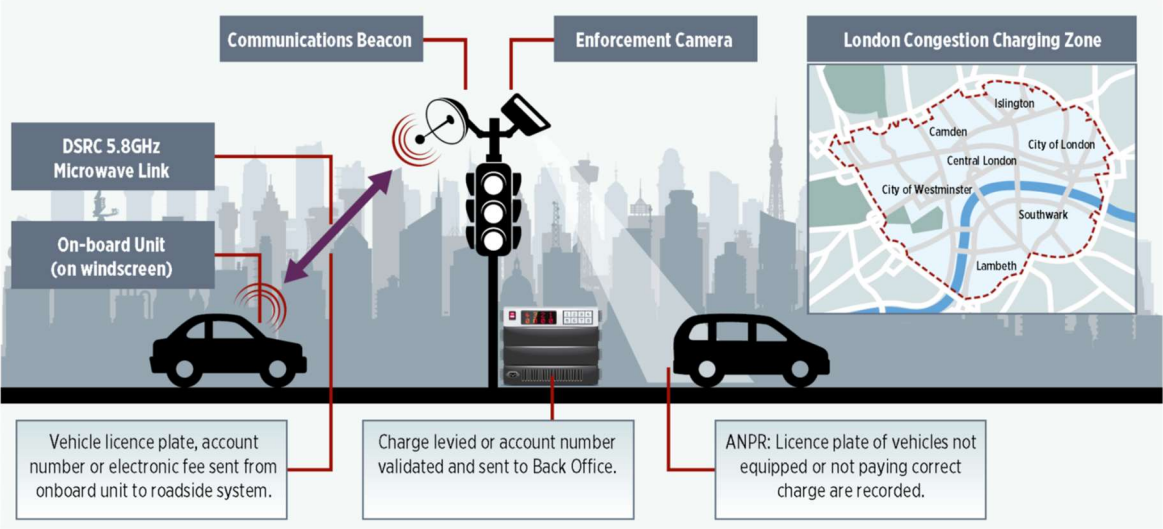


Figure 5.10: DSRC for Tolling System Applications
(Source: GSMA, 2015)

DSRC can enable V2V and V2I. An example of DSRC for autonomous vehicle application is in the Delphi Automotive PLC’s automated vehicle, which was showcased at the Consumer Electronics Show 2016. The vehicle used DSRC to recognize the status of traffic lights and to anticipate yellow and red lights. While it will take a while for V2V to be widely adopted after a substantial number of vehicles on the road are equipped with built-in DSRC systems, V2I has been around for some time in electronic toll collections (Walker, J., 2015). Some proponents of 5G technologies also viewed DSRC as a potential backup communications technology to cater for redundancy in autonomous vehicles⁶⁶.

⁶⁶ <http://www.forbes.com/sites/huawei/2016/06/21/why-5g-leads-format-war-over-which-tech-will-control-autonomous-cars/#15c5ec85798c>

Bluetooth

Bluetooth is a wireless technology standard for exchanging data over short distances from fixed and mobile devices, creating personal area networks. Specifically, Bluetooth is a collection of communication modules or profiles that defines how a particular feature operates or how paired devices communicate with each other. Examples of such profiles include: Hands-free profile, Phone Book Access profile, Advanced Audio Distribution, Audio/Video Remote Control profiles for audio streaming, Message Access profile to display or read aloud incoming messages by a text-to-speech system, and Secure Simple Pairing for secure pairing of the mobile phone with a Bluetooth speakerphone or headset⁶⁷. While the primary use of Bluetooth is currently for hands-free communications and infotainment applications, it may be used as part of roadside infrastructure to collect vehicle data in the future⁶⁸.

Wi-Fi

Wi-Fi is a protocol standard for short-range wireless communications and typically occupies the 2.4 GHz and 5 GHz bands. Unlike cellular networks, Wi-Fi is location-based, hence is limited in range, but is typically faster than cellular data⁶⁹. Wi-Fi can possibly be used for V2V communications to exchange vital safety and performance data when the two vehicles are located in close proximity of each other. However, the projected increase in Wi-Fi hotspots and wireless mesh extensions could result in intolerable and uncontrollable levels of interference that may hamper the reliability and effectiveness of active safety applications for autonomous vehicles.

5.4 TRL Assessment of Autonomous Vehicle Capabilities

Using the available literature on the research and development of autonomous vehicle technologies, as well as understanding of the TRL scale, we perform an assessment on the technology readiness level of the autonomous vehicle capabilities.

⁶⁷ <https://www.cnet.com/roadshow/news/what-can-bluetooth-do-besides-make-calls-abcs-of-car-tech/>

⁶⁸ <http://www.its-ukreview.org/trl-and-its-uk-its-student-prize/>

⁶⁹ <http://www.boingo.com/faq/what-is-the-difference-between-wi-fi-and-cellular-data-3g-and-4g-2/>

5.4.1 Adaptive Cruise Control

The first modern cruise control system was invented by Ralph Teetor in 1948 with the intent to design a device that can control the speed of a car automatically. In 1958, the Chrysler Imperial, New Yorker, and Windsor models were incorporated with the cruise control feature. The conventional cruise control maintained a speed set by the driver by adjusting the throttle position.

Today, the conventional cruise control system continues to evolve, into what is known as the Adaptive Cruise Control (ACC) and more recently, the Stop and Go Cruise Control. The ACC aims to assist the driver in keeping a safe distance from the preceding vehicle. The working principle of ACC is based on detection of distance, speed, angular position, and lateral acceleration of the preceding vehicle using a Lidar or Radar sensor. The sensor data is then processed to generate commands to the actuators of the engine throttle and brakes using the control area network of the vehicle. When a slower moving vehicle is detected, the ACC will slow the vehicle down to maintain the clearance between the ACC vehicle and the preceding vehicle. When the preceding vehicle is no longer in the path of the ACC vehicle, the ACC will accelerate back to the preset cruise control speed. The acceleration and deceleration are controlled via the engine throttle control and limited braking operation, without the need for driver intervention. However, such ACC systems are designed primarily for highway applications with considerably homogeneous traffic behavior (US DOT, 2015).

The Stop and Go Cruise Control is an enhancement to the ACC, to expand the application of adaptive cruise control to slow and highly congested traffic in the cities. An example of ACC with Stop and Go Cruise Control feature is the ACC from Delphi.

The ACC is a driver-assist feature and is insufficient to address the complex demands of a fully autonomous vehicle. As such, research on the next generation of cruise control, known as Cooperative Adaptive Cruise Control (CACC) is in progress. CACC presents the possibility of increasing traffic throughput without requiring construction of additional lanes. Direct radio communications between equipped vehicles (V2V) and roadway

infrastructure (V2I) allows vehicles to travel closer together and better inform drivers of the surrounding driving environment. The applications for CACC include bus or truck platooning and virtual carpooling. Besides improved road capacity, it is also postulated that CACC presents other benefits such as increased efficiency and reduced fuel usage.

It is assessed that the technology readiness level for the **adaptive cruise control** system is **TRL 8-9** as this feature is commercially available in selected luxury cars. For the **cooperative adaptive cruise control**, it ranges from **TRL 3 to TRL 5**, with The Netherlands Organization for Applied Scientific Research (TNO) being one of the forerunners in this area of research. At the European Truck Platooning Challenge in April 2016, it was reported that platoons of two to three trucks from Sweden, Germany and Belgium drove on the European motorways cooperatively to the Maasvlakte near Rotterdam. A number of truck manufacturers were claimed to be using the platooning technology developed by TNO in this small-scale demonstration.

5.4.2 Lane Departure Warning System and Lane-Keeping Assist System

The Lane Departure Warning System (LDWS) is claimed to be an effective countermeasure against road departure crashes, many of which are attributed to driver distraction or fatigue. Majority of the LDWS in the commercial market is based on image recognition technologies, which uses a camera to track the lane markings, performs analysis, and predict when a vehicle unintentionally drifts out of the travel lane. If the vehicle begins to deviate from the travel lane without a turn signal, the LDWS alerts the driver using audible, visual, and/or tactile cues. According to literature (US California DOT, 2007), the performance of image-recognition-based LDWS is heavily dependent on environmental and lighting conditions of the driving environment, as these factors can affect the visibility of the lane markings. Other technologies that are being researched on for LDWS include active wire guidance, laser, magnetic sensing, and differential GPS.

Lane-keeping or lane departure systems can be categorized according to the extent of automatic vehicle control that the system can perform. The LDWS is an example of a passive warning system that alerts the driver in the event of lane departures, but does not

intervene or control the vehicle trajectory. Some commercial products that fall under this category are: AutoVue by Iteris, SafeTRAC by AssistWare Technology, Forewarn by Delphi, and LDS by Mobileye.

Other more advanced lane-keeping systems are considered active systems because they can have the ability to affect the vehicle trajectory and augment driver commands (also known as “intervention system”), or even to assume full automatic control of steering the vehicle (“control system”). The passive warning system and “intervention system” are considered to be driver-assist features. To realize a fully autonomous vehicle, it is assessed that a “control system” type of lane-keeping system is necessary.

Currently, while there are some automobiles in the market that feature “intervention” or “control” type of lane-keeping system, it should be noted that that automated control and steering only operates for a few seconds to mitigate a crash (if possible) and the driver is still required to take over control for safe driving.

It is assessed that the technology readiness level for the **passive lane departure warning** system is **TRL 8** as this feature is commercially available and operational in expected conditions. To achieve TRL 9, the system has to address variances in environmental and lighting conditions in the driving environment such that it can still have visibility of the lane markings. For the **active lane-keeping assist** system, it is assessed to be at **TRL 5-6**, because while it has been proven to operate for seconds, the technology has not been demonstrated in an operational autonomous vehicle scenario where it needs to operate continuously throughout the driving journey.

5.4.3 Collision Avoidance System

The primary goal of a collision avoidance system is to prevent crashes by detecting a conflict, alerting the driver, and in more advanced systems, also aiding in brake application or automatically applying brakes. Each system typically comprises three modules: (1) A collision warning system to alert the driver via auditory, visual and/or haptic cues when there is a risk of rear-end collision, (2) A dynamic braking support to assist the

driver in emergency braking, and (3) An autonomous emergency braking that autonomously applies the brakes in order to prevent or mitigate a collision, if the driver fails to respond after receiving the warning.

A collision avoidance system operates by monitoring the driving environment using Lidar, Radar, cameras, or a fusion of different sensor technologies, for potential conflicts, such as a slow-moving or stationary vehicle. When this happens, the system alerts the driver through different warning cues. If the driver does not respond to the warning, or applies the brakes too slowly or too late, the system triggers the autonomous emergency braking. Given the time criticality in response, the effectiveness of the collision avoidance system relies heavily on the type of sensor technology used as well as the associated detection algorithms. The braking distance of different size and weight of vehicles should also be considered when designing the system.

Currently, most luxury car models come with an optional package for a collision warning system, while autonomous emergency braking is only available in limited models. Autonomous emergency braking is viewed to be one of the key enablers to ensure safety in a fully autonomous vehicle. However, results from a test (US NTSB, 2015) conducted by the US Insurance Institute for Highway Safety in 2013 seemed to suggest that the current state of technology of the autonomous emergency braking may not yet be as effective as intended. The test was performed on 13 passenger vehicles equipped with autonomous emergency braking feature, and only one tested vehicle managed to avoid the collision in both test conditions of 12 miles per hour (20 kilometers per hour) and 25 miles per hour (40 kilometers per hour). Although more than half of the tested vehicles were able to completely avoid a collision at 12 mph, there were several test vehicles that exhibited limited or no reduction in impact velocity in the 25 mph test (US NTSB, 2015).

It should be highlighted that current collision avoidance systems are designed to detect and react to potential collisions with another vehicle. In the context of a fully autonomous vehicle, the system needs to be able to detect and distinguish other potential conflicts, such as pedestrians, cyclists, animals, road works etc., in addition to other vehicles. It is

also interesting to note that some automotive manufacturers, such as Toyota, have incorporated a Pedestrian Detection capability as part of their collision avoidance system. By combining a millimeter-wave radar with a camera capable of shape recognition, Toyota claims that the system is able to detect pedestrians under certain conditions and applies automatic braking to prevent collision with a pedestrian.

It is assessed that the technology readiness level for the **collision warning module** (driver-assist feature) is at **TRL 8-9**, as it is commercially available and has been demonstrated to function as intended. As for the **autonomous emergency braking**, it is assessed to be at **TRL 7** as improvements are still being made to prove that the system can and will trigger as expected in the event of an imminent collision with another vehicle. Finally, the **collision avoidance system** for a fully autonomous vehicle is assessed to be at **TRL 4-5**, as there has been no representative model or prototype that can fully demonstrate the capability to detect and avoid collision with all potential road hazards in the driving environment.

5.4.4 Parking-Assist and Self-Parking

Active parking-assist is another feature that serves as a parking aid to driver when performing parallel parking. When the Park-Assist is activated, the system uses ultrasonic sensors and cameras to identify a suitable parking space. The driver then selects the reverse gear and releases his or her hands from the steering wheel. The system automatically steers the vehicle into the parking space while the driver is still required to control the accelerator, brakes, and gearshift. This feature is available in selected car models from manufacturers such as Ford and Volkswagen. However, there is a limitation to the current state of technology, as it may not work in heavy rain or other conditions that cause disruptive reflections. Ford also cautions that the sensors may not detect objects with surfaces that absorb ultrasonic waves.

Moving towards higher levels of autonomy, several companies involved in autonomous vehicle projects are looking into self-parking technology. Self-parking is broadly defined

as the vehicle being able to drive itself to a parking space when activated by the driver, and return itself to the designated location when the driver requests for a pick-up.

In early 2016, the Japanese automaker, Nissan, demonstrated a prototype of a mobile application that can automatically park a Nissan Leaf electric car without driver intervention. However, it is uncertain when a commercially viable product will be available. In Tesla's firmware version 7.1 for its Model S and Model X vehicles, it introduces the first iteration of "Summon", which can trigger the vehicle to park itself and shut down when activated, and also allow the driver to summon the car when required. As this "Summon" feature is still in the Beta phase, the firmware is continuously being updated, with the recent being addition of a driver input requirement to select the "Summon" direction prior to exiting the car when "Summon" is initiated by the Parking Brake.

Preliminary demonstrations of these technologies appear promising, but it will take some time before a robust and proven system is ready. The technology readiness level for the **active parking-assist** is assessed to be **TRL 8**, as it is proven to work under expected conditions. For the **self-parking capability**, it is assessed to be at **TRL 5-6**, where some manufacturers have attempted to demonstrate the capability in a simulated environment, while others have developed a representative model or prototype that is being tested in a small-scale environment.

5.4.5 Simultaneous Localization and Mapping

Simultaneous Localization and Mapping (SLAM) is the process of creating a map using an unmanned vehicle that navigates the environment while using the map that it generates. The SLAM framework was first developed by Hugh Durrant-Whyte and John L. Leonard in the early 1990s.

SLAM is an emerging field of research and promises greater flexibility and potentially better cost-effectiveness as compared to the traditional technology used in autonomous guided vehicles. In those vehicles, additional infrastructure such as embedded sensors, magnetic tracks, or beacons have to be pre-laid along the route to guide the vehicles as

it travels from one point to the other. The additional infrastructure translates to higher capital and operating costs, and limits the path of travel. This approach is more feasible for fixed route applications or within designated sites such as an industrial park or factory.

SLAM relates each new observation of the environment to previous observations by understanding how much the vehicle has moved or by recognizing features of the environment from new angles. As the map is built incrementally, the vehicle understands its position on the map and senses how to move within it efficiently. This process is iterative; and detection of environment landmarks is performed using sensors such as Lidar. Comparing the position of the same landmarks relative to different vantage points, the vehicle is able to determine its relative position to the landmarks, hence creating or updating the map based on these inputs.

A relevant example of SLAM application is the Google car. The vehicle is equipped with a Velodyne 64-beam laser range finder to generate a detailed three-dimensional map of the environment. It then combines the laser measurements with external high-resolution maps of roads and terrains to produce different types of data models that allows it to drive autonomously in compliance with traffic laws and avoiding obstacles. Google claims that the SLAM-based technique demonstrates superiority in terms of accuracy as compared to solely GPS-based techniques.

However, a caveat is that before sending the self-driving car on a road test, Google engineers have to drive along the route once or more times to gather data about the environment. Subsequently, when the autonomous vehicle drives itself, it will compare the data it is acquiring in real-time with the previously recorded data, to distinguish stationary objects (e.g., trees, buildings, and lamp posts) from moving objects (e.g., pedestrians). The labor effort to generate an initial map of the environment or to update the map when environment landmarks change may not be practical as we consider scaling up the development from small-scale test routes to the entire city, state, or country. Nonetheless, we acknowledge that three-dimensional mapping has far-reaching applications beyond autonomous driving; it can also be used for urban planning, urban

heat effect assessment, solar potential studies, flight safety assessment, terrains model studies for flood management, and carbon accounting using three-dimensional tree information.

Assuming if we are able to overcome the current challenge of three-dimensional mapping over huge landscapes, another area to consider will be the detailed map requirements that an autonomous vehicle need in order to navigate safely. It is uncertain at this point if the accuracy, precision, level of detail, extent of coverage, data model and format, currency and reliability of landmark data gathered by current three-dimensional mapping technologies are sufficient for the purpose of autonomous driving applications.

Therefore, it is assessed that the technology readiness level for **SLAM** is **TRL 3-4**, and it is likely to take a sufficiently longer period of time before the technology reaches maturity for transition to a full-scale development in an autonomous vehicle.

5.4.6 Embedded Deep Learning, Planning and Decision-making

The planning and decision-making module is the brain of a fully autonomous vehicle that is enabled by an integration of sensor data, embedded deep learning techniques, navigation controls, localization data, and communications. Katrakazas, C., et al (2015) defines three terms associated with autonomous driving: (1) Path Planning, (2) Maneuver Planning, and (3) Trajectory Planning.

Path planning refers to the process of finding a geometric path from an initial configuration to a given terminating configuration such that each configuration and state on the path is feasible. After finding the optimal geometric sequence of waypoints to follow, the vehicle needs to decide the best and safest maneuver, taking into consideration the interactions with the driving environment. This is termed as maneuver planning, where the vehicle must anticipate the behavior of the dynamic road elements, with current research focusing on: (1) Motion modelling and obstacle prediction, and (2) Decision-making based on modelling of the traffic environment. Thereafter, a trajectory that satisfies both kinematic

and motion model constraints is generated, and may be further optimized using geometric curves or model predictive controls.

Deep learning is entrenched in the planning process as the vehicle needs to continuously learn and update its understanding of the driving environment and interactions with other road users, vehicles, and infrastructure in a mixed-use road, such that it can intelligently ascertain the intention and behavior of other road users, minimize confusion, and mitigate potential accidents.

The accident between a Google autonomous vehicle and a human-driven bus in February 2016 epitomizes the importance of learning to achieve greater vehicle autonomy. In this accident, the Google car was travelling in autonomous mode eastbound on El Camino Real in Mountain View and signaled its intent to make a right turn on red at a road intersection. The Google car then moved to the right-hand side of the lane to pass traffic in the same lane that was stopped at the intersection and proceeding straight. However, the Google car had to come to a stop and go around sandbags positioned around a storm drain that were blocking its path. When the light turned green, traffic in the lane continued past the Google car. After a few cars had passed, the Google car began to proceed back to the center of the lane to pass the sand bags. A public bus was approaching from behind. The Google car test driver saw the bus approaching in the left side mirror but believed the bus would stop or slow to allow the Google car to continue. Approximately three seconds later, as the Google car was re-entering the center of the lane, it made contact with the side of the bus. Following investigations, Google further refined its software and explained that “Our cars will more deeply understand that buses and other large vehicles are less likely to yield to us than other types of vehicles, and we hope to handle situations like this more gracefully in the future”.

Many questions on how an autonomous vehicle can learn, plan, perceive, and make decisions in different scenarios and operational environments in the real world remain to be answered, before the autonomous vehicle can completely take over the role of a human driver. Therefore, it is assessed that the technology readiness level for the

planning and decision-making module of the autonomous vehicle is at **TRL 2-4**. Numerous technology concepts and visions have been proposed, and active research and development has been initiated for some of the selected domains. However, the current state of technology is still considered to be of low fidelity, but this is envisaged to improve in the future, complemented by better accuracy and precision in perception technologies as well as greater synergy and integration with navigation and localization techniques such as SLAM.

5.4.7 Dedicated Short-range Radio Communications

While research on autonomous vehicle technologies are ongoing, there is also a parallel research on connected vehicle technologies, or what is commonly known as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) or generally Vehicle-to-Everything (V2X) communications. Many will associate the connected vehicle research as complementary to autonomous vehicle research, as it is postulated that V2V and V2I will enable autonomous vehicles to achieve a higher level of autonomy with enhanced reliability. However, it is important to note that connected vehicle technology is not a prerequisite for autonomous driving. Also, in contrast to autonomous vehicles, connected vehicles exhibit more significant network effects i.e., the greater the number of vehicles equipped with connected vehicle technologies, the greater the value that V2V communications can bring to the users.

Dedicated Short-range Radio Communications technology has been primarily developed and promoted for the purpose of delay-sensitive vehicular communications (e.g., safety messages) by the US Department of Transportation (US DOT). Studies by the US DOT have shown that combining perceived intelligence and V2V/V2I capabilities can enable more accurate localization, especially in the absence of GPS in urban canyons, and in blind spot detection. In the context of planning and decision-making, the US DOT claims that V2V and V2I can enhance the performance range or mitigate the performance gaps of sensors' perceptions to allow more accurate path planning and prediction of obstacle trajectory. Research is also proposed to evaluate the potential of DSRC-based vehicle safety communications to enhance the capabilities of autonomous safety systems, such

as radar-based collision avoidance systems and perhaps, to enable new safety applications to be developed (US DOT, 2015).

In terms of technology maturity, the US DOT and its collaborators performed a large-scale model deployment and evaluation of prototype DSRC technologies, V2V and V2I safety applications in 2012, with drivers in over 2,800 vehicles. The study concluded that DSRC is sufficiently robust to proceed with preparations for deployment of connected vehicle environments, while improvements in DSRC equipment, technologies, and applications continue to be driven by the industry and research entities. The study also highlighted the importance to establish and implement standards for performance validation and certification of DSRC devices from different manufacturers and support interoperability across vehicles and devices. On this note, the technology readiness level of **DSRC** is assessed to be at **TRL 6**.

It is important to highlight that the US DOT study was focused on evaluating the effectiveness of DSRC and connected vehicle technologies to assist drivers in the complex driving environment to ensure enhanced safety. It did not specifically address how DSRC technologies can be incorporated in a fully autonomous vehicle, where the human driver is not required to be in control of the vehicle. Therefore, with the gradual maturity of connected vehicle technologies, there is a need to assess the suitability of the current DSRC, V2V, and V2I technologies and identify the technology gaps should the human driver be relieved of vehicle control in the future. As such, the technology readiness level of **DSRC for autonomous vehicle applications** currently remains low, at **TRL 2-3**.

5.4.8 Human-Machine Interface (HMI)

The human-machine interface is the communication bridge between the human and the vehicle. The new era of connectivity, increased vehicle autonomy, and the Internet of Things are reshaping the human's expectations and redefining the human's relationship with the vehicle. Conventional HMI designs are primarily focused on the utility, with

emphasis on design principles such as usability, pictorial realism, standardization, visual acuity, color coding, and conspicuity. Going forward, the automotive HMI design also needs to consider the integration across different systems (e.g., infotainment), and be easily adaptable to different user needs, so as to continue to provide delightful user experiences, and nurture trust between the human and the vehicle.

Handling the evolution of HMI design will be more complex as vehicles progress up the higher levels of autonomy. At SAE Level 2, the driver is overall responsible for driving, while at SAE Level 4, the vehicle is the responsible party. Ambiguity lies at SAE Level 3, where responsibility can alternate between the human and the vehicle depending on the driving circumstances, within an extremely short notice of 10 seconds. The HMI needs to allow for a seamless and instant transition of control between the human controller and the vehicle controller.

In addition, the psychological shift in humans from human-driven vehicles to self-driving vehicles should not be overlooked when designing new HMI. In general, humans trust technology to follow rules, but only trust humans to make judgements⁷⁰. In a highly automated or fully autonomous vehicle, the vehicle is responsible for making decisions in the presence of the human. The HMI needs to be designed in a way that the vehicle behaves, reacts, communicates, and responds in a manner that instills trust, so that the human passengers feel comfortable and confident even though they are not in physical control of the vehicle. A human-centric approach should be adopted in the HMI design, where the human is still being kept in the loop for situational awareness. Suggestions on the considerations⁷¹ in HMI design to engender trust have been proposed but will still require further research and analysis:

(1) The human needs to feel safe in an autonomous vehicle. The behavior of the vehicle and its interactions with the driving environment needs to demonstrate that the vehicle knows what it is doing so as to assure the passenger.

⁷⁰ <http://www.automotiveworld.com/analysis/hmi-2-0-symbiotic-relationship-car-driver/>

⁷¹ <https://blogs.intel.com/iot/2016/09/30/building-trust-human-machine-road-automated-vehicles/>

(2) The human will always want to be aware of and stay connected with what the autonomous vehicle is doing. The HMI design should enable the vehicle to clearly and timely communicate intentions, choices, and actions upon request by the human, or simply to keep the human informed, but not at the expense of information overload. The HMI should also allow the human to communicate his or her needs e.g., changes in journey plan to the vehicle after the vehicle has embarked on the pre-selected route.

(3) Even though the human may not be physically driving the vehicle, humans have the tendency to want to feel that they are in control. The human may also want to be given the option to easily stop or make any changes to the journey when required.

(4) Confidence in the vehicle is achieved if the human can engage unreservedly in other activities and enjoy the travel experience without having to consciously keep in view of the vehicle's maneuvers or divert their attention between other activities and preparing to or taking over control of the vehicle.

Future mobility also plays up the importance of creating personalized user experiences customized according to individual human's needs. The vehicle is no longer perceived as just a physical platform, but as a mobility and connectivity platform, allowing the passenger to immerse in multi-tasking, socializing, infotainment, and productivity activities on the move while still ensuring a safe travel experience.

To realize the next generation of HMI concepts, additional design principles and technologies have been explored by various HMI developers and manufacturers. Examples^{72,73,74} include: (1) Clear, functional, and control HMI hierarchy with distinct mechanical and digital functions, (2) Hybrid interfaces comprising haptic controls with embedded touch surfaces, (3) Touchscreens with haptic feedback, (4) Spatial gesture control with visual, aural, and haptic feedback, (5) Semantic voice control and feedback,

⁷² <https://ustwo.com/blog/looking-ahead-designing-for-in-car-hmi/>

⁷³ <http://punchcut.com/perspectives/the-connected-car/>

⁷⁴ <http://pch-innovations.com/the-blended-drive#2StatusHMI2015>

(6) Soft interactions aided by computer vision such as monitoring movement of the human's eyelids, (7) Contextual information on secondary displays such as heads-up display, (8) Adaptive interface options to the context at hand with the aid of predictive intelligence, and (9) Projection of current and future driving situations using augmented reality techniques.

From market survey, it appears that the bulk of the investments and resources in autonomous vehicle research are focused on improving the performance of hardware and software technologies, with little emphasis on HMI at the moment. While some manufacturers have showcased concept vehicles articulating their vision for the future HMI designs, only some of the features are being incorporated and evaluated in the prototypes. As mentioned, integration and adaptability are key considerations in the HMI design of highly automated or fully autonomous vehicles. Therefore, it is assessed the technology readiness level for the **human-machine interface** design of the autonomous vehicle currently ranges between **TRL 3 to TRL 6**.

5.4.9 Summary

In this section, we studied the technology readiness level of the key features associated with autonomous driving, and this is summarized in **Figure 5.11**. From this assessment, we observe that autonomous vehicles are not yet ready for the road. While some of these features are already commercially available, they are primarily designed for driver-assist applications. We believe that these technologies have the potential to be scalable for autonomous vehicle applications, and we should continue to pursue breakthroughs in research, test, and evaluation of these technologies so as to better understand the interactions among vehicles, with other road users, as well as between vehicle and the surrounding driving environment. At this point, we can only speculate the future of autonomous vehicle technologies, and it is uncertain how and when a fully autonomous vehicle can be operationalized.

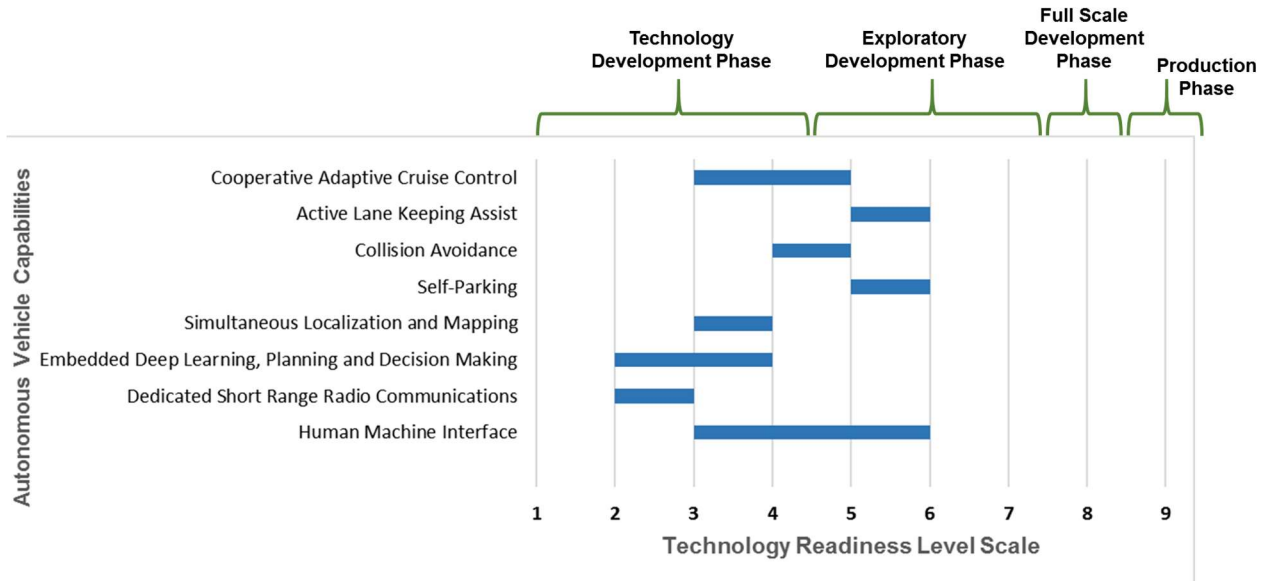


Figure 5.11: Summary of TRL Assessment of Technologies for Autonomous Vehicle Applications

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CHAPTER 6 – DISCUSSION AND RECOMMENDATIONS

From market survey, we observe that there is no clear single pathway in the development of autonomous vehicle capabilities. Different industry players are still experimenting with various approaches and exploring possibilities. From the analysis of the current state of technology of autonomous vehicle capabilities, we also note that while the technologies present immense potential, they are not quite yet ready. In this chapter, we will highlight some of the competing pathways, examine the uncertainties in outcomes, and analyze the implications to policymaking. In addition, we will provide recommendations on how policymakers can employ flexibility in capability development while not being committed too early to a specific solution.

6.1 Competing Pathways

Level of Autonomy

The choice of the level of autonomy to be developed in the vehicles varies across companies. Many are still adopting a more conservative approach to start with partial automation (NHTSA Level 2; SAE Level 2) and incrementally builds up towards higher levels of autonomy as the technology evolves. For example, the Tesla’s “autopilot” system (in beta testing) falls under the NHTSA Level 2 category, and similar features (albeit marketed as enhanced safety options) are also available in some luxury car models. Some companies such as Nissan and Jaguar Land Rover chose not to develop a fully autonomous vehicle; rather they prefer to focus their efforts on driver-assist capabilities. There are also some that decide to directly pursue revolutionary research in high or full automation (NHTSA Level 4; SAE Levels 4-5), of which Google, and more recently, Ford, prominently feature in this category. Both Google and Ford had the view that the intermediate Levels 2 and 3 will create more human-machine interface imperfections⁷⁵ as one tries to balance the preservation of the human’s situational awareness with automated driving.

⁷⁵ <http://www.fool.com/investing/2016/09/27/why-ford-is-taking-the-slow-road-to-self-driving-t.aspx>

Instead of incrementally advancing the technology through different levels of autonomy, the Chinese Internet search provider, Baidu, employs a different strategy to progress the technology through different applications of autonomous driving e.g., from fixed route (where maps of the route are pre-loaded and updated as the vehicle travels) to dynamic and mobility-on-demand type of driving (where the vehicle travels and creates a visualization of the surrounding environment in real-time).

Rate of Development

Several leading automotive companies such as Ford, and Daimler-Benz, have been involved in autonomous vehicle research for some time, particularly through DARPA challenges in the United States and the PROMETHEUS project in Europe. However, in terms of the actual total vehicle miles driven, these companies pale in comparison to Google, who claimed it started development in 2009 and has since clocked more than 1.9 million miles in autonomous test mode as of August 2016. There are also some late entrants to the autonomous vehicle technology domain; for instance, Toyota was not inclined to invest in research on autonomous technology up till 2015, but they have since aggressively accelerated their investments by acquiring technology companies e.g., Jaybridge Robotics, and establishing collaboration with Microsoft and KDDI Corporation.

Terrain Type

The selection of terrain type for autonomous driving affects the choice of perception technologies and the level of sense-making to be developed in the vehicle. Urban city driving appears to be more challenging as compared to highway driving, due to additional considerations for traffic lights, intersections, pedestrians, and other road obstacles. Google is developing its autonomous vehicle for urban and suburban driving up to 25 miles per hour. In contrast, Tesla and Volvo have decided to design for autonomous driving on highways, but there is still a difference in the application of autonomy. Tesla's autopilot is designed to be activated only at speeds exceeding 18 miles per hour on the highway, while Volvo's system is customized for stop-and-go traffic up to 30 miles per hour on the highway as a form of traffic-jam-assist to the human driver.

Activation of Automated Driving

With the exception of the Google car which is planned to be fully autonomous with no steering wheel, accelerator or brakes, most of the autonomous vehicles being developed requires certain conditions to be met before autonomy takes control. Several approaches are being considered: (1) Autonomous drive mode is automatically activated when pre-defined road and environmental conditions are satisfied, otherwise this mode will remain disabled, (2) The human driver will be prompted with the option to intervene to activate the autonomous drive mode when the pre-conditions are met, or (3) The human driver remains in control of driving and the vehicle only takes over when collision is imminent, also known as the “Guardian Angel” in Toyota’s concept of autonomous driving. In all three cases, the human driver will be prompted via visual, audible, and/or tactile cues to resume control of the vehicle in the event that the vehicle deems that the conditions become unfavorable for the autonomous drive mode to continue.

Technology Selection

Technology drives the final form of the product, and covers perception, navigation, and communications. Some companies such as General Motors and Hyundai believe that connected vehicle technology is a key enabler for autonomous driving, and are investing heavily in V2V and V2I communications, while others like Google are focused on artificial intelligence, in particular, deep learning to allow the vehicle to sense-make the driving environment even without V2V communications.

In terms of perception technologies, many (e.g., Ford, General Motors, Google, Nissan and Toyota) are using Lidar as the primary sensor for mobile mapping and perception applications. An interesting point to note is that Tesla’s vehicle is not equipped with a Lidar sensor; it relies primarily on Radar, Sonar, and cameras only.

Most companies also believe that highly detailed maps are necessary for autonomous navigation, with companies like Audi, BMW, and Daimler acquiring high-definition mapping company, HERE, in 2015, while Uber is planning to invest \$500 million to

develop its own maps. However, contrary to popular belief, another company, Nissan, is relying on sparse maps which are less detailed, for navigation.

Application of Autonomous Vehicle Technologies

The intended applications for autonomous vehicle also differ. Majority of the traditional automotive manufacturers are pursuing the concept of replacing the human driver partially or entirely. In addition, some manufacturers such as Ford, General Motors, Tesla, and Toyota, are also venturing into the shared mobility transportation landscape, along with technology companies such as Apple and Google, as well as ride-hailing company, Uber. The idea of shared mobility anchors on the objective of reducing the number of cars on the road and enhancing urban mobility, vide ride-sharing, car-sharing, and/or mobility-on-demand.

There is also a unique group of companies (e.g., EasyMile, Navya, 2getthere) that are specifically targeting the driverless shuttle market, for first-mile, last-mile applications and transportation within confined environments such as amusement parks, airports, campuses, and business parks.

In countries such as the United States, the trucking industry is a key contributor to the economy, and nearly 70% of the total freight tonnage⁷⁶ moved in the US goes on trucks. According to statistics by the US Department of Transportation, nearly 4,000 people⁷⁷ die in truck-related accidents each year, and driver fatigue was deemed to be the leading factor for the cause of accident. Companies such as Daimler, are developing semi-autonomous trucks to help alleviate the driver's workload and hopefully enhance driver safety. In July 2016, Tesla also indicated that the company is interested to expand into the truck business and plans to unveil its first model of autonomous trucks in 2017. Otto, a start-up acquired by Uber made its first revenue-generating delivery in October 2016 using its developed autonomous truck⁷⁸, where the autonomous driving mode was

⁷⁶ http://www.trucking.org/News_and_Information_Reports_Industry_Data.aspx

⁷⁷ <https://www.transportation.gov/fastlane/why-we-care-about-truck-driver-fatigue>

⁷⁸ <http://www.reuters.com/article/us-uber-trucking-beer-idUSKCN12P13N>

enabled for the highway portion of the journey. The feasibility of autonomous truck platooning for specific areas such as mines and seaports is also being studied, with the aim of increasing productivity gains.

Furthermore, there is a group of companies that are looking at applying autonomous vehicle technologies to mass transportation, such as buses. Mercedes-Benz and Yutong have been experimenting with their developed autonomous buses on the public roads of Haarlem in Netherlands, and Henan province in China respectively. Similarly, Tesla has also expressed interest in this domain and plans to showcase its first model of autonomous buses in 2017.

6.2 Uncertainties in Outcomes

6.2.1 How Safe is Safe?

In the United States, the Bureau of Transportation Statistics reports that about 32,000 people are killed, and more than two million are injured in vehicle crashes every year, and the National Highway Traffic Safety Administration claims that more than 90% of the crashes are attributable to human error, such as driving too fast, misjudging other drivers' behaviors, alcohol impairment, distraction, and fatigue (Anderson, J.M., 2016). In Singapore, from 2012 to 2015, there are on average 193 road accident fatalities and 7,070 road accident injuries each year. More than 80% of the fatalities and over 93% of the injuries are due to the human driver. More than half of the road accidents are due to the drivers failing to keep a proper lookout for traffic and pedestrians, as well as failing to maintain proper control over the vehicle⁷⁹.

The use of a fully autonomous vehicle to replace the human driver sounds like a good solution to eliminate mistakes that human drivers routinely make, such as inadequate steering, braking, and acceleration, or failure to check blind spots. However, is the

⁷⁹ https://data.gov.sg/dataset/causes-of-road-accidents-causes-of-accidents-by-severity-of-injury-sustained?view_id=ab70136f-5e29-4be6-bc91-c30fa5bed3ae&resource_id=d68321b6-c438-425d-b9f4-d577eee9e77

autonomous vehicle really much safer than a human-driven car? Does the autonomous vehicle always perform better than the human driver, even in inclement weather, or complex and dynamic driving environments? How about new risks that arise due to autonomous vehicle technologies, such as cyber threats, and how will that impact the safety of the passengers and other road users?

Just as what many companies have been doing, a logical way to evaluate the safety of the autonomous vehicles is to test-drive them in the real traffic environment, after going through simulations and test tracks. A key question is, “To what extent of test-driving is required before we can be assured that the autonomous vehicle is safe for deployment on the roads?”

Kalra, N., and Susan, M.P. (2016) performed a statistical analysis to estimate the number of autonomously-driven miles required to meet a certain performance target. In 2013, road accidents in the United States resulted in 1.09 fatalities per 100 million miles. To demonstrate that the autonomous vehicle is comparable to the human-driven car in terms of safety, measured by fatality rate (i.e., using 1.09 fatalities per 100 million miles as a benchmark) with 95% confidence level, they calculated that it will take 12.5 years with a fleet of 100 units of autonomous vehicles being test-driven 365 days a year, 24 hours per day at an average speed of 25 miles per hour to accumulate a total travelled distance of 275 million failure-free miles. It should be noted that this is the minimum distance that needs to be clocked merely to prove that the autonomous vehicle is as safe as a human-driven car.

To validate that the autonomous vehicle is safer than a human-driven car, additional mileage and more realistic use cases are required. Assuming if we want to prove with 95% confidence level that the autonomous vehicle results in a fatality rate that is 20% lower (i.e., 0.872 fatalities per 100 million miles) than the 2013 statistics, it is assessed that the vehicles need to be test-driven for at least five billion miles, equivalent to a duration of 225 years for a fleet of 100 units of autonomous vehicles being tested around the clock (Kalra, N., and Susan, M.P., 2016).

For comparison, the Google Self-Driving Car project which started since 2009 has only clocked slightly more than 1.9 million miles in autonomous mode⁸⁰, out of the 3.1 million miles travelled, as of August 2016. Based on the test data collected so far, Blanco, M., et al (2016) compared the performance of the Google fleet with human-driven performance, and concluded that the Google fleet might result in fewer crashes with only property damage, but were unable to establish the relative performance of autonomous driving with human driving in terms of the other metrics (injuries and fatalities).

Alternative methods such as accelerated testing, virtual testing and simulations, mathematical modeling and analysis, scenario and behavior testing, as well as extensive focused testing of hardware and software systems have been proposed (Kalra, N., and Susan, M.P., 2016). However, there is a limit to the extent in which how realistic such alternative testing can resemble the real-world driving environment. It is also more challenging to establish a set of validation principles and acceptance criteria for software than for hardware. Moreover, even with these methods in place, it may not be possible to assure the safety of autonomous vehicles prior to making them available for public use.

While safety and security are two distinct domains, another perspective to consider is the risk of cyber-attacks on the safe operation of autonomous vehicles. Car-jacking, a term used to describe the hacking of automobiles is already a threat today, and is likely to be a greater concern in the future as cars are increasingly equipped with connectivity and networking capabilities. “White Hats” have demonstrated how easily it is for malicious hackers to remotely and wirelessly disable and hijack a vehicle, and assume control over its steering, brakes, transmission, and dashboard functions⁸¹.

More recently, a Chinese group called Keen Security Lab claimed that they have successfully exploited the security vulnerabilities in an unmodified Tesla Model S vehicle and assumed remote control in both parking and driving modes. The hackers have since

⁸⁰ <https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports/report-0816.pdf>

⁸¹ <https://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/>

disclosed the technical details of the vulnerabilities discovered in their research to the Tesla Product Security Team, and Tesla has subsequently issued a software update to the affected cars⁸².

Autonomous vehicles are heavily reliant on sensors, software, and vehicle networks to intelligently make driving decisions for the human passenger, which are increasingly becoming vulnerable targets for cyber-attacks. Using an example involving the cooperative adaptive cruise control system, Amoozadeh, M. et al. (2015) explained that security attacks can be targeted at the application layer, network layer, system level, and privacy leakage attacks, all of which can potentially compromise the safety and privacy of the passengers in the autonomous vehicle.

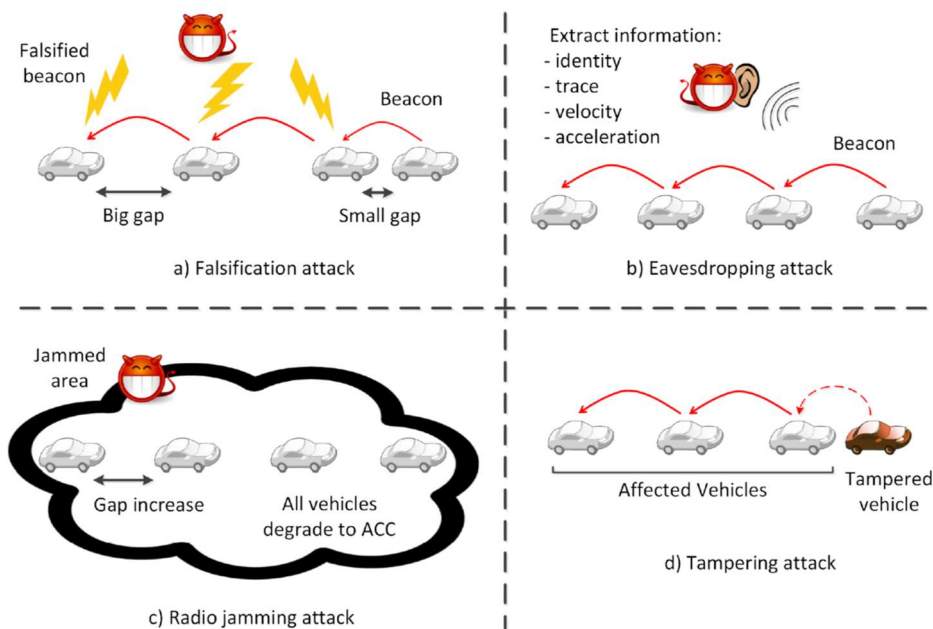


Figure 6.1: Example of Security Attacks on Cooperative Adaptive Cruise Control
(Source: Amoozadeh, M. et al. (2015))

For instance, application layer attacks (through message falsification, spoofing, or replay) can affect the functionality of the cooperative adaptive cruise control beaconing in a platoon of vehicles or the message exchange in the platoon management protocol. This

⁸² <http://www.theinquirer.net/inquirer/news/2471440/tesla-issues-self-driving-car-software-update-after-hackers-cause-a-crash>

can result in a temporary instability in the vehicle stream, and in severe cases, can lead to rear-end collisions.

The ambitious goal to deploy a fully autonomous vehicle by 2020 appears unrealistic. Without sufficient test data and robust cybersecurity measures in place, it is not advisable to assume that autonomous vehicles are as safe as, or safer than human-driven cars. Also, we should not overlook the risk that the number of accidents may increase with the initial introduction of autonomous vehicles, as human drivers try to adapt to sharing the road with autonomous cars (whose programmed driving behavior is unlikely to assimilate exactly how a human driver makes judgement and handles the control of the car in the driving environment).

Rather, one should think about innovative test methods to accelerate the understanding of the performance and limitations of autonomous vehicles, and present the information and associated risks involved to the informed consumers to make their decisions on technology adoption. To the policymaker, regulations and policies also need to continue to evolve and adapt as the technology continues to progress.

6.2.2 Transition from Demonstration to Operationalization

Many developers of autonomous vehicles have conducted high-profile demonstrations to showcase the performance of their prototype vehicles on test tracks and public roads. The routes of travel for each demonstration are usually pre-determined and selected to ensure that the autonomous vehicle can successfully handle them. During the demonstration, there is always a trained professional test driver behind the driver's seat, always ready to take over control when: (1) The autonomous mode decides that the environment is too complex or not within the programming rules to continue autonomous driving, or (2) The human driver assesses that it is unsafe for autonomous mode in complicated driving situations. Unlike the ordinary human driver or passenger, these test drivers have undergone rigorous training and know intimately how the car works, both in terms of hardware and software. Moreover, the test vehicles are well-maintained and thoroughly tested before embarking on their pilot runs.

From the assessment of the current technology developments in Chapter 5, a fully autonomous vehicle is unlikely to be available anytime soon. Apparently, there is a mismatch between the developers' point of view of autonomous driving, versus the consumers' expectations of an autonomous vehicle. From the developers' point of view, they presume that the human in the vehicle will remain vigilant at all times even when the autonomous mode is in operation, and is expected to promptly resume control when prompted by the vehicle. However, from the consumers' perspective, they expect the autonomous vehicle to maintain full control of the vehicle in all driving conditions such that he or she can completely detach himself or herself from the driving experience and utilize the travelling time for personal activities such as catching up on sleep, emails, or enjoying the in-vehicle infotainment. In potential applications such as mobility-on-demand services, there may not even be a human present in the vehicle when a consumer "summons" for a ride in an autonomous vehicle.

The pilot demonstrations have shown that fully autonomous driving is still limited in scope. Glare, reflections, thunderstorms, fading lane markings, poor visibility, snow, and night driving are examples of situations where the autonomous mode may not work reliably, due to limitation of the sensors to perceive the driving environment accurately and navigate safely in such driving conditions. Autonomous vehicles largely operate on programming if/then rules; but the problem space in the complex driving environment is so huge that it is almost impossible to enumerate and validate all possible problematic scenarios. A case in point is during the early phase of Google's self-driving car project, the prototype car was driving autonomously on the highway; it had rained shortly before and truck tires occasionally sprayed water high into the air. This led to problems because the car interpreted the spray as a solid object which unexpectedly got into the way. It did not take long for the engineer to analyze and resolve this problem by modifying the algorithms, but this is an example of the issues that are difficult to anticipate without rigorous testing⁸³.

⁸³ http://www.driverless-future.com/?page_id=774

Furthermore, autonomous driving hinges very much on the ability of the multiple complementary vehicle sensors to perceive the surroundings and navigate safely, of which, a sensor fault or failure to upkeep the maintenance of these sensors may just render the autonomous mode non-operational. Worse still, what happens if the hardware or software encounter errors when the autonomous vehicle is in operation and there is no “trained” professional onboard? Are there fail-safe mechanisms in place to allow for graceful degradation of the autonomous mode in such situations? Robustness, reliability, and failure mode management are just some of the attributes that the developer needs to ensure as the system transits from technology demonstration to an operational vehicle.

Even if the human accepts that the current state of technology does not allow for a fully autonomous driving journey, how can the human-machine interface be designed to allow for transfer of vehicle control from the human to the vehicle, and vice-versa? It is easy for the human to activate the autonomous mode once certain pre-programmed conditions are met, but it is a challenge to timely re-engage the human when required. Essentially, the “Drive Me” project, which is an initiative between the Volvo Car Group, the Swedish Transport Administration, the Swedish Transport Agency, Lindholmen Science Park, and the City of Gothenburg, plans to solicit data on how drivers switch in and out of autonomous driving mode in this public pilot study.

Lastly, the transition from prototyping to full-scale development transcends beyond the technology elements. It involves considerations for manufacturability, quality control and assurance, liability, insurance, service support, and maintenance, and the cost of production and operations. To the consumer, besides quality and safety, the additional cost incurred to acquire a vehicle with autonomous driving capabilities is also a key consideration affecting the adoption rate.

Therefore, the technology maturity of an autonomous prototype vehicle cannot be judged solely by observing the demonstrations. Lots of planning goes into the preparatory efforts to conduct a demonstration (in terms of route selection, weather, environmental conditions, day, and time of demonstration) to minimize the risk of problematic situations

during the actual demonstration. As such, a prototype vehicle only proves that the system has reached a certain level of capability, but does not guarantee a smooth and successful transition to a full-fledged operational system.

6.2.3 Road Congestion may not be Alleviated

Road congestion is a serious concern in many major cities, resulting in not only losses in productive time, but also additional costs incurred from wasted fuel, as well as increased air pollution. While advocates of autonomous vehicle technologies have alluded that autonomous vehicles can help solve this issue, it remains to be seen if the introduction of autonomous vehicles will be a panacea or will it exacerbate the congestion problem.

In a 2013 report published by the US Department of Transportation, bottlenecks, traffic incidents, and bad weather were named the top three contributors to road congestion in the United States, accounting for 40%, 25%, and 15% of congestions respectively. The report also pointed to too many cars on the road as a key reason leading to bottlenecks.

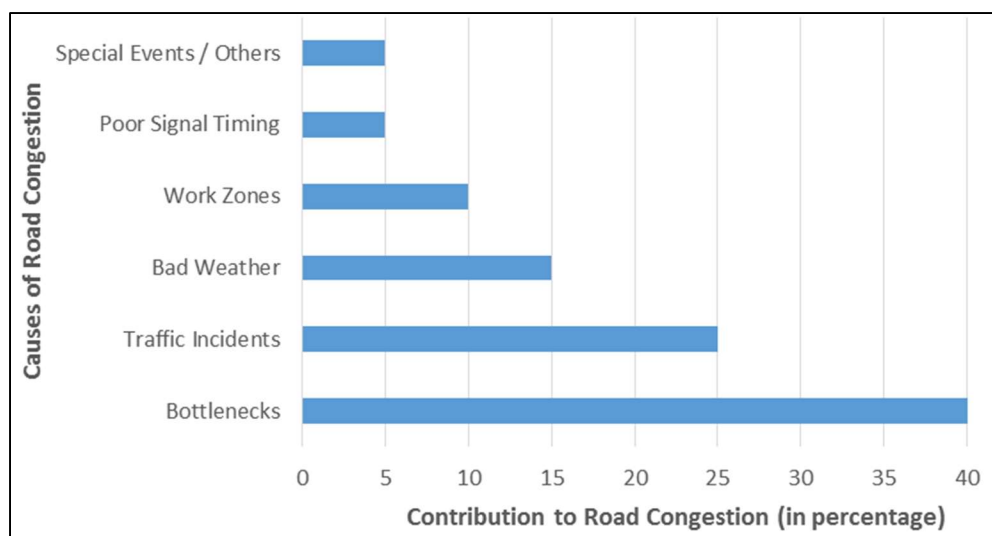


Figure 6.2: Key Causes of Road Congestion in the United States
(Adapted from Source: US DOT, 2012⁸⁴)

The current state of technology of autonomous vehicles is not ready to handle complex situations such as bad weather. The development of such capabilities is dependent on

⁸⁴ <http://www.ops.fhwa.dot.gov/publications/fhwahop13016/index.htm>

advancement in perception technologies as well as the ability of the vehicle to be programmed to make accurate sense-making and intelligent decisions in difficult and uncommon circumstances. Even if the autonomous vehicle demonstrates the capability, it remains uncertain if it can match or surpass the human's judgement and vehicle control in hazardous weather conditions. As such, it is unlikely that having autonomous vehicles will reduce road congestion in bad weather.

The second key cause of road congestion is traffic incidents. Autonomous vehicles have the potential to reduce the frequency and severity of traffic incidents because of better perception, decision-making, and execution abilities. However, this belief is premised on the assumption that the autonomous vehicle is "safer" than a human-driven car in all if not most of the driving environments, and that the introduction of autonomous vehicles does not result in undesirable side-effects such as new safety-related risks (e.g., interaction between a mixed fleet of human-driven cars and autonomous vehicles, and cybersecurity vulnerabilities).

Bottlenecks are identified as the main causal factor of congestion, arising from excessive number of cars on the road. Common solutions to mitigate the bottlenecks are to either increase the road capacity, or to reduce the number of cars on the road. An attractive hypothetical claim of autonomous vehicles is the reduced clearance between cars travelling on the road, enabled by V2X technologies, hence increasing road capacity. This claim associates increased road capacity with reduced congestion. However, what was disregarded in this claim is a phenomenon known as "induced demand", which was studied by two economists – Matthew Turner of the University of Toronto, and Gilles Duranton of the University of Pennsylvania, using the data on the amount of new roads and highways built in different states in the United States between 1980 to 2000, and the total number of miles driven over the same period. The study concluded that if a city increased its road capacity by 10%, the amount of driving went up by the same rate⁸⁵.

⁸⁵ <http://www.wired.com/2014/06/wuwt-traffic-induced-demand/>

Moreover, autonomous vehicles may not lead to a reduction in the number of cars on the road. Presently, road congestion could have discouraged some drivers from driving due to frustrations and unproductive time spent in a stop-and-go traffic. If the autonomous vehicle can assume the role of driving without intervention from the driver, the human would be able to enjoy the in-vehicle infotainment services or spend time more meaningfully even when they are caught in a traffic congestion. The favorable shift in the “user experience” of congestion may actually attract more people to own cars.

Even as less costly options to car access such as car-sharing and ride-sharing are gradually gaining popularity in many parts of the world, many drivers are still attached to their private cars and are unlikely to give up car ownership. For many, owning a car is a symbol of status; while to others, they relish the travel convenience and privacy. For example, let us consider the car ownership situation in Singapore. To curb the ownership and usage of private cars in Singapore, various fiscal disincentives (e.g., import duty, additional registration fee, and annual road tax), quota system (e.g., certificate of entitlement to own a new car), and road pricing (e.g., electronic road pricing) are introduced (Lim, L.Y., 1997). Despite all these deterrent measures, the statistics from 2005 to 2014 showed that the number of private cars as a percentage of the total population remains largely unchanged (less than 1% difference over 10 years). See **Figure 6.3**. Therefore, unless car-sharing and ride-sharing become a mainstream behavior, autonomous vehicles may actually lead to an increased number of cars on the road, contrary to popular belief that it will reduce congestion.

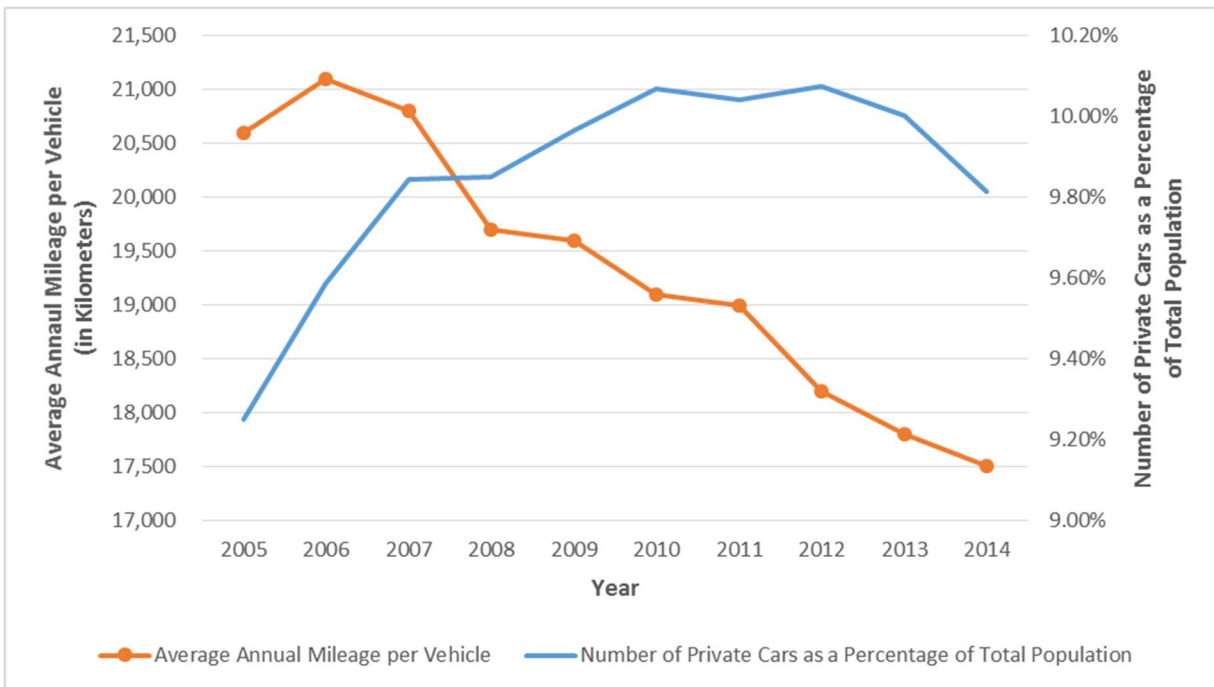


Figure 6.3: Car Ownership in Singapore from 2005 to 2014
 (Data Source: Land Transport Authority, 2015)

Assuming that car-sharing and ride-sharing becomes prevalent, it is likely only to have a modest improvement to road congestion. Take for example the situation in Singapore, where as of 2014, there were 536,882⁸⁶ private cars registered in Singapore, and about 10% of the fleet was renewed every year (as the certificate of entitlement to register, own and use a vehicle in Singapore is for 10 years). Studies⁸⁷ by the Transportation Sustainability Research Center at UC Berkeley claimed that each shared vehicle can remove between seven to 11 vehicles from the road. Consider a 10-year period where 100 shared autonomous vehicles were introduced each year, resulting in 10 times the number of private vehicles (i.e., 1,000) not being renewed as drivers give up car ownership. At the end of 10 years, the percentage reduction in the number of vehicles on the road is merely less than 2%, as shown in **Table 6.1**. That is assuming that car ownership does not go up due to other expected benefits offered by autonomous vehicles.

⁸⁶ Rounded up to 550,000 for illustration purposes in Tables 6.1 and 6.2.

⁸⁷ http://innovativemobility.org/wp-content/uploads/2016/07/Impactsofcar2go_FiveCities_2016.pdf

Table 6.1: Effect of Car-sharing on the Number of Vehicles on the Road (constant growth rate)

Year	Number of Vehicles for Car Sharing	Number of Cars due for Renewal	Number of Cars not Renewed	Total Number of Cars	Cumulative % Change in Number of Cars
Year 0	-	55,000	-	550,000	0%
Year 1	100	55,000	1,000	549,100	-0.16%
Year 2	100	54,910	1,000	548,200	-0.33%
Year 3	100	54,820	1,000	547,300	-0.49%
Year 4	100	54,730	1,000	546,400	-0.65%
Year 5	100	54,640	1,000	545,500	-0.82%
Year 6	100	54,550	1,000	544,600	-0.98%
Year 7	100	54,460	1,000	543,700	-1.15%
Year 8	100	54,370	1,000	542,800	-1.31%
Year 9	100	54,280	1,000	541,900	-1.47%
Year 10	100	54,190	1,000	541,000	-1.64%

In a more optimistic scenario where the number of shared vehicles increased by 25% each year, the resultant effect is just a slightly over 5% reduction after a decade.

Table 6.2: Effect of Car-sharing on the Number of Vehicles on the Road (25% growth rate year-on-year)

Year	Number of Vehicles for Car Sharing	Number of Cars due for Renewal	Number of Cars not Renewed	Total Number of Cars	Cumulative % Change in Number of Cars
Year 0	-	55,000	-	550,000	0%
Year 1	100	55,000	1,000	549,100	-0.16%
Year 2	125	54,910	1,250	547,975	-0.37%
Year 3	156	54,798	1,563	546,569	-0.62%
Year 4	195	54,657	1,953	544,811	-0.94%
Year 5	244	54,481	2,441	542,614	-1.34%
Year 6	305	54,261	3,052	539,867	-1.84%
Year 7	381	53,987	3,815	536,434	-2.47%
Year 8	477	53,643	4,768	532,142	-3.25%
Year 9	596	53,214	5,960	526,778	-4.22%
Year 10	745	52,678	7,451	520,072	-5.44%

The availability of autonomous vehicles may also result in an increase in demand for travel, due to enhanced mobility. For the past decade, the annual vehicle miles travelled in the United States has remained largely constant (US DOT, 2016). In Singapore, a

declining trend (drop of 15% from 2005 to 2014) in the average annual mileage per vehicle was observed (see **Figure 6.3**). The introduction of autonomous vehicles may have a knock-on effect on changes in commuters' travel patterns, as people may start to travel more frequently and for longer distances, arising from the convenience enabled by autonomous driving.

6.3 Policy Implications

Singapore's plan for autonomous vehicles is unique in many ways. Firstly, Singapore continues to value public transportation for mass commute and does not view that the introduction of autonomous vehicles will render public transit obsolete in the near to mid-term. Moreover, Singapore envisions autonomous vehicles to be employed as a complementary means of public transportation e.g., autonomous buses, for first-mile and last-mile travelling. Secondly, Singapore does not intend for autonomous vehicles as a direct replacement for human-driven cars; rather, the focus is on mobility as a service via ride-sharing and car-sharing. Thirdly, Singapore is application-specific but remains technology-agnostic, partly because while Singapore is one of the first movers to embrace autonomous vehicle capabilities, the comparatively small size of the potential market limits her leverage to drive the technological decisions of manufacturers and developers.

Compared to the experimentation with electric vehicles in Singapore, there may be a greater incentive for the government to drive and commit to autonomous vehicle developments. While promoting electric vehicles is aligned with the objective of moving towards a cleaner and greener environment, encouraging the use of electric vehicles does not help to resolve any of the current challenges faced, such as road congestion, first-mile and last-mile transportation gaps or limited land use for road infrastructure. To the individual driver, the switching costs to an electric vehicle are still high despite the tax incentives and rebates, coupled with current technology limitations on battery duration and charging speed, as opposed to the negligible personal benefits gained from a purportedly quieter in-vehicle environment.

Conversely, autonomous vehicle technologies prove to be more attractive to the policymaker because: (1) It can possibly eliminate the human driver when fully autonomous, thus can be deployed as autonomous buses for first-mile and last-mile commuting and at the same time alleviate the labor shortage of bus drivers, (2) With possibly shorter headway between autonomous vehicles when coupled with V2V and V2I connectivity, road congestion can be alleviated assuming the number of vehicles on the road does not go up, and (3) The concept of autonomous vehicles for transportation as a service may encourage car-sharing and ride-sharing behaviors, which favors Singapore's intent to control the number of vehicles on the road.

This section summarizes the author's thoughts on the policy implications arising from the possible deployment of vehicles with autonomous driving capabilities.

Autonomous Vehicle Capabilities Development Playing Field

With strong support from the Singapore government on autonomous vehicle initiatives, Singapore is an attractive place for autonomous vehicle technology developers to test and launch self-driving cars. As a taker of technologies, Singapore needs to be aware of the evolving ecosystem and the direction that the developments are heading towards, so that she can make informed assessments and decisions when establishing partnerships and collaborations with the key players. The automotive industry used to be primarily product-specific; however, with the entrance and competition from new players, the automotive industry is reshaping itself, gradually towards a platform-centric and service-oriented model. **Figure 6.4**⁸⁸ presents a snapshot of the increasing connectivity of the ecosystem.

⁸⁸ "Partnership" icon retrieved from:

<https://www.digistor.com.au/media/wysiwyg/images/digistor/blog/Partnership-your-road-map-to-success/partnership-icon.gif> on October 1, 2016. "Investment" icon retrieved from:

<http://www.iconsdb.com/icons/download/green/money-bag-512.gif> on October 1, 2016. "Personnel" icon retrieved from: <http://www.clker.com/cliparts/3/u/P/P/q/W/walking-icon-hi.png> on October 1, 2016.

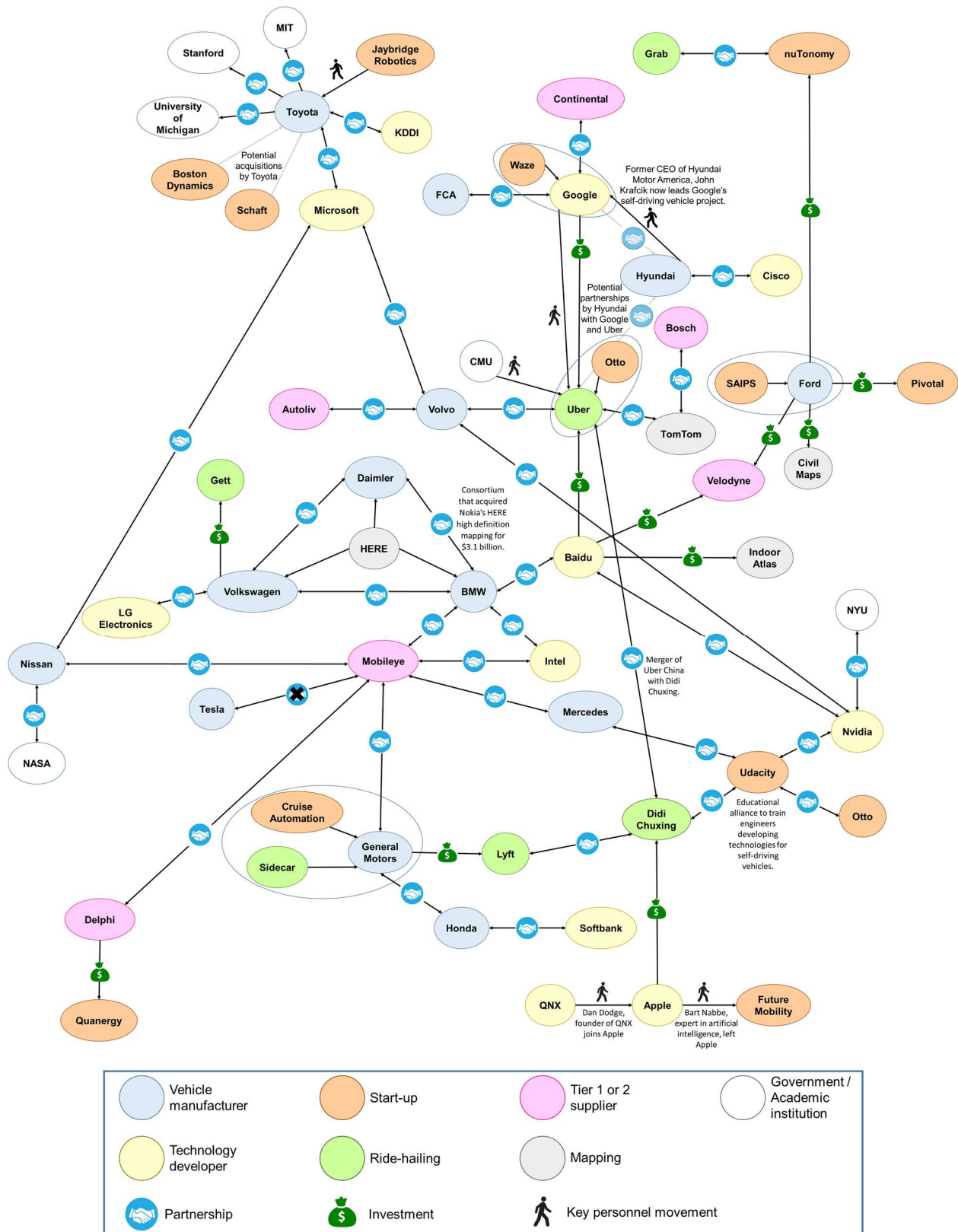


Figure 6.4: Connectivity Diagram of Key Players in the Autonomous Vehicle Developments

Balancing Regulations with Encouraging Innovation

Autonomous vehicle related technologies span over a spectrum, resulting in different levels of vehicle autonomy, from the simple driver-assist features to the complex full self-driving. Instead of a straightforward policy governing human-driven vehicles, they may be a need for a separate set of policies to regulate autonomous vehicles. Even so, ambiguity may still arise when one has to decide if a SAE Level 3 vehicle should be subjected to the regulations for a human-driven vehicle, or to that for an autonomous vehicle, given that it can assume either mode during the driving journey. Another aspect that policymakers need to think about is the extent of regulation that should be applied and weighed against the possible trade-offs, such as discouraging innovation or imposing barriers on rapid technological experimentation. One example is: Should the policymaker standardize how the manufacturer or technology developer program the decision and response rules in the autonomous vehicle to react in certain life-threatening scenarios? Or should such ethical considerations be left unregulated? Another example is: Should the policymaker require that drivers remain seated in front of the steering wheel, as proposed by the German transport ministry, so that they can intervene in an emergency, and which means a steering wheel must still exist in the vehicle? Will that stifle the SAE Level 5 innovations that are being done by companies such as Google and Ford?

Personal Benefits vis-à-vis Societal Benefits

Vehicles with advanced driver-assist capabilities are expected to improve personal road safety, with the postulation that highly automated or fully autonomous vehicles when technologically mature and widely adopted may reduce the average number of road accidents significantly. Besides safety, the potential benefits of autonomous vehicles to the individual include a more pleasant travelling experience in terms of ride comfort and productive use of travelling time, increased accessibility for the disabled and elderly populations, ease of commuting on public transportation from origin to destination (including first and last-mile), and increased transportation options available to the average commuter.

In terms of societal benefits, enhanced individual safety on the roads has a consequential effect on reduced social burden in terms of productivity losses and healthcare. In addition, if the deployment of autonomous vehicles can reduce the human's desire for personal car ownership, then the land use for roads and parking spaces may be reallocated for other purposes such as housing and commerce. Urban sprawl will not be that evident in Singapore, given her small land mass and robust existing road and public transportation infrastructure. However, it can allow the city planners to create more decentralized business districts, similar to the plans for Jurong Lake District, yet still remain accessible and attractive for individuals to work there and for businesses to thrive. As deep learning techniques mature progressively, the autonomous vehicles are likely to respond more effectively in varied driving environments as compared to humans, and this may result in a more compliant driving behavior, possibly leading to fewer driving violations and road accidents.

Personal Costs vis-à-vis Societal Costs

Besides the benefits, we need to consider the cost implications due to self-driving vehicles as well. For the individual, the capital cost of personal car ownership is expected to go up during the initial years of launch of vehicles with autonomous features. However, the total cost of ownership may remain relatively consistent or even lower with more efficient driving and improved fuel consumption. For the individuals benefiting from the convenience of travel enabled by the mobility-on-demand services or autonomous buses, the personal cost depends on the relative cost per trip in an autonomous vehicle as compared to the current public transportation modes.

In terms of societal cost, there is a risk that certain jobs (e.g., taxi drivers, bus drivers, parking attendants, valet parking attendants etc.) could be eliminated or restructured as autonomous vehicles become prevalent. In addition, the revenue that the government collects from road taxes, parking fees, speeding fines, and incident management costs could be affected. Policymakers may need to analyze how the individuals in the affected job roles can be redeployed or retrained, as well as to review the current revenue mechanisms.

Transportation as a Service

The introduction of autonomous vehicles will be a huge push towards transportation as a service to provide enhanced accessibility without individual ownership of a vehicle. New shared service business models are already present today, run by companies such as Uber, Lyft, Grab, and Zipcar. Going forward, the service model could take the form of a fleet of self-driving cars owned by service providers and operated like an on-demand car or rental service, or the autonomous vehicles could be owned by individuals and operated like an Uber or Airbnb service. Policymakers may need to study the impact of competition led by the new sharing economy models on the point-to-point transportation pie currently dominated by traditional taxi companies such as ComfortDelGro and SMRT.

In addition, currently, the private ride-hailing companies adopts a largely self-policing system, and are not subjected to the same level of regulation (e.g., in terms of service quality and safety) as the taxi companies. Another point for policymakers to consider is also the degree to which owners, drivers, service providers, and the larger shared transportation service business should be regulated, of which most of the considerations should be addressed as part of the new Private Hire Car Driver Vocational Licensing framework scheduled to be in place by the first half of 2017.

Pricing

The initial cost of a highly automated or fully autonomous vehicle is likely to be prohibitive for the average car owner. For example, a Mercedes E-class with a semi-autonomous package is expected to cost \$11,250 more than the standard model. Therefore, it is economically more sensible to start with the use case of autonomous vehicles as a fleet for ride or car-sharing. However, if the global adoption of autonomous vehicle capabilities picks up over time, the price difference is expected to shrink significantly, increasing the attractiveness of personal ownership of an autonomous vehicle. Another watch area is the automotive aftermarket. Upgrade kits may be offered by companies to convert a partially autonomous vehicle to a highly autonomous vehicle. Competition from the aftermarket manufacturers may put pressure on carmakers to sell autonomous vehicles at affordable prices (Toole, R. O., 2014).

Policymakers may need to review the adequacy of the current vehicle quota system and pricing strategies to control or reduce the total number of vehicles on the road. In addition, currently, the certificate of entitlement is categorized by engine capacity. It may be worth considering if the criteria should also include the level of vehicle autonomy in the future.

Also, with the competition from private ride-hailing companies, the policymaker has to consider how autonomous bus services for first and last-mile travel should be positioned and priced as part of the larger public transportation structure. The policymaker should be mindful that the policy should not result in the commuter behavior tipping towards simply hailing a private autonomous vehicle ride from origin to destination (which may give rise to increased number of vehicles on the road, especially during peak travel hours), instead of having to transfer to and from the Mass Rapid Transit system.

Ethical Considerations and Social Dilemma

According to NHTSA, more than 90% of the road crashes are attributed to human error, and there is a general belief that widespread deployment of autonomous vehicles may reduce the number of road accidents by 90%, by eliminating human error⁸⁹. Even if that is true, it still means there is still about 10% of road accidents that are unavoidable even with self-driving vehicles. Take for example the case of a highly automated or fully autonomous vehicle, in the event of an emergency situation, the vehicle may have to choose between two evils, such as stay on course and run over pedestrians or swerve into a concrete wall and sacrifice itself and its passengers in order to save the pedestrians (Bonneton, J. F. et al, 2016). This moral decision will be made by the vehicle system, and not by human judgement. Moreover, the decision rules have to be pre-programmed in the vehicle at the time of production using hypothetical scenarios.

Bonneton, J. F. et al (2016) explored this social dilemma using a series of survey experiments. They concluded that while most participants approve of utilitarian autonomous vehicles (i.e., to sacrifice its passengers for the greater good), and would

⁸⁹ <http://www.wsj.com/articles/self-driving-cars-could-cut-down-on-accidents-study-says-1425567905>

want others to purchase such vehicles; they would rather prefer to ride in autonomous vehicles that protect the passengers at all costs.

It is expected that the autonomous vehicle technologies will still take some time to mature, before they are able to provide the richness of content required to program the exact behavior of the autonomous vehicle when faced with different situations. Meanwhile, most autonomous vehicles are likely to just strictly adhere to the rules of the road.

However, understanding the human's behavior to moral quandaries is important in policymaking. Policymakers need to decide if there is a need to regulate the ethical decision rules programmed in the autonomous vehicles, and if yes, how they should be programmed. From the perspective of the manufacturer and the technology developer, it is in their interest to program the autonomous vehicle to protect the passengers at all costs, so as to increase its appeal to prospective car buyers. On the other hand, the government may prefer a more utilitarian approach so as to minimize the number and/or severity of casualties in the event of an accident. However, such an approach may deter the consumer's acquisition of utilitarian autonomous vehicles, slow down the adoption rate, and potentially reduce the number of lives that could have been saved had the passengers ride in an autonomous vehicle.

In a policy guidance released by the NHTSA in September 2016, the agency has requested for manufacturers to provide voluntary submission of a safety assessment of their autonomous vehicle, which covers 15 different areas, of which, ethical consideration is one of them. It is unknown at this point if and when NHTSA may make this process mandatory, and how the NHTSA plans to make use of this data to regulate the autonomous vehicle industry.

Social Acceptance

Interestingly, as in many socio-technical systems, autonomous vehicle development is not just solely about the technology; it is also about social cooperation. Although there has been a lot of discussion about the potential benefits in safety and enhanced travelling

experience that autonomous vehicles may bring about, a significant proportion of the population still remains conservative on autonomous vehicle adoption. In a survey⁹⁰ conducted by the Institute of Electrical and Electronic Engineers in 2015 with its members (experts) and social media followers, about 63% of the experts and 54% of the social media followers expressed unease over the safety of the autonomous vehicles, and attributed vehicle technology and cyber security as the key reasons that hinder vehicle safety. Many of the survey respondents acknowledged that while there is no technology or system that can assure perfect safety, the capabilities of the autonomous vehicle have to attain a demonstrated level of maturity, with a residual level of socially acceptable risk, prior to deployment. While the survey results only express the humans' perception to an abstract concept (since most of the surveyees have not had the first-hand experience in an autonomous vehicle), the crucial question lies in what constitutes a socially acceptable level of risk, and this question is not one that can be easily answered by any single stakeholder; it is somewhat a societal consensus.

Another factor that may influence the adoption rate is the user experience, which can be analyzed from two angles: (1) How close the autonomous vehicle mimics the way a typical human driver drives the car, and (2) How effectively and efficiently can the human communicate with the autonomous vehicle such that he or she can feel assured yet not being subjected to information overload from the vehicle system. For example, a common after-ride feedback in an autonomous vehicle prototype is that the vehicle was behaving over conservatively as compared to a typical human driver. The same observation was also made by Google after its self-driving cars were rear-ended several times by human-driven cars at traffic lights and road junctions⁹¹. In some situations, good judgement perceived by the human driver may compel one to act illegally, but how can such thought process be taught (subject to legal framework) to the autonomous vehicle? These questions are examples of green-field research areas that the technology developers are still trying to grapple with.

⁹⁰ <https://www.pddnet.com/news/2015/10/survey-shows-amount-trust-autonomous-vehicles>

⁹¹ <http://arstechnica.com/tech-policy/2015/06/google-self-driving-car-gets-rear-ended-in-13th-accident-since-2009/>

The level of social acceptance will influence the adoption rate, in addition to other factors such as the willingness to pay, and technology maturity. Policymakers may need to leverage policy tools to steer the direction of autonomous vehicle adoption, especially if they intend to incorporate fleet-sized self-driving vehicles to complement the public transportation system.

Data Management and Privacy

Connected mobility enables convenience and productivity gains for the consumer and the society, but also gives rise to concerns over how the voluminous datasets generated should be managed. In the context of an automobile, the data generated and collected may contain details on vehicle identifiers, travelling habits of the driver or passenger, and information about other road users (through the V2V and V2I communications). The fundamental question lies in the ownership of these data, as in are these data considered personal data and hence fall within the purview of the Personal Data Protection Act, or do these data belong to the manufacturers (for personal vehicles) or to the operators (for vehicles on vehicle-sharing or leasing arrangements)? In addition, with increasing concerns over data monetization, theft, and fraud, it is important to think about the role that the policymaker should play in safeguarding personal privacy and data security.

In July 2016, the German Transport Minister proposed new legislation to require carmakers to install a black box⁹² in autonomous vehicles that records when the autopilot system was active, when the driver did the driving, and when the system requested for the driver to take over, so as to help determine responsibility in the event of a crash, although privacy advocates may raise concerns over the proposed legislation.

Ultimately, policymakers need to consider how to balance the data requirements for autonomous vehicles with privacy protection. Lari, A. et al (2015) have suggested that policymakers may consider setting restrictions on secondary uses of data collected from autonomous vehicles, or setting time limits for the retention of the collected data. Depending on the nature of the policy, the participation can take the form of an opt-in

⁹² <http://www.reuters.com/article/us-germany-autos-idUSKCN0ZY1LT>

model (where consent has to be sought from individual before policy is effected) or opt-out model (policy is assumed to be effected unless individual choose to opt-out).

Liabilities and Insurance

As vehicle technologies move towards higher levels of autonomy, the responsibility or duty-of-care also gradually shifts from the human driver to the vehicle system. In a highly automated or fully autonomous vehicle, where the human has no decision control over the vehicle, attribution is likely to lean towards product liability than personal liability in the event of an accident. Complexity in the assignment of responsibility is further intensified if an autonomous vehicle gets into an accident with a human-driven car. Moreover, the emergence of private ride-hailing services, where the same vehicle can be used for both personal travel and for-profit ride-hailing transportation can also complicate liability claims.

Like in many countries, car owners in Singapore need to have insurance in order to drive. Most basic motor vehicle insurance policies cover third-party liability such as damage to other vehicles involved in an accident, injuries to their drivers and passengers, as well as injuries to the policyholder's passengers. It is unclear if the same insurance policy provides coverage for the driver and fee-paying passengers when the private vehicle is used for ride-hailing services.

Currently, ride-hailing companies in Singapore, such as Uber and Grab, require their drivers to possess a valid commercial insurance policy before they are allowed to pick up passengers⁹³. Commercial insurance is more expensive than private insurance, and some ride-hailing companies see this as a potential barrier to entry for new drivers. Therefore, new insurance schemes are being established, such as the collaboration between Grab and AXA Insurance on a usage-based commercial motor insurance⁹⁴ for private-hire car drivers in Singapore.

⁹³ <http://www.channelnewsasia.com/news/singapore/our-drivers-are-covered/2194362.html>

⁹⁴ <https://www.techinasia.com/grab-axa-launch-payasyougo-car-insurance-drivers-road>

With increasing complexity in driving scenarios and involvement of new actors (autonomous vehicles), as well as the changing and emerging business models (changing roles of vehicle owners, vehicle manufacturers, and vehicle operators), existing policies on regulation of insurance requirements may have to be reviewed. Eventually, if the driver is no longer required to operate the highly automated or fully autonomous vehicles, how should the passengers be insured, how can manufacturers prove themselves in an alleged liability claim, and who should be bearing the cost of the liability insurance?

Infrastructure

Singapore has a relatively robust road infrastructure, with standardized signage, and visible lane markings to facilitate the autonomous vehicle in perceiving the surrounding road environment. Nonetheless, to enable deployment of autonomous vehicles, policymakers may need to consider the need for additional physical and/or digital infrastructure for V2X applications (for connected vehicles), as well as review current policies on speed limits, traffic signal timings, traffic control devices, road lighting, and parking spaces. Decisions also have to be made on whether the highly automated or fully autonomous vehicles will operate on a dedicated lane or maneuver among human-driven vehicles in a mixed-use road environment.

Should V2X communications be enabled, policymakers will also need to determine the baseline standards for encryption and security protocols that critical infrastructure design must conform to prior to implementation⁹⁵. Best practices for cyber defense and response plans to address cyber breaches may also need to be established in tandem with the development of the autonomous and connected vehicle technologies, and infrastructure.

6.4 Recommendations

The implementation of autonomous vehicle capabilities is more than just a technological venture. Besides competing pathways in the research and development of autonomous

⁹⁵ <https://cdt.org/blog/self-driving-into-the-future-putting-automated-driving-policy-in-top-gear/>

vehicles, uncertainties in the extent of technology readiness, adoption and social acceptance also pose a challenge when developing policies to guide the development and operationalization of such new capabilities. However, these constraints should not deter one from embracing new technologies and applications.

In the following section, we will provide recommendations on the areas that policymakers can consider when developing a technology policy or implementation plan so as to: (1) Exploit the emerging technologies as they evolve, and (2) Monitor and intervene timely to adapt the policy or plan as the future picture becomes clearer.

Central to these recommendations are three key considerations: (1) The current technology readiness level of the autonomous vehicle technologies has not reached sufficient maturity for operationalization, (2) There is uncertainty in the timeline for vehicles to achieve full autonomy, with proven safety and reliability records, and (3) The forecast in adoption rate and market saturation of autonomous vehicles is hypothetical.

6.4.1 Kick-start with Driver-Assist Technologies

With fully autonomous vehicles, it is envisaged that the frequency and impact of crashes will be dramatically reduced, inferred from the fact that about 95% of road accidents today in the United States are caused by human error (Ernst & Young, 2014). This statement is premised on the belief that autonomous vehicle technologies will develop to a phase where the automated controls are proven to be safer than the human controls. While we work towards realizing this vision, a shorter term approach is to encourage the adoption of driver-assist technologies in current automobiles so as to minimize the risk of road accidents associated with driver distraction.

Currently in the market, driver-assist option packages are offered in luxury car models and include enhanced safety features such as adaptive cruise control, lane departure warning system, and collision warning system to alert the human driver of a possible impending collision. As per NHTSA's definition, these technologies are considered Level

1 to Level 2 automation, where they are intended to assist the driver in steering and/or braking while the human driver is still in overall control of the vehicle.

Policymakers in transportation agencies can encourage the promulgation of such driver-assist technologies through the following ways: (1) Raise awareness among drivers on the potential safety benefits of the driver-assist technologies, (2) Encourage automobile manufacturers to market enhanced safety driver-assist technologies as part of the mainstream car sales rather than exclusively to luxury car owners, (3) Incentivize car owners to consider models with enhanced safety driver-assist features when purchasing new cars, and (4) Impose regulations that mandate the installation of certain safety enhanced driver-assist features, such as in the case of air bags.

Besides enhanced safety, this approach enables policymakers to educate the general population on automated vehicle technologies, as a prelude to longer term plans to expand to fully autonomous vehicles when the technology, market, and environment are ready. Policymakers can also assess the effectiveness of incremental changes to current policies and observe the social perception and acceptance to such technologies. Another potential value of promulgation of driver-assist technologies is to progressively bring down the substantial price premium associated with the novel car technologies, as they gradually gain significant market share, leading to economies of scale.

6.4.2 Prototype and Pilot to Validate Hypotheses before Scaling Up

From the perspective of a policymaker, the uncertainties involved in being the forerunner in deploying autonomous vehicles are multifaceted. Firstly, the actual performance may not match expectations, both in terms of technical performance and adoption rates. Secondly, the timeline for technology maturity and operationalization is ambiguous, with market dominance even more indefinite. Thirdly, establishing performance assessment criteria (e.g., how safe is safe?), guidelines, and legislation to optimally safeguard the interests of key stakeholders are a challenge without sufficient knowledge about the limitations of the technology. Fourthly, the number of vehicle miles clocked does not

equate directly to the robustness of testing or maturity of technology; the use case i.e., test environment (urban versus highway) should be taken into consideration as well. In addition, there are also the unknown unknowns that may not be evident through theoretical studies, especially in such complex socio-technical systems that involve system-system, system-environment, and human-system interactions.

Therefore, an approach to mitigate the technical, schedule, and cost risks associated with the uncertainties is to start on a small scale, both in terms of size and complexity. It is important to understand that the progression from NHTSA's Level 1 to Level 4 autonomy is not a continuous path; in particular, the leap from Level 2 to Level 3 signifies a transfer of decision authority from the human driver to the autonomous vehicle. This implies that Level 2 technologies that appear to work favorably in the few seconds to provide driver-assist to the human driver during contingencies may require substantial improvements before they are capable of performing throughout the driving journey.

The proposed approach is targeted at deploying autonomous vehicles at NHTSA's Level 3 to Level 4. For example, an initial trial can be conducted in a test-circuit alike confined environment on a fixed route with supporting roadside infrastructure. While such a controlled test environment is not representative of the actual driving environment, this phase allows researchers to understand the basic behavior of the autonomous vehicle without interferences from external variables, and identify the learning requirements of the autonomous vehicle before proceeding to more complex dynamic driving environments. A test-circuit alike setting also reduces the associated safety hazards and mitigates the cost to set up the supporting roadside infrastructure and to conduct the test.

After the basic performance of the autonomous vehicle is sufficiently verified in a test circuit, it can progress to a more realistic driving environment on the public roads, on a limited scale, perhaps in a small town. Such environment allows for further testing of the vehicle's perception and navigation capabilities, as well as interactions with external elements such as its own fleet of autonomous vehicles, pedestrians, human-driven cars, dynamic road obstacles, and actual environmental conditions such as sunlight, rain, wind,

humidity, and temperature. Depending on the type of application, the testing can take place on a pre-determined fixed route on the public road, before expanding to navigation on a random route selected by the user.

Following small-scale testing in a town environment, the performance of the autonomous vehicle should be further validated in larger fleets and more complex driving environments (e.g., business districts, highways, and peak hour traffic) prior to operationalization. This is also likely the phase where majority of the vehicle miles will be accumulated to statistically evaluate the reliability and safety of the autonomous vehicle.

The entire process from prototyping to full-scale development is iterative, and the timeline for each phase of testing is variable and can be adjusted depending on the outcome of the testing, and the extent of effort required to analyze the test data, modify the system, and perform the testing again. Dividing the development and testing phase into multiple sub-phases allows the policymaker to easily track the progress of technology development, and more importantly exercise the option to accelerate or exit the investment depending on the outcomes of the testing. This in turn mitigates the risk of excessive outlays of budget, resources, and time in the investment.

During each phase of testing, adaptations to the current land transport policies, rules, and standards must be timely made to facilitate the commercial testing of autonomous vehicles on public roads yet ensuring safety compliance. Unlike the traditional policymaking process that is typically reviewed less frequently and at fixed intervals, the policy review for autonomous vehicles in this case is a continuous process and the frequency depends on the pace and scope of technology development over time. However, we should also recognize not all requirements can be easily adapted from current policies, as new technologies or capabilities may require a total reassessment of current policies or development of new policies.

6.4.3 Collaborate and Leverage

The diversity of players getting involved in the autonomous vehicle market and the amount of investments being ploughed into the research and development of autonomous driving technologies is a stark reflection of the complexity of the issue. Unlike past automotive-related innovations such as air bags or automatic transmission, development of systems is no longer restricted to a single domain and hence requires multidisciplinary knowledge from different players in the market. Take the example of autonomous vehicles, traditional automotive companies have deep expertise in building vehicle hardware and controls, but are less familiar with the perception and navigation technologies required to enable autonomous driving. Similarly, technology companies such as Google may have the capabilities in sensing and localization, but lack the experience and know-how in scaling up manufacturing for mass production of vehicles. Therefore, we see that numerous collaborations, partnerships, and acquisitions have taken place in the recent years between automotive companies, technology companies, research institutes, and other suppliers so as to leverage expertise and hopefully accelerate their developments to stay ahead of the curve in autonomous vehicle developments.

On the receiving end of the eventual capability, proactive engagement with the commercial companies is useful to allow the policymaker to understand the technology, its progress, capabilities, and limitations so as to develop suitable policies and legislation to allow for testing, certification, licensing, and deployment of autonomous vehicles in parallel with the technology developments. Unlike a customer-contractor relationship which is focused on delivering a specific solution, a partnership will enable the policymakers to: (1) Stay informed and make timely investments in requisite infrastructure, if required, to facilitate the deployment of autonomous vehicles, and (2) Align future city or town-planning masterplans taking cognizance of the potential introduction of autonomous vehicles.

For instance, using Singapore as an example, the Land Transport Authority can leverage its ongoing project in the next generation satellite-based electronic road pricing system to cater provisions for the requirements of dedicated short-range radio communications for V2X capabilities in autonomous vehicles. In addition, inter-agency collaboration would be beneficial too. The Singapore Land Authority (SLA) is leading a whole-of-government initiative to create and maintain a high-resolution accurate three-dimensional national map to support the increasing needs of government and agencies in operations, planning and risk management. Phase 1 of the project involved airborne data capturing to create terrain models and 3D building models, and the product was showcased at the Esri International User Conference in June 2016⁹⁶. Phase 2 of the project will involve mobile data capturing primarily to create 3D road models, and this is expected to be completed by 2017⁹⁷. 3D maps are essential for the operation of autonomous vehicles, and this is an opportune timing for LTA to collaborate with SLA as they embark on Phase 2 of the project.

Government research agencies and institutions can also explore collaboration with the commercial companies to bridge the connection between laboratory research and field-testing of autonomous vehicle technologies. Participation in international and regional conferences or multilateral meetings also serves as an ideal platform to learn, share, and exchange information in the research domain as well as at the policy level. Such involvement also helps the policymaker to keep tab on the global initiatives, coordination and standardization efforts, such as in DSRC or mapping requirements, across different autonomous vehicle platforms and in different regions of the world.

Policymakers can also encourage the private sector involvement in the development of autonomous vehicle technologies and capabilities through public-private partnerships with selected market players. Conventionally, public agencies tend to only engage the private sector to construct facilities or to supply equipment. Increasingly, public agencies

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<http://www.sla.gov.sg/News/tabid/142/articleid/621/category/Press%20Releases/parentId/97/year/2016/Default.aspx>

⁹⁷ <http://www.clc.gov.sg/documents/books/3D%20Mapping%20-%202027jan.pdf>

are also acquiring services from the private industries, and the services could for instance, take the form of a test and evaluation service, or a project on research and prototyping, in the context of autonomous vehicle developments. Through such collaborations and seeding of technologies, services may be delivered in a more value-for-money way and within a shorter timeline, without compromising quality and safety, through optimal use of the expertise, resources, and innovation in the private sectors to meet public needs effectively and efficiently (Singapore MOF, 2012).

6.4.4 Diversify and Keep the Options Open

Uncertainties in the technology and future outcomes can mean both an opportunity and a risk. Traditionally, decisions are made to mitigate downside consequences, but do not place much emphasis on capitalizing the upside opportunities. As discussed in Chapters 5 and 6, the technologies in autonomous vehicle developments are evolving and there are multiple possibilities and pathways that the eventual capability can take. At this point, it is unclear on the ideal approach that a technology developer should take, or a particular product that the consumer should adopt.

Therefore, the policymaker should not constrain his or her mindset to a particular solution and define policies around that limited space. Rather, an open outlook of the technologies and developments in the market is useful to identify leading indicators and trends as the technology developers continue to innovate, test, and validate their concepts and methodologies for the deployment of autonomous vehicles.

Policymakers should not be in a haste to secure commitments with specific manufacturers or developers, so as to avoid the situation of being locked-in to a premature solution. By keeping abreast with market developments and maintaining close relationships with the industry, the policymaker can: (1) Track the progression of the developments, (2) Evaluate the extent to which the developments could satisfy the required applications, (3) Gain clarity and assurance on the performance, safety, and life cycle properties of the system, and (4) Obtain a better sensing of the development timeline, before contractual

obligations are made. Flexibility should also be designed into the contracts to allow for small-scale implementation, while keeping the options to exercise for larger-scale deployment or variation in the system configuration depending on user feedback and adoption.

Interfaces between the autonomous vehicles and the interacting systems or infrastructure should be standardized where possible. Open architectures are preferred so as to allow ease of adapting to different solutions from different service providers and manufacturers, as well as to cater for system variants or similar applications. Embedding such flexibility in the system design can potentially lead to substantial savings as compared to the traditional deterministic approaches.

However, that does not equate to having a fixed set of specifications. For example, an autonomous vehicle with a definite set of sensors and proprietary software that does not provision for addition or upgrade with newer sensor technologies or improved software will render the system obsolete in a short time. Given the rapid developments and hype in this domain, a solution that is considered the state-of-the-art at the point of contract commitment may be superseded by more advanced systems at the point of delivery.

6.5 Application of Approach for Addressing Uncertainty in Policy Planning to the Case of Autonomous Vehicle Development in Singapore

In the last section of this chapter, we will illustrate a flexible approach for addressing uncertainty in policy planning using the case of autonomous vehicle development in Singapore. This approach is inspired from: (1) Flexibility in design by considering a wide range of possible scenarios and outcomes (de Neufville, R., 2011), and (2) Adaptive planning considerations by Kwakkel, J. H., et al. (2010).

Objectives, Constraints and Available Policy Options

Singapore has a vision to “move towards a more connected and interactive land transport community” by leveraging intelligent transport systems. In her strategic plan on Smart Mobility 2030, four key focal areas are identified, of which the focal area on “Assistive” encompasses connected and autonomous vehicles (LTA and ITS, 2014). Specifically, the main goals are to: (1) Enhance road safety, (2) Optimize road capacity, and (3) Increase labor productivity. There is a variety of strategies available to the policymaker, as summarized in **Table 6.3**, and the deployment of autonomous vehicles is recognized as one of the promising tools to complement existing policies to achieve these goals.

Table 6.3: Available Policy Options

Goal	Examples of Policy to Address Goal
Enhance road safety	<ul style="list-style-type: none"> • Legislation • Impose speed limits • Education • Driver certification • Driver training • Promulgation of driver-assist features • Connected vehicle technologies
Optimize road capacity	<ul style="list-style-type: none"> • Quota system for car ownership • Road pricing • Road expansion • Optimized traffic incident management • Optimized traffic signal timing • Increase reliability, density, and coverage of public transportation system • Autonomous vehicles for first-mile, last-mile • Promote car-sharing and ride-sharing • Promote walk, cycle, and taking public transportation
Increase labor productivity ⁹⁸	<ul style="list-style-type: none"> • Automation, innovation, and technology improvement • Training towards higher skilled workforce • Foreign manpower • Progressive wage model • Autonomous vehicles as driverless buses • Truck platooning technologies

⁹⁸ <http://lkyspp.nus.edu.sg/wp-content/uploads/2014/11/Productivity-challenges-in-Singapore-Part-3.pdf>

Some of these policies have already been implemented for years and the effectiveness may be approaching or have reached a saturation point. For other policies under consideration, such as introduction of autonomous vehicles, an adaptive approach would be to begin with plans to enable research, development, and testing of autonomous vehicles, as well as to provision for requisite infrastructure in master planning, but only to execute (i.e., build infrastructure or commit to acquisition) when conditions show that it to be favorable for mass deployment. The constraints to policy implementation include public cost, road safety, social behavior, public acceptance, technology limitations, and security considerations. The definition of policy success might include for instance, reduced injury or fatality rates due to road incidents, reduced number of vehicles on the road hence shorter travelling times, and reduced reliance on foreign manpower to supplement labor shortage in drivers.

Basic Policy and Conditions for Success

A basic policy could be to support the adoption of driver-assist features in all new car purchases, and to promote the usage of car-sharing and ride-sharing services. The implementation of the basic policy enables enhanced road safety features to be realized immediately, while raising the awareness of car-sharing and ride-sharing helps to gradually shift societal behavior from car ownership towards shared utilization.

The policy should also include options that allow for future possible additions, such as vehicles with higher level of autonomy, driverless buses or taxis, as the technology matures and public acceptance is being gained. The necessary conditions to measure the success of the basic policy could be: (1) The number of injuries or fatalities in road incidents attributed to driver distraction should be reduced, (2) The number of private car ownerships should not increase, and (3) The total number of vehicles on the road inclusive of shared vehicles should not increase.

Vulnerabilities and Opportunities of the Basic Policy, and Anticipatory Actions

The long term development of autonomous vehicles for deployment in Singapore is complicated by many factors, such as: (1) Multiple possible technological pathways, (2) Unintended consequences that may compromise safety and security due to the expected increased connectivity, and (3) Public resistance to shift behavior from car ownership towards public transportation and car or ride-sharing. Some of these developments are less certain than others, but they all present both opportunities and vulnerabilities.

Table 6.4 and **Table 6.5** list some examples of the policy actions that can be taken in response to the anticipated opportunities and vulnerabilities. The response actions are broadly categorized into: (a) Mitigating, (b) Shaping, and (c) Seizing to represent how the consideration of uncertainty in policymaking can help to both mitigate downside risks, and at the same time, take advantage of the upside opportunities.

Table 6.4: *More Certain* Vulnerabilities and Opportunities, and Response Actions

Vulnerabilities and Opportunities	Mitigating, Shaping, and Seizing Actions
Increased risk of cyber threats on connected vehicles.	<p>Consider and develop tools for detection and prevention of cyber threats as part of the design of connected vehicle systems. [Mitigating]</p> <p>Invest in research and development efforts to detect and analyze cyber vulnerabilities, and safeguard V2X data. [Shaping]</p>
Resistance from private car owners to give up car ownership.	<p>Continue to regulate number of private cars using existing quota system and road pricing. [Mitigating]</p> <p>Promote adoption of car-sharing and ride-sharing services prior to deployment of autonomous vehicles. [Shaping]</p> <p>Incentivize car owners to switch to alternative transportation means, by expanding the public transit network and reliability. [Shaping]</p>
Resistance from drivers on possible loss of livelihood due to introduction of driverless vehicles.	<p>Progressive introduction of driverless vehicles on a small-scale. [Mitigating]</p> <p>Review current manpower policy to align with the demand for manpower. [Shaping]</p>

Vulnerabilities and Opportunities	Mitigating, Shaping, and Seizing Actions
	Offer upgrading opportunities for existing employees to pursue higher-skilled level roles. [Seizing]
Increased attraction of Singapore as an ideal test bedding site for autonomous vehicles.	<p>Design and implement plans to support testing and evaluation of autonomous vehicle technologies. [Seizing]</p> <p>Promote a community of practice or center of excellence among the research institutions, government agencies, and industry partners to share and collaborate on autonomous vehicle development. [Seizing]</p>

Table 6.5: **Less Certain** Vulnerabilities and Opportunities, and Response Actions

Vulnerabilities and Opportunities	Hedging and Shaping Actions
A fully autonomous vehicle is launched to market faster than expected.	<p>Provision for (e.g., leverage satellite-based road pricing system, and SLA’s 3D mapping project) necessary infrastructure to enable deployment of autonomous vehicles. [Hedging]</p> <p>Develop legislation, standards, and guidelines and adapt to manage mixed fleet of human-driven and autonomous vehicles. [Hedging]</p> <p>Develop requirements for regular inspection, maintenance, and certification to ensure autonomous vehicles are fit for operation and do not endanger public road safety. [Hedging]</p> <p>Develop partnerships with industry players. [Shaping]</p>
A fully autonomous vehicle is launched to market slower than expected.	<p>Continue to strengthen robustness of public transit network. [Shaping]</p> <p>Promote car-sharing and ride-sharing in-lieu of car ownership. [Shaping]</p> <p>Promote driver-assist capabilities (lower autonomy levels) to enhance safety. [Shaping]</p>
A fully autonomous vehicle failed to make it to market due to technology difficulties.	<p>Prepare to accept vehicles with limited autonomy or constrained to specific driving conditions. [Hedging]</p> <p>Delink connected vehicle technology developments from fully autonomous vehicle developments. [Hedging]</p> <p>Invest in research and development on focal technology areas. [Hedging]</p> <p>Review manpower policy to upkeep demand for manpower. [Shaping]</p>

Vulnerabilities and Opportunities	Hedging and Shaping Actions
Decrease in number and severity of injuries and fatalities due to road incidents.	<p>Prepare to expand autonomous fleet of public buses and taxis as part of fleet renewal plans. [Hedging]</p> <p>Encourage car owners who still wish to retain car ownership to adopt car models with enhanced safety features. [Shaping]</p>
Increase in number and severity of injuries and fatalities due to road incidents.	<p>Review test and evaluation procedures of autonomous vehicles to identify safety issues. [Hedging]</p> <p>Restrict activation of autonomous driving modes to selected driving conditions. [Hedging]</p>
Demand for autonomous mobility-on-demand services grows faster than forecast.	<p>Design a good connection between the mass rapid transit stations and bus interchanges with the mobility-on-demand stops for first-mile and last-mile commuting. [Hedging]</p> <p>Develop applications to enable ease of accessing mobility-on-demand services by the general public. [Hedging]</p> <p>Have plans to expand requisite infrastructure (if required) to support mobility-on-demand services. [Hedging]</p> <p>Given the expected higher mileage accumulated by a shared vehicle, review requirements for regular inspection, maintenance, and certification to ensure the shared fleet is fit for operation and does not endanger public road safety. [Hedging]</p> <p>Prepare to adapt for private and public transit operating in parallel. [Hedging]</p>
Increased car ownership due to enhanced driving experience enabled by autonomous vehicles.	<p>Publicize for mobility-on-demand services in terms of potential cost and time savings, and convenience, as opposed to car ownership. [Shaping]</p> <p>Review quota system and road pricing to shape driver behavior. [Shaping]</p>
Worsening of road congestion due to enhanced mobility enabled by autonomous vehicles.	<p>Invest in research and development on real-time analytics of traffic conditions to anticipate emerging congestion situations and reroute drivers to avoid bottlenecks. [Hedging]</p> <p>Review quota system and road pricing to shape driver behavior. [Shaping]</p> <p>Review urban planning norms to decentralize business hubs but with easy access to public transit. [Shaping]</p>

Contingency Planning

After identifying the less-certain vulnerabilities and opportunities associated with autonomous vehicle developments, a monitoring and trigger system must be put in place to initiate a response when the trigger event is met. Numbers can be added to the trigger events to moderate the different levels of trigger and corresponding response. The response actions can be broadly categorized into: (1) Capitalizing, (2) Corrective, (3) Defensive, and (4) Reassessment.

Table 6.6: Contingency Planning – Monitoring and Trigger System

Vulnerabilities and Opportunities	To Monitor	Actions
A fully autonomous vehicle is launched to market faster than expected.	The progress of autonomous vehicle developments in the market.	If time to market is faster than forecast, begin to: (1) implement integration with supporting infrastructure and systems, (2) execute and adapt legislation, standards and guidelines for deployment of autonomous vehicles, and (3) execute requirements for inspection, maintenance and certification of autonomous vehicles. [Capitalizing] Reassessment of entire policy may be required if the actual scenario differs drastically from forecast. [Reassessment]
A fully autonomous vehicle is launched to market slower than expected.	The performance of existing public transit systems, and progress of transit network expansion.	If time to market is slower than forecast, reassess the capacity of existing public transit systems and ongoing expansion projects to handle the demand requirements. [Reassessment]
A fully autonomous vehicle failed to make it to market due to technology difficulties.	The technology readiness levels of the autonomous vehicle capabilities.	If the end product fails to achieve the desired level of full autonomy, but is proven to function safely in specific driving environments, adapt plan to allow for small-scale deployment of vehicles with limited autonomy. [Corrective] If the end product fails to demonstrate track records of safe operation, delay deployment of autonomous vehicles. [Defensive]
Decrease in number and severity of injuries	The incident records of autonomous vehicles at different phases as the	If autonomous vehicles are proven to result in lower number and severity of road incidents, begin plans to: (1) incorporate autonomous buses and taxis as part of fleet renewal plans,

Vulnerabilities and Opportunities	To Monitor	Actions
and fatalities due to road incidents.	technology transits from concept to an operational system.	and (2) attract adoption of vehicles with enhanced safety features. [Capitalizing]
Increase in number and severity of injuries and fatalities due to road incidents.	The casual factors attributed to incidents involving autonomous vehicles.	<p>If autonomous vehicles result in increased number and/or severity of road incidents, reassess the test and evaluation procedures to uncover deficiencies in safety validation. [Corrective]</p> <p>If the key causal factors attributing to the increased incident rates are due to interactions between human drivers and autonomous driving, reassess the mismatch in judgement and response behavior designed in autonomous vehicles vis-à-vis the real world driving environment. [Reassessment]</p> <p>If more time is required to analyze the causal factors leading to increased incident rates, withdraw deployment of autonomous vehicles. [Defensive]</p>
Demand for autonomous mobility-on-demand services grows faster than forecast.	The growth of car-sharing and ride-sharing, in terms of passenger numbers, as well as the number of car-sharing and ride-sharing service providers in the market.	<p>If mobility-on-demand services grow faster than forecast, accelerate: (1) development of applications to facilitate ease of usage of service, and (2) connections between existing public transit network with the mobility-on-demand stops. [Capitalizing]</p> <p>If car-sharing becomes more popular, reassess the requirements for inspection, maintenance, and certification to ensure shared fleet is fit for operations. [Reassessment]</p> <p>If the demand for car-sharing and ride-sharing continues to grow, reassess the policy to adapt for parallel operations of private and public transit. [Reassessment]</p>
Increased car ownership due to enhanced driving experience enabled by autonomous vehicles.	The changes in private car ownership numbers.	<p>If private car ownership numbers go up, expand publicity plans to promote the benefits of mobility-on-demand services that can provide equitable commuting experience without the cost burden of car ownership. [Corrective]</p> <p>There may also be a need to slow down the growth of private ownership of autonomous</p>

Vulnerabilities and Opportunities	To Monitor	Actions
		vehicle through the quota system and road pricing. [Defensive]
Worsening of road congestion due to enhanced mobility enabled by autonomous vehicles.	The road congestion situation, in terms of the number of vehicles on the road, occupancy rate per vehicle and the mileage travelled per vehicle.	<p>If the road congestion situation worsens, exercise plan to invest in real-time analytics of traffic conditions to advise drivers on reroutes to avoid bottlenecks. [Defensive]</p> <p>There may also be a need to slow down the growth of private ownership of autonomous vehicle through the quota system and road pricing. [Defensive]</p>

Implementation

Implementation refers to the execution of the basic policy, taking into consideration the opportunities and vulnerabilities, and being mindful of the monitoring and trigger system being put in place. Note that the basic policy does not include the actual commitment to deploy autonomous vehicles yet, but can be exercised when the technology readiness levels are attained, and when the demand for alternative mobility services increases. Therefore, this can be considered as a real option. Similarly, the associated infrastructure to support the deployment of autonomous vehicles need not necessarily be built yet, but are provisioned for in related projects so that they can be triggered when greater visibility on the forthcoming launch of an autonomous vehicle product is obtained.

During the implementation phase, the responsible agency needs to monitor the technology progress, market developments, and social acceptance in the local scene. The triggers are signposts to guide the focus of the monitoring activity. When the actual conditions turn out to be more favorable than predicted, capitalizing actions can be taken to leverage the upside opportunities. In the event that negative consequences arise, defensive or corrective actions can be taken timely to mitigate the side-effects. The policy is a live document that is constantly reassessed for adequacy and alignment to the evolving technologies and demand landscape. With the range of possibilities envisaged for the future, a proactive approach in policymaking is key in creating a coherent yet flexible series of plans.

CHAPTER 7 – CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Developing a policy amidst limited knowledge of future outcomes has been particularly challenging for the policymaker. The ability of the policymaker to conceive a set of policy options and adapt them in a timely fashion is a necessary condition for a successful policy implementation.

The hypothesis of this thesis is that autonomous vehicle technologies are evolving and there is no clearly defined technological pathway leading to a marketable product. This was evidenced from the market survey of the various automotive companies, technology developers, and start-ups involved in the development of autonomous vehicles, where the industry is experimenting with different approaches and exploring possibilities. The thesis also postulates that there is too much hype and over-expectations placed on the capabilities of autonomous vehicles at the current stage of development.

To substantiate the claim that the autonomous vehicle technologies are premature for operationalization, the thesis applied an established methodology known as the technology readiness level scale to measure the state of maturity of different technology components. It demonstrates that while the technologies may be proven to some extent for driver-assist applications, there is still a long way to go before they are ready for a fully autonomous drive.

With a realistic assessment of the technology developments, the thesis introduced the concept of real options to recognize and consider uncertainty so as to enable flexibility in policy design. This thesis identifies and analyzes three areas of uncertainty: (1) Rigor of safety validation, (2) Operationalization timeline, and (3) Expected benefit to manage road congestion. It discusses policy implications and proposes actionable recommendations to the policymaker for consideration, which are summarized as follows:

- (1) State policy objectives and identify policy options.
- (2) Start with a basic policy e.g., kick-start with driver-assist technologies.
- (3) Recognize areas of uncertainty and plan for a set of response actions.
- (4) Prototype and pilot to validate hypotheses before scaling up towards deployment.
- (5) Collaborate and leverage, across agencies and globally.
- (6) Do not commit prematurely; maintain options and diversify.
- (7) Establish trigger events and conduct active monitoring of developments.
- (8) Exercise response actions when trigger levels are met.
- (9) Review and adapt policy in tandem with technology and market developments.
- (10) Do not overlook possible unintended consequences as a result of new policy introductions, and manage them appropriately.

The thesis concludes by applying the real options based methodology to a case study of autonomous vehicle implementation in Singapore, and illustrates how an adaptive policy can allow the policymaker to timely apply policy levers to mitigate downside risks and leverage upside opportunities in situations where the future outlook is uncertain, as opposed to being restricted to a single definite plan. This approach can also allow for policies to gain traction first before they are implemented at scale.

The key takeaway message for the reader is: To be capability-defined but technology-agnostic; application-specific but solution-neutral.

7.2 Recommendations for Future Work

Besides the qualitative assessment of considering uncertainty in policymaking to develop a range of flexible and adaptive policy options as presented in this thesis, it will be interesting to quantify the value of the real options when more statistical data related to autonomous vehicle implementation becomes available.

Another interesting approach would be to apply system dynamics methodology to examine the behavior of the system variables over time. The system in this context refers to the autonomous vehicle and its interactions with the environment that it operates in. Using the reinforcing and feedback loop structures, one can better appreciate the sensitivity of the system model to perturbations in system elements, policies, delays, and uncertainties. The approach may also serve to validate and improve the policy options proposed in this thesis.

Finally, this thesis emphasizes the uncertainties related to technology, demand, social behavior, and more specifically to the context of Singapore. Future work can look into a comparative study of the effects of cultural and societal differences on the implementation of new technology policies.

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APPENDIX A – GLOBAL INVESTMENTS IN AUTONOMOUS VEHICLE DEVELOPMENTS

Table A-1: Investments by Automotive Manufacturers

Company	Development Efforts
Audi	<p>Adopts a gradual strategy by incorporating autonomous features into production models as they prove reliable. Currently offers production car technologies such as assisted driving in traffic jams in the Audi A4 and Audi Q7.</p> <p>In 2009, its self-driving TTS hit 130 miles per hour on the Bonneville Salt Flats. In 2010, it ran the 156-turn Pikes Peak mountain race circuit in 27 minutes, and raced on the California’s Thunderhill race track in 2012. In 2014, the RS7 “Bobby” completed a lap on Germany’s Hockenheimring, only slower than professionally trained humans by 30 seconds⁹⁹. In 2015, the RS7 “Robby”, which is 400 pounds lighter than “Bobby” completed a 2.5-mile circuit in California’s Sonoma Raceway¹⁰⁰.</p> <p>Was part of the 31-partner UR:BAN (a German acronym for Urban Space: User-oriented assistance systems and network management) cooperative project from 2012 to 2016 to develop driver assistance and traffic management systems for cities. Also part of the German consortium that acquired Nokia’s HERE high-definition mapping for \$3.1 billion.</p> <p>Claimed to be the world’s first carmaker to drive with an Audi A7 Sportback piloted car on a public road (Lee Roy Selmon Expressway near Tampa) in Florida in August 2014¹⁰¹.</p> <p>Demonstrated a 560-mile piloted highway driving (up to 70 miles per hour) from Silicon Valley to Las Vegas in January 2015 as part of the Consumer Electronics Show¹⁰².</p> <p>Reported in May 2016 that its latest research car, Audi A7 piloted driving concept “Jack” is now driving “more naturally¹⁰³”, such as passing trucks with a slightly wider lateral gap, and signaling upcoming lane changes by activating the turn signal and moving closer to the lane marking first, akin to a human driver behavior, through improvements in its central driver assistance controller (zFAS). Testing primarily conducted on expressways, the A9 autobahn, and included validation of V2X communications.</p>

⁹⁹ <https://www.wired.com/2014/10/audis-self-driving-car-hits-150-mph-f1-track/>

¹⁰⁰ <http://www.digitaltrends.com/cars/audi-rs-7-self-driving-prototype-news-pictures-specs/>

¹⁰¹ <https://www.audi-mediacycenter.com/en/press-releases/first-carmaker-worldwide-audi-tests-piloted-driving-systems-in-florida-511/download>

¹⁰² <https://www.audi-mediacycenter.com/en/press-releases/long-distance-test-drive-successfully-completed-audi-a7-sportback-piloted-driving-concept-arrives-in-las-vegas-following-560-mile-drive-411/download>

¹⁰³ <https://www.audi-mediacycenter.com/en/press-releases/audi-at-the-berlinale-piloted-drive-up-to-the-red-carpet-5515/download>

Company	Development Efforts
	<p>Plans to produce its first piloted system in the next model generation of Audi A8, capable of taking charge of driving in stop-and-go traffic at up to 37.3 miles per hour¹⁰⁴.</p> <p>Plans to invest a third of its R&D budget in electric vehicles, digital services, and autonomous driving. Targets to have electric cars accounting for 25% of its sales (equivalent to about 450,000 cars per year) by 2025. In 2015, Audi spent approximately \$4.69 billion on R&D¹⁰⁵.</p> <p>Will be testing construction methods such as the use of different types of pavement, as well as different technical solutions on the use of sensors at intersection zones at the city of Ingolstadt from 2017 to perform driving in an urban environment.</p>
BMW	<p>Launched its first connected car in 2002, and have delivered 8.5 million connected vehicles to customers as of July 2016. Every BMW is equipped with an embedded SIM, and 4G LTE is also being offered. The car also comes with the BMW ConnectedDrive to assist drivers in finding parking and charging spots. Currently offers automated driving features such as lane-keeping and remote control parking in the BMW 7 series models.</p> <p>Has been working with Baidu since 2014, and reported to have successfully tested a modified BMW 3-series autonomous car on an 18.6-mile route in Beijing in December 2015.</p> <p>Showcased the i-Vision Future Interaction concept at the Consumer Electronics Show 2016, using the BMW's i8 Concept Spyder. The concept included a fully gesture-based control user interface, a heads-up display showing important vehicle data on the windscreen, an instrument cluster displaying other information auto-stereoscopically¹⁰⁶, and uses a physical toggle switch to select between three different modes: Pure Drive (human in control), Assist (adaptive cruise control and lane-keeping) and Auto (steering wheel retracts towards the dashboard and the LEDs in the rim changes color)¹⁰⁷.</p> <p>At the Annual Accounts Press Conference in Munich in March 2016, BMW reveal initial details of their new strategy, of which Project i 2.0¹⁰⁸ aims to focus on high-definition digital maps, sensor technology, cloud technology, and artificial intelligence for automated and fully networked driving. BMW is also part of the German consortium that acquired Nokia's HERE high-definition mapping for \$3.1 billion.</p>

¹⁰⁴ <https://www.audi-mediacycenter.com/en/press-releases/safer-and-smoother-urban-traffic-audi-in-urban-collaborative-project-4942/download>

¹⁰⁵ <http://fortune.com/2016/07/19/audi-electric-cars-2025/>

¹⁰⁶ <https://www.press.bmwgroup.com/global/article/detail/T0262138EN/bmw-i-vision-future-interaction-wins-special-prize-at-auto-test-sieger-2016-awards-concept-car-shown-at-the-ces-2016-earns-new-distinction>

¹⁰⁷ <http://arstechnica.com/cars/2016/01/bmw-uses-ces-to-show-its-autonomous-i8-concept-to-the-world/>

¹⁰⁸ <https://www.press.bmwgroup.com/global/article/detail/T0258269EN/bmw-group-driving-the-transformation-of-individual-mobility-with-its-strategy-number-one-next>

Company	Development Efforts
	<p>In July 2016, BMW Group, Intel, and Mobileye jointly announced their collaboration on autonomous vehicles, with series production of an all-electric car targeted for 2021¹⁰⁹, and a fully autonomous version planned for 2025¹¹⁰.</p> <p>The BMW iNEXT model will serve as the foundation for the development for both highway and urban environment driving applications. The focus will be to lead in the development of an industry standard and define an open platform that can address different levels of automated driving: “hands off” (SAE Level 3), “mind off” (SAE Level 4) and “eyes off” (SAE Level 5). Based on an agreed common reference architecture, the partnership plans to demonstrate an autonomous test drive with a highly automated driving prototype in the near term, and extend to fleets with extended autonomous test drives in 2017¹¹¹.</p>
Daimler	<p>In May 2015, Daimler Trucks (a division of Daimler AG) was granted the first license to test the Freightliner Inspiration driverless truck on a public highway in Nevada, US, using a combination of GPS, Radar, and video cameras¹¹². The Freightliner Inspiration truck was based on the Freightliner Cascadia Evolution series production model. The similar technology is available on the Mercedes-Benz C-Class, known as the Steering Assist in the Distronic Plus adaptive cruise control system¹¹³.</p> <p>Daimler AG is also part of the German consortium that acquired Nokia’s HERE high-definition mapping for \$3.1 billion.</p> <p>Currently focusing on semi-autonomous trucks; does not have plans to develop fully autonomous trucks yet.</p>
Ford	<p>The second largest carmaker in the United States. An active participant in the DARPA controlled autonomous vehicle challenges in 2004, 2005, and 2007.</p> <p>Built its first-generation autonomous vehicle platform using a Ford F-250 Super Duty for participation in the DARPA challenges in 2005 and 2007. In 2013, Ford introduced its second-generation autonomous vehicle platform, using a Fusion Hybrid sedan.</p> <p>Announced in 2015 that it has created a team devoted to autonomous vehicle developments, based in Palo Alto. Also established the Ford Smart Mobility plan, with focus on the following technology areas: Connectivity (e.g., Ford SYNC entertainment and communications system, SYNC Connect to remotely access vehicle features, AppLink for drivers to voice control smartphone applications from the driver’s seat), Mobility (e.g., GoPark pilot program to build</p>

¹⁰⁹ <https://www.press.bmwgroup.com/global/article/detail/T0261655EN/statements-harald-krueger-klaus-froehlich-press-conference-memorandum-of-understanding-between-bmw-intel-and-mobileye>

¹¹⁰ <http://www.automobilemag.com/news/bmw-doubles-evs/>

¹¹¹ <https://www.press.bmwgroup.com/global/article/detail/T0261586EN/bmw-group-intel-and-mobileye-team-up-to-bring-fully-autonomous-driving-to-streets-by-2021>

¹¹² <http://www.bbc.com/news/business-32837071>

¹¹³ <http://www.forbes.com/sites/dougnewcomb/2015/05/08/daimler-autonomous-truck-has-huge-commercial-implications/#642e002a4978>

Company	Development Efforts
	<p>a predictive parking system in London, GoDrive car-sharing program in London, Dynamic Shuttle program at Ford's Dearborn campus to summon point-to-point rides on-demand), Autonomous Vehicles, Consumer Experience, and Data Analytics.</p> <p>Plans to have pre-collision assist and pedestrian detection features in all their vehicles by 2019¹¹⁴.</p> <p>Has been working with Carbon3D, a Redwood City-based company since 2014, which developed an advanced 3D printing process (Continuous Liquid Interface Production technology) that can grow car parts from plastic resins at speeds that are 25 to 100-times faster than conventional 3D printing processes, applicable for manufacture of automotive-grade parts¹¹⁵.</p> <p>Officially transited its autonomous vehicle development program from the research phase to the advanced engineering phase in summer 2015¹¹⁶.</p> <p>First carmaker to test a fully autonomous vehicle at Mcity, a simulated urban environment at the University of Michigan. Conducted the industry's first autonomous driving in snow-covered environments¹¹⁷ in Michigan in January 2016, using high-resolution 3D maps developed in collaboration with the University of Michigan.</p> <p>Plans to triple its investment in semi-autonomous driver-assist technologies including Traffic Jam Assist (to assist driver with steering, braking, and acceleration in heavily congested traffic situations), and Fully Active Park Assist (to help drivers with parking), to be rolled out by 2019¹¹⁸.</p> <p>In March 2016, established a new subsidiary, Ford Smart Mobility LLC to design, build, grow, and invest in new mobility services, as it expands its business model to be both an auto and a mobility company¹¹⁹. Plans to add 20 Fusion Hybrid autonomous vehicles in 2016 to a total fleet of 30 vehicles for testing on roads in California, Arizona, and Michigan. The vehicles will be equipped with Velodyne's new solid-state hybrid ultra-PUCK auto sensors. In May 2016, announced investment of \$182.2 million in Pivotal, a cloud-based software company headquartered in San Francisco, to strengthen its core software abilities¹²⁰.</p>

¹¹⁴ <http://www.businessinsider.com/ford-joins-rivals-developing-self-driving-cars-2015-6>

¹¹⁵ <http://www.forbes.com/sites/joannmuller/2015/06/23/ford-takes-a-step-closer-to-self-driving-cars/2/#111e22317a47>

¹¹⁶ <https://media.ford.com/content/fordmedia/fna/us/en/news/2015/06/23/ford-collaborates-with-silicon-valley-innovation-ecosystem.html>

¹¹⁷ <https://media.ford.com/content/fordmedia/fna/us/en/news/2016/03/10/how-fusion-hybrid-autonomous-vehicle-can-navigate-in-winter.html>

¹¹⁸ <http://www.cnbc.com/2016/02/22/ford-boosts-investment--semi-autonomous-cars-kuga-suv-mobile-world-congress-mwc16.html>

¹¹⁹ <https://media.ford.com/content/fordmedia/fna/us/en/news/2016/03/11/ford-smart-mobility-llc-established--jim-hackett-named-chairman.html>

¹²⁰ <https://media.ford.com/content/fordmedia/fna/us/en/news/2016/05/05/ford-invests-in-pivotal.html>

Company	Development Efforts
	<p>In July 2016, announced a research collaboration with MIT Aerospace Controls Laboratory to measure how pedestrians move in urban areas to improve ride-hailing and point-to-point shuttle services, using a fleet of on-demand electric shuttle vehicles¹²¹.</p> <p>Announced in August 2016 its intention to deliver high volume, fully autonomous vehicles (SAE Level 4 capable) for ride-sharing or ride-hailing services in a city area in 2021. To achieve that, Ford has increased investments in research in advanced algorithms, 3D mapping, Lidar, Radar, and camera sensors. Specifically, the four key recent investments are: (1) accelerate mass production of an affordable automotive Lidar sensor with Velodyne, (2) acquired Israel-based computer vision and machine learning company, SAIPS, to strengthen expertise in artificial intelligence and computer vision, (3) established an exclusive licensing agreement with Nirenberg Neuroscience LLC, a machine vision company to bring human-like intelligence to the machine learning modules of the autonomous vehicle virtual driver system, and (4) invested in Civil Maps to develop high-resolution 3D mapping capabilities¹²².</p>
General Motors	<p>Reported to be the largest carmaker in the United States.</p> <p>Announced a strategic partnership with South Korea’s LG Electronics Inc. in 2015 for supply of a majority of key components for its Chevrolet Bolt electric vehicle¹²³.</p> <p>In January 2016, launched its own car-sharing service, “Maven” in Ann Arbor, Michigan. Also acquired a ride-hailing San Francisco-based start-up, Sidecar Technologies.</p> <p>Entered into a strategic alliance with ride-share company, Lyft in January 2016, at an estimated investment of \$500 million. Plans to launch its first driverless electric car on the Lyft platform.</p> <p>Assembled a new team known as the Autonomous and Technology Vehicle Development Team, to map out an engineering strategy and seek partnerships and investments in self-driving. The team is led by Doug Parks, former vice president of global product programs in GM. The creation of this team was said to indicate GM’s transition from a research project to development of a production feature¹²⁴.</p>

¹²¹ <https://media.ford.com/content/fordmedia/fna/us/en/news/2016/07/27/ford--mit-project-uses-lidar--cameras--to-measure-pedestrian-tra.html>

¹²² <https://media.ford.com/content/fordmedia/fna/us/en/news/2016/08/16/ford-targets-fully-autonomous-vehicle-for-ride-sharing-in-2021.html>

¹²³ <http://www.wsj.com/articles/samsung-electronics-team-to-focus-on-parts-for-self-driving-cars-1449648196>

¹²⁴ <http://www.forbes.com/sites/dougnewcomb/2016/01/29/gm-assembles-dedicated-autonomous-vehicle-development-team/#be3da23f918d>

Company	Development Efforts
	<p>Acquired Cruise Automation, a San Francisco-based start-up that develops vehicle sensors, for an undisclosed sum (The Fortune reported it to be north of \$1 billion¹²⁵) in June 2016¹²⁶. As reported in August 2016, Cruise Automation has been testing autonomous driving on the GM's all-electric Chevrolet Bolt electric vehicle in Scottsdale, Arizona¹²⁷.</p> <p>Plans to launch the Super Cruise lane-centering system in the 2017 Cadillac CT6 which will allow drivers to take hands off the wheel when the vehicle is in cruise control, in limited driving environments, geo-fenced using high-detail maps. The system will also include a driver monitoring system to ensure that the driver is alert and paying attention to the road. GM is also leveraging on its OnStar telematics with its live human call center to ensure safety. The launch was deferred by a year from 2016 to 2017 to allow more time to refine the system¹²⁸.</p> <p>Collaborating with Mobileye to explore the use of cameras onboard its vehicles to automatically build high-definition mapping data for autonomous driving. It will use the cellular connection in its OnStar modules to upload a low bandwidth stream of differential mapping data to update a master database of information such as lane markings and precise location information¹²⁹.</p>
Honda	<p>Majority of Honda's core models such as the Civic, CR-V, Accord, and Pilot are able to be equipped with "Honda Sensing", while every Acura model is available with the "AcuraWatch" suite of safety and driver-assistive technologies. Aims to release its first self-driving cars in 2020.</p> <p>Approach is to promulgate autonomous vehicle technologies to the mass market, rather than selected luxury models.</p> <p>Received the license in 2015 to test its self-driving cars on public roads in California, but plans to spend more time on the test track to fine-tune its artificial intelligence algorithms with repeated testing in a controlled environment¹³⁰.</p> <p>In June 2016, Honda R&D Co, a research and development subsidiary of Honda, announced the establishment of a new R&D Innovation Lab in Tokyo. The new facility will be dedicated to the research and development of intelligent technologies associated to automated driving, connectivity, and robotics, and is expected to be opened by September 2016. The new lab is the latest addition</p>

¹²⁵ <http://fortune.com/2016/03/11/gm-buying-self-driving-tech-start-up-for-more-than-1-billion/>

¹²⁶ <https://techcrunch.com/2016/03/11/gm-buys-self-driving-tech-start-up-cruise-as-part-of-a-plan-to-make-driverless-cars/>

¹²⁷ <http://fortune.com/2016/08/09/cruise-automation-arizona-gm/>

¹²⁸ <http://www.forbes.com/sites/samabuelsamid/2016/07/23/general-motors-seeks-to-avoid-the-bleeding-edge-in-automating-vehicles/2/#4ba1c0fa71ad>

¹²⁹ <http://www.theverge.com/2016/1/5/10714374/gm-crowdsourced-self-driving-maps-onstar-ces-2016>

¹³⁰ <http://www.robotictrends.com/article/honda-self-driving-cars-test-skills-at-gomomentum-station>

Company	Development Efforts
	to its existing network of R&D facilities, including the ones in Frankfurt, Germany, Wako-City, Japan, Silicon Valley, and Columbus, Ohio ¹³¹ .
Hyundai	<p>South Korean carmaker. Plans to develop highly autonomous vehicle technology by 2020, and fully autonomous vehicle technology by 2030. In 2015, announced that Hyundai Motor Group will invest \$9.75 billion in R&D over the next five years for future driverless car technology, including the new Advanced Driver Assistance system.</p> <p>Launched the Hyundai Genesis EQ900 in 2015, which is equipped with an advanced highway driving assist system including the advanced smart cruise control, automatic emergency braking, and lane keep assist. The system is claimed to be able to autonomously maintain its distance from objects and other vehicles on the highway, and permits hands-free overtaking or passing of other vehicles when necessary¹³².</p> <p>Obtained the approval from the Korean transport ministry in March 2016 to trial its self-driving Genesis sedans on public roads (two sections of expressways and four sections of regular roads, with a combined distance of about 200 miles). Hyundai has previously obtained licenses to test its self-driving vehicles in Nevada in 2015¹³³.</p> <p>In April 2016, presented its roadmap for connected car development to collaborate with global IT and networking companies to develop its “Hyper-connected and Intelligent Car” concept. Four key areas were identified in the roadmap: (1) smart remote maintenance services, (2) autonomous driving, (3) smart traffic, and (4) a connected mobility hub¹³⁴. As a start, Hyundai will focus on the next generation in-vehicle networks for the connected car, and optimize the transmission and reception of data within the vehicle, and subsequently V2I and V2X communications. Hyundai is also collaborating with Cisco to create a testing environment for vehicle simulation with a Korean start-up, to verify new technologies for connected cars¹³⁵.</p> <p>In July 2016, established the Project IONIQ Lab, an open innovation organization to explore future mobility solutions. The Lab has identified 12 future megatrends that are likely to affect the car industry in 2030, ranging from hyper-connected society and eco-ism to decentralization of power and mega-urbanization¹³⁶.</p>

¹³¹ <http://hondanews.eu/en/corporate/media/pressreleases/73777/honda-opens-its-doors-to-co-creators-with-new-randd-innovation-lab>

¹³² <http://www.zdnet.com/article/hyundai-to-develop-fully-autonomous-cars-by-2030/>

¹³³ http://www.koreatimes.co.kr/www/news/biz/2016/03/123_199840.html

¹³⁴ <http://www.hyundaimotorgroup.com/MediaCenter/News/Press-Releases/hmc-roadmap-160405.hub#.V5zvoLgrl2w>

¹³⁵ <http://www.hyundaimotorgroup.com/MediaCenter/News/Press-Releases/hmc-Connectedcar-Cisco-160419.hub#.V5zvxbgrl2w>

¹³⁶ <http://www.hyundaimotorgroup.com/MediaCenter/News/Press-Releases/hmc-ioniq-lab-160722.hub#.V5zvObgrl2w>

Company	Development Efforts
	<p>Plans to launch a G80 model with fully autonomous driving capability in 2019, of which Uber is reported to be interested in¹³⁷.</p> <p>Was reported to be in talks with Google where it will bring its manufacturing prowess to Google, while Google will help advance Hyundai's autonomous technology developments¹³⁸. The former CEO of Hyundai Motor America, John Krafcik left Hyundai in 2013 and is now leading Google's self-driving vehicle project. Hyundai has also been aggressive in adopting Alphabet's Android Auto and Apple's CarPlay, which allow the Android smartphones and iPhones to connect wirelessly to car infotainment systems.</p>
Jaguar Land Rover	<p>Owned by India's Tata Motors, and is UK's largest automotive manufacturing business. Key player in the MOVE-UK project that is led by Bosch.</p> <p>In 2013, led a GBP 10 million, five-year collaboration with the UK Engineering and Physical Sciences Research Council, and four UK universities to study virtual simulation technologies¹³⁹.</p> <p>In 2015, announced a joint collaboration on a GBP 11 million research program on driverless automobiles with the UK Engineering and Physical Sciences Research Council¹⁴⁰.</p> <p>Approach is to focus on driver-assistance systems, and announced in 2016 that it plans to create a fleet of more than 100 research vehicles over the next four years to be tested on a 41-mile corridor in UK. The initial tests will involve V2V and V2I communications. Plans to design self-driving cars that operate "more like human drivers than a robot"¹⁴¹.</p> <p>Using a Range Rover research vehicle, Jaguar Land Rover is demonstrating a "Transparent Trailer" concept using a combination of a video feed from the vehicle's surround camera system and another video feed from the digital wireless camera on the rear of a trailer to create live video images that makes the trailer behind appear see-through, i.e., to remove the blind spot created when a vehicle is towing a trailer¹⁴².</p> <p>The company is also working on the following features: (1) Roadwork Assist that uses a forward-facing stereo camera to generate a 3D view of the road ahead and coupled with image processing software to recognize cones and barriers. The system will identify an ideal path and inform the driver that the road is narrowing ahead, and will then apply a small amount of steering resistance to help the driver remain centered in lane, (2) Safe Pullaway where</p>

¹³⁷ <http://readwrite.com/2016/06/16/uber-hyundai-talks-collaborate-self-driving-cars-korea-tt4/>

¹³⁸ <http://www.pcworld.com/article/3109498/car-tech/hyundai-in-talks-with-google-on-developing-self-driving-cars.html>

¹³⁹ <https://www.epsrc.ac.uk/newsevents/news/virtualengineeringresearchprogramme/>

¹⁴⁰ <http://www.techweekeurope.co.uk/e-innovation/jaguar-land-rover-announces-11m-driverless-car-plan-178686>

¹⁴¹ <http://fortune.com/2016/02/02/jaguar-self-driving-cars/>

¹⁴² <http://fortune.com/2015/09/01/jaguar-land-rover-blind-spot/>

Company	Development Efforts
	<p>the stereo camera will monitor the area ahead automatically apply brakes if objects are detected along a collision path, while the driver receives an audible warning, and (3) Over the Horizon Warning that uses radio signals to transmit relevant data from V2V to warn drivers of hazards ahead or around bends¹⁴³.</p>
<p>Mercedes-Benz</p>	<p>A brand of Daimler AG.</p> <p>Daimler-Benz initiated the EUREKA PROMETHEUS research project in 1986 and the test vehicles demonstrated largely autonomous driving on a multi-lane expressway in the greater Paris area, covering about 620 miles in 1994. One of the outcomes of the PROMETHEUS project was the DISTRONIC adaptive cruise control, which went into production in the S-Class in 1998. The project also resulted in the development of Speed Limit Assist, which went into production in 2005. The project also seeded the development of “6D Vision” stereo cameras, currently available in the S-, E-, C- and CLS-Class of vehicles¹⁴⁴.</p> <p>In August 2014, demonstrated autonomous driving on inter-urban and urban routes from Mannheim to Pforzheim (about 62 miles), using the S 500 Intelligent Drive research vehicle.</p> <p>Showcased the fully autonomous concept using the F015 Luxury in Motion research vehicle at the Consumer Electronics Show in 2015.</p> <p>Launched the 2017 model of E-Class that has an optional semi-autonomous Drive Pilot system, claimed to be capable of detecting and adjusting to different speed limit signs, change lanes on its own at the request of the driver, when travelling at a speed of up to 130 miles per hour¹⁴⁵.</p> <p>Besides cars, Mercedes-Benz is also developing autonomous buses. In July 2016, Mercedes-Benz unveiled its new “Future Bus with CityPilot”, claimed to be an upgrade of its Highway Pilot technology. This technology was demonstrated on a Bus Rapid Transit route from Schiphol Airport in Amsterdam to a town called Haarlem in the Netherlands¹⁴⁶. The 12-mile route comprises traffic lights, bendy roads, and tunnels. During the demonstration, the human driver needed to take control when there was oncoming traffic, as required by the local laws. The technology utilizes cameras, Radar, and connected data to navigate in urban areas with people, traffic lights, and obstacles. However, the company has no plans for a near-term rollout of the technology yet^{147,148}</p>

¹⁴³ <http://www.jaguarlandrover.com/gl/en/about-us/news/2016/07/13/jaguar-land-rover-to-start-real-world-tests-of-innovative-connected-and-autonomous-vehicle-technology/>

¹⁴⁴ <https://www.daimler.com/documents/innovation/other/daimler-theresearchcarsofmercedesbenzen-2011.pdf>

¹⁴⁵ <http://www.bmwblog.com/2016/05/29/bmw-needs-catch-mercedes-autonomous-tech/>

¹⁴⁶ <http://roboticsandautomationnews.com/2016/07/29/mercedes-autonomous-bus-takes-passengers-towards-a-future-of-spectacular-smart-cities/6405/>

¹⁴⁷ <https://cleantechnica.com/2016/07/25/mercedes-autonomous-bus-drives-12-miles-amsterdam/>

¹⁴⁸ <https://www.engadget.com/2016/07/18/mercedes-autonomous-bus-makes-a-landmark-trip-on-public-roads/>

Company	Development Efforts
Nissan	<p>Japan's second largest automotive company and is part of the Renault-Nissan Alliance.</p> <p>Plans to have 10 vehicles on sale by 2020, with "significant autonomous functionality"¹⁴⁹. Does not plan to build a fully self-driving car; rather aiming to build a car that can avoid most accidents while also allowing the driver to hand over control to the car at certain times. The systems are also designed to allow the driver to manually take over control at any time¹⁵⁰.</p> <p>Revealed its autonomous drive prototype technology at "Nissan 360" in California in 2013, and was granted the first license in Japan to test its modified Nissan LEAF research vehicle on public roads in 2013.</p> <p>In 2013, opened a research center in Silicon Valley as Nissan's hub for research in self-driving vehicles and Internet-connected auto technology, staffed by more than 60 engineers and technicians within the next three years. The center is led by Maarten Sierhuis, a former NASA scientist in artificial intelligence¹⁵¹.</p> <p>In 2015, established a five-year research and development partnership with NASA to advance autonomous vehicle systems. The focus will be on creating autonomous drive systems, network-enabled applications, human-machine interface solutions, software analysis and verification, involving hardware and software used in space applications¹⁵².</p> <p>Also begun testing its first prototype vehicle that demonstrates piloted driving on both highways and city urban roads in 2015. Key technologies on the vehicle include a miniature high-specification laser scanner to derive precise measurements for navigating routes in tight spaces, and an 8-way, 360-degree view camera system for accurate routing when driving through intersections and sharp curving roads¹⁵³.</p> <p>Unlike Google that uses highly detailed maps, Nissan's plan is to use sparse maps for navigation, which are less detailed and are based on third party data¹⁵⁴.</p> <p>Launched the new Serena minivan model in late August 2016, which is equipped with the Nissan ProPILOT autonomous drive technology for single</p>

¹⁴⁹ <http://www.cnet.com/roadshow/news/nissan-ceo-carlos-ghosn-talks-self-driving-cars-evs/>

¹⁵⁰ <http://www.recode.net/2016/1/12/11588668/riding-in-nissans-self-driving-car-is-still-a-white-knuckle-affair>

¹⁵¹ <http://www.bloomberg.com/news/articles/2013-02-18/nissan-opens-silicon-valley-center-for-self-driving-car-research>

¹⁵² <https://www.rt.com/business/221151-nasa-nissan-autonomous-cars/>

¹⁵³ <http://nissannews.com/en-US/nissan/usa/channels/us-nissan-technologies-autonomous-driving/releases/nissan-conducts-first-on-road-test-of-prototype-vehicle-featuring-piloted-drive-on-highway-and-city-urban-roads?page=2&query>

¹⁵⁴ <http://www.fastcompany.com/3040699/what-its-like-to-ride-the-streets-of-silicon-valley-in-nissans-autonomous-electric-car>

Company	Development Efforts
	<p>lane highway driving only^{155,156}. The technology when activated by the driver will automatically control the distance between the vehicle and the preceding vehicles, using a speed preset by the driver. The system will also keep the car in the middle of the highway lane by reading lane markers and control steering, even when driving through curves¹⁵⁷.</p> <p>Also plans to introduce ProPILOT in the Qashqai model in Europe in 2017. A multi-lane autonomous driving technology to enable automatic lane change on highway is planned for introduction in 2018, while autonomous driving on urban roads and intersections is planned for 2020.</p>
PSA Peugeot Citroen	<p>A French vehicle manufacturer with brands including the Peugeot, Citroen, and DS. Obtained approval to conduct tests for its self-driving cars on the public roads in France in July 2015. As of April 2016, four Citroen C4 Picasso prototypes were reported to have clocked more than 12,000 miles in autonomous mode from Paris to Bordeaux, and Paris to Vigo in Spain.</p> <p>In April 2016, announced that two Citroen C4 Picasso cars had driven more than 186 miles in SAE Level 3 autonomous mode from Paris to Amsterdam as part of “The Experience” event at the informal summit of EU transport ministers¹⁵⁸. Currently, the driver-assist system works primarily on freeways and is activated at the driver’s request, when driving conditions permit.</p> <p>Plans to offer driver-monitored automated driving features (e.g., traffic jam assist) from 2018, and introduce completely autonomous driving features from 2020. Also plans to introduce an over-the-air updating system in 2018 that will automatically download new versions of the infotainment software without input from the driver, similar to the system that Tesla has for its current vehicles¹⁵⁹.</p>
Tesla	<p>Released the first mass-produced Tesla Roadster electric car in US in 2008.</p> <p>Described as adopting an aggressive strategy¹⁶⁰ and fast-moving pace in the introduction of technologies by pushing improvements down to car owners nearly immediately via the over-the-air updates¹⁶¹.</p> <p>In October 2014, started to equip its Model S with hardware to allow for incremental introduction of self-driving technology, that included a forward</p>

¹⁵⁵ <https://newsroom.nissan-global.com/releases/160824-01-e>

¹⁵⁶ <http://www.forbes.com/sites/bertelschmitt/2016/07/13/nissans-autonomous-propilot-like-teslas-autopilot-very-carefully/#2439a919791d>

¹⁵⁷ <http://nissannews.com/en-US/nissan/usa/channels/us-nissan-technologies-autonomous-driving/releases/nissan-s-new-serena-propilot-technology-makes-autonomous-drive-first-for-japanese-automakers>

¹⁵⁸ <http://media.groupe-psa.com/en/psa-peugeot-citroen/C3%ABn/press-releases/innovation-technology/autonomous-cars-paris-amsterdam>

¹⁵⁹ <http://www.digitaltrends.com/business/peugeot-citroen-push-to-pass-plan-news-details/>

¹⁶⁰ <http://money.cnn.com/2016/07/28/technology/elon-musk-tesla-autopilot/index.html>

¹⁶¹ <http://www.roadandtrack.com/new-cars/car-technology/news/a30186/tesla-autopilot-crash-employees-worried/>

Company	Development Efforts
	<p>Radar, a forward looking camera, 12 long range ultrasonic sensors, and a digitally-controlled electric-assist braking system. The Radar is meant to be a supplementary sensor to the primary camera and image processing system.</p> <p>In October 2015, released the Version 7.0 software that allows the “Autopilot” function to steer within a line, change lanes, and manage speed using active, traffic aware cruise control when driving on the highway. A Version 7.1 was released in early 2016 that was claimed to expand its autopilot functionality, and introduced the first iteration of Summon, a remote parking technology¹⁶². An interesting point to note is that the vehicle only had Radar and an eight-camera system to see all around the car, but no Lidar (which is a common technology used by other manufacturers; but Tesla said that Lidar was an overkill for driving vehicles).</p> <p>A 2015 Tesla Model S was travelling eastbound on US Highway 27A in Florida where it collided with a 2014 Freightliner Cascadia truck-tractor in combination with a 53-foot trailer. The driver of the Tesla died as a result of the crash. Preliminary investigations by NTSB revealed that the Tesla was travelling at 74 miles per hour prior to impact, that was above the speed limit of 65 miles per hour, and the car was operating using the advanced driver assistance features Traffic-Aware Cruise Control and Autosteer Lane-keeping Assistance¹⁶³.</p> <p>Announced in its Master Plan, Part Deux released in July 2016 that Tesla will “expand to cover the major forms of terrestrial transport”, and unveil the first models of autonomous buses and trucks in 2017¹⁶⁴.</p> <p>Announced in September 2016 that it is preparing for a significant upgrade to its autopilot technology, and that will be featured in the Version 8 of its autopilot software¹⁶⁵. The noteworthy change is the switch of its primary control sensor from the camera and image processing system to the onboard Radar coupled with more advanced signal processing, without requiring the camera to confirm visual image recognition. It will also include a “geo-coded whitelist” of objects such as road signs and bridges to help prevent false positives and allow the system to notice the potential for crashes that may previously have been ignored. The software upgrade will also incorporate visual and audible warnings to reduce inattentive autopilot usage¹⁶⁶.</p> <p>Tesla was also reported to be entering the car insurance business starting with the “<i>InsureMyTesla</i>” program in Australia and Hong Kong, in partnership with QBE Insurance and AXA General Insurance respectively¹⁶⁷.</p>

¹⁶² <https://www.tesla.com/blog/enhancing-safety-and-convenience-summon>

¹⁶³ <http://www.nts.gov/investigations/AccidentReports/Pages/HWY16FH018-preliminary.aspx>

¹⁶⁴ https://www.tesla.com/en_GB/blog/master-plan-part-deux

¹⁶⁵ <http://www.theverge.com/2016/9/11/12880814/tesla-preparing-significant-autopilot-upgrade-will-use-radar-as>

¹⁶⁶ <https://www.tesla.com/blog/upgrading-autopilot-seeing-world-radar>

¹⁶⁷ <https://electrek.co/2016/08/30/tesla-enters-car-insurance-business-self-driving-cars-prepare-disrupt-industry/>

Company	Development Efforts
Toyota	<p>Considered a late entrant to the autonomous vehicle technology domain. As recent as 2014, Toyota CEO, Toyoda, said that he was not inclined to take autonomous technology seriously until a self-driving car could beat the best humans in a 24-hour test on a top German racetrack. Previously, Toyota has also turned down the offer from Google to cooperate on the technology due to reluctance to share manufacturing know-how¹⁶⁸.</p> <p>In 2015, announced that a new company, Toyota Research Institute Inc. will be established in January 2016 as an R&D enterprise with an initial focus on artificial intelligence and robotics. The company is headquartered in Silicon Valley, with a second facility near MIT in Cambridge, Massachusetts. The initial investment is estimated to be \$1 billion over five years.</p> <p>Toyota also has a separate \$50 million investment with MIT and Stanford to establish joint fundamental artificial intelligence research centers at the universities over the next five years, focusing on advanced architecture to enable cars to perceive, understand, and interpret, as well as computer vision and machine learning¹⁶⁹. In April 2016, Toyota announced its third university collaboration in the US with the University of Michigan on artificial intelligence research¹⁷⁰.</p> <p>Recruited all the 16 software and hardware engineers at Jaybridge Robotics Inc., a 7-year old MIT spinoff, to be involved in the work at Toyota Research Institute¹⁷¹.</p> <p>In May 2016, was reported to invest in Uber, with no disclosure on the size and scope of the investment. The companies plan to create new leasing options such that Uber drivers can lease Toyota vehicles and cover their payment through driving income¹⁷².</p> <p>Toyota have also partnered with KDDI Corp. to establish a global communications platform. The platform will enable the operation of communications networks throughout the world to support car connectivity¹⁷³.</p> <p>Was reported to be collaborating with Microsoft to consolidate its research in telematics, data analytics, and network security services, using Microsoft's Azure cloud technology, at an initial investment of \$5.5 million.</p>

¹⁶⁸ <https://www.technologyreview.com/s/601504/toyota-makes-a-u-turn-on-autonomous-cars/>

¹⁶⁹ <http://pressroom.toyota.com/releases/toyota+establish+artificial+intelligence+research+development+company.htm>

¹⁷⁰ <http://www.wsj.com/articles/toyota-teams-up-with-university-of-michigan-researchers-on-autonomous-driving-1460056847>

¹⁷¹ <http://www.wsj.com/articles/toyota-grabs-tech-talent-by-hiring-entire-jaybridge-staff-1457553870>

¹⁷² <http://www.freep.com/story/money/cars/2016/05/24/toyota-invests-uber-ride-sharing-lease-vehicles-drivers/84863156/>

¹⁷³ <http://www.hybridcars.com/toyota-and-honda-investing-in-connected-cars-and-a-i-to-compete-with-silicon-valley/>

Company	Development Efforts
	<p>Also said to be planning to acquire two robotics divisions from Alphabet Inc., Google's parent company: Boston Dynamics, a US-based firm, and Schaft, founded by a University of Tokyo graduate¹⁷⁴.</p>
Volkswagen	<p>Part of a consortium involved in Project V-Charge¹⁷⁵, that aims to develop a smart car system that allows for autonomous driving in designated areas and can offer advanced driver support in urban environments. The project started in 2015 and plans to demonstrate a fully operational future car system including autonomous local transportation, valet parking, and battery charging on the campus of ETH Zurich and TU Braunschweig¹⁷⁶.</p> <p>At the Geneva International Motor Show in February 2016, announced three new "Future Centers" in Europe, Asia, and California where designers and digitalization experts will work together on the car of the future¹⁷⁷.</p> <p>In May 2016, announced that it has made a \$300 million investment in Gett (formerly GetTaxi), a ride-hailing provider, with the intent to jointly expand on-demand mobility services in Europe¹⁷⁸.</p> <p>Volkswagen is also acquiring a stake in the German Research Center for Artificial Intelligence to reinforce its research activities in the field of future oriented digital technologies¹⁷⁹.</p> <p>Announced plans to produce 2 to 3 million all-electric cars a year by 2025. Reportedly to be working on a plan for a multi-billion-euro battery factory, comparable in scale to Tesla's Gigafactory¹⁸⁰.</p> <p>Signed a memorandum of understanding with LG Electronics on joint research and development for the next generation connected car service platform. The collaboration specifically focused on: (1) developing technologies that bring together the connected car and the smart home, (2) developing a context-sensitive notification center that can deliver messages in an intuitive and safe manner and provide optimized recommendations to the driver in real time, and (3) developing the next generation infotainment technology for connected cars¹⁸¹.</p> <p>Unveiled its VW ID electric vehicle at the 2016 Paris Auto Show in September 2016, which plans to be shipped in 2020, and will be equipped with self-driving capabilities by 2025. The VW ID motor configuration is similar to the BMW i3,</p>

¹⁷⁴ <http://www.hybridcars.com/toyota-may-buy-two-robotics-units-from-googles-parent-company/>

¹⁷⁵ <http://www.digitaltrends.com/cars/volkswagen-v-charge-project-self-driving-cars-self-charging-cars-pictures/>

¹⁷⁶ <http://www.v-charge.eu/>

¹⁷⁷ http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2016/02/Digitalisierung.html

¹⁷⁸ http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2016/05/Gett.html

¹⁷⁹

http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2016/05/Kuenstliche_Intelligenz.html

¹⁸⁰ <http://electrek.co/2016/06/16/vw-2-3-million-all-electric-cars-2025/>

¹⁸¹ http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2016/07/connected_car.html

Company	Development Efforts
	with the engine driving the rear wheels, unlike the Nissan Leaf nor Chevrolet Bolt ¹⁸² .
Volvo	<p>Acquired by Zhejiang Geely Holding of China in 2010. The company has a “Vision 2020” plan that is by year 2020, no one should be killed or seriously injured in a new Volvo.</p> <p>Created a Volvo “Concept 26”, a dual-function car interior with seats built for the autonomous vehicle customer who wants to drive a luxury vehicle sometimes, but who also wants to delegate the time spent commuting (26 minutes on average for an American driver). Volvo believes that people do want to drive, but they just do not want to drive when driving is boring¹⁸³.</p> <p>Unveiled its IntelliSafe Auto Pilot interface in October 2015, which allows drivers to switch in and out of the autonomous mode and claimed that the company will accept full liability whenever one of its cars is in autonomous mode. The IntelliSafe Auto Pilot will be available on 100 units of XC90 model cars that Volvo will make for its Drive Me project in Gothenburg, Sweden in 2017. The public pilot study will involve self-driving cars on about 30 miles of selected roads in and around Gothenburg, including commuter arteries with motorway conditions and frequent queues. The 100 units of XC90 were developed using the new Scalable Product Architecture that is designed for continuous introduction of new support and safety systems, and technologies that enable highly autonomous driving¹⁸⁴.</p> <p>The interface was developed to oversee how drivers will transfer control to a car’s autonomous driving mode in future cars¹⁸⁵. The Drive Me – Self-driving cars for sustainable mobility project is a joint initiative between Volvo Car Group, the Swedish Transport Administration, the Swedish Transport Agency, Lindholmen Science Park, and the City of Gothenburg. The project started in 2014. In 2016, Volvo also announced that they planned to initiate similar public pilot projects in the United States and China, with no details on the timeline¹⁸⁶.</p> <p>As of June 2016, the XC90 production models are equipped with lane assist technology that allows self-driving on a freeway, up to 30 miles per hour, as well as automatic braking at intersections.</p>

¹⁸² <http://www.extremetech.com/extreme/236613-meet-the-vw-id-electric-car-300-plus-mile-range-in-2020-self-driving-by-2025>

¹⁸³ <http://arstechnica.com/cars/2015/11/hanging-out-in-volvos-concept-26-a-reinvented-seat-for-a-self-driving-car/>

¹⁸⁴ <https://www.media.volvocars.com/global/en-gb/media/pressreleases/136182/volvo-car-group-initiates-world-unique-swedish-pilot-project-with-self-driving-cars-on-public-roads>

¹⁸⁵ <http://fortune.com/2015/10/07/volvo-liability-self-driving-cars/>

¹⁸⁶ <http://www.autonews.com/article/20160411/OEM06/304119957/volvo-plans-self-driving-trial-in-u.s.>

Company	Development Efforts
	<p>Entered into a partnership with Uber, at an estimated combined investment of \$300 million, to produce a road ready autonomous car based on the XC90 platform by 2021¹⁸⁷.</p> <p>Volvo is also forming a joint venture with the Swedish automotive safety supplier (a Tier 1 supplier), Autoliv¹⁸⁸ to develop autonomous driving software and sell it to other automakers. Plans to target the upmarket personal car ownership as its initial customers, and estimates the autopilot function to add about \$10,000 to the car price¹⁸⁹.</p>
Yutong	<p>A Chinese large-scale industrial group specialized in the bus business, and is also involved in construction machinery, automotive parts and components, and real estate, with headquarters in Zhengzhou, Henan province.</p> <p>In August 2015, demonstrated a driverless bus on a 20-mile route on an intercity road from Zhengzhou to Kaifeng in China, performing automatic lane change, overtaking, and responding to traffic lights, with its highest speed reaching 42 miles per hour¹⁹⁰.</p> <p>Reported to have spent three years of R&D in autonomous driving technologies prior to the demonstration. Plans to subject the driverless bus to another three development stages, namely basic movement control, driving on average road conditions, and driving on race lanes.</p>

¹⁸⁷ <https://techcrunch.com/2016/08/18/uber-and-volvo-put-300m-into-building-self-driving-cars-ready-for-sale-by-2021/>

¹⁸⁸ <http://www.theverge.com/2016/9/6/12805388/volvo-autoliv-autonomous-self-driving-joint-venture>

¹⁸⁹ <https://techcrunch.com/2016/09/29/volvo-to-target-luxury-buyers-with-self-driving-car-coming-in-5-years/>

¹⁹⁰ <http://en.yutong.com/pressmedia/yutongnews/2015/2015IBKCFbteUf.html>

Table A-2: Investments by Technology Developers

Company	Development Efforts
Apple	<p>Has never publicly acknowledged its work on autonomous cars, but was rumored to be running a secret autonomous electric vehicle initiative, codenamed Project Titan.</p> <p>Appointed Bob Mansfield, a senior Apple executive to oversee the project in July 2016¹⁹¹, after the previous head, Steve Zadesky left. CB Insights claims that the Apple team for this project has grown to over 1,000 employees, many of which were poached from Tesla, Carnegie Mellon, Volkswagen, and Nvidia¹⁹². It was reported that Apple has delayed its target launch date of the “Apple Car” or “iCar” from 2020 to 2021¹⁹³.</p> <p>Also recruited Dan Dodge, the founder of QNX (the operating system developer that Blackberry acquired in 2010). The operating system is used in the car infotainment systems used by Volkswagen, Daimler, and Ford¹⁹⁴.</p> <p>There were also reports suggesting that Apple is considering the BMW’s i3 as the basis for its project and is in talks with BMW for potential partnership in automotive manufacturing¹⁹⁵. The Guardian also reported that Apple was in contact with GoMentum Station, a 2,100-acre former naval base near San Francisco, which is being turned into a high security test ground for autonomous vehicles¹⁹⁶, and had also met with officials at the California Department of Motor Vehicles in September 2015¹⁹⁷.</p> <p>As of May 2016, Apple has invested \$1 billion in Chinese ride-hailing service, Didi Chuxing (which has its strategic partnership with Lyft)¹⁹⁸.</p> <p>Apple was also reported to have spent \$10 billion in research and development costs, which is more than triple of what it spent four years ago (about \$3 billion), with observers speculating that the massive increase in R&D could be an indication that Apple is developing something more than simply a new iPhone, iPad or Mac device¹⁹⁹.</p>

¹⁹¹ <http://www.wsj.com/articles/apple-taps-bob-mansfield-to-oversee-car-project-1469458580>

¹⁹² <https://www.cbinsights.com/blog/autonomous-driverless-vehicles-corporations-list/>

¹⁹³ <http://fortune.com/2016/07/21/apple-car-delay/>

¹⁹⁴ <http://www.bloomberg.com/news/articles/2016-07-28/apple-taps-blackberry-talent-as-car-project-takes-software-turn>

¹⁹⁵ <http://appleinsider.com/articles/15/09/15/apples-project-titan-car-faces-manufacturing-roadblocks-could-necessitate-partnership>

¹⁹⁶ <https://www.theguardian.com/technology/2015/aug/14/apple-self-driving-car-project-titan-sooner-than-expected>

¹⁹⁷ <https://www.theguardian.com/technology/2015/sep/18/apple-meets-california-officials-self-driving-car>

¹⁹⁸ <http://www.forbes.com/sites/rahilbhagat/2016/05/16/apple-all-but-confirms-auto-ambitions-with-latest-billion-dollar-investment/#2a026c334df9>

¹⁹⁹ <http://www.macworld.co.uk/news/apple/will-apple-make-icar-project-titan-rumour-roundup-ford-tesla-budget-date-3425394/>

Company	Development Efforts
	<p>Lost Bart Nabbe, who worked on computer vision, navigation, and artificial intelligence on Apple’s special projects team to an electric car start-up, Faraday Future, in July 2016²⁰⁰.</p> <p>Reported to be rethinking about its strategy in self-driving car developments, with rumors of layoffs of some employees, and purported shift in focus²⁰¹ from design and production of an automobile (hardware) to building the underlying technologies (software and services) for an autonomous vehicle.</p>
Baidu	<p>A leading Chinese language Internet search provider and has its own data-mapping service. Invested \$10 million in a Finnish mapping start-up IndoorAtlas in September 2014²⁰². Also a strategic investor in ride-sharing company, Uber.</p> <p>Started its self-driving program in 2013²⁰³. Established a partnership with BMW in April 2014 and reported to have successfully tested a modified BMW 3-series autonomous car on an 18.6-mile route in Beijing in December 2015. Plans to have a self-driving shuttle on Chinese public roads by end-2018, launch autonomous vehicles in 10 Chinese cities (including Wu Hu) by 2019 and ramp up to mass production by 2021. Intends to swap the modified BMW 3-series to a modified Chery EQ for the Chinese market.</p> <p>Partnered with BYD, a Chinese electric carmaker to equip the vehicles with Baidu’s AutoBrain system, a software for autonomous driving²⁰⁴.</p> <p>Announced in April 2016 that it has established a research and development center for self-driving car technology in Silicon Valley and plans to grow the team to over 100 researchers and engineers by end-2016²⁰⁵. Obtained its autonomous vehicle testing permit from California DMV in September 2016²⁰⁶.</p> <p>Strategy is to incrementally advance the technology through different environments (e.g., fixed route), rather than through different levels of driving autonomy. Currently, detailed maps of the driving environment for the fixed route is pre-loaded, while the vehicles focus its sensors and computing power and temporary obstacles such as pedestrians and other cars²⁰⁷.</p>

²⁰⁰ <http://fortune.com/2016/08/15/apple-car-project-faraday-future/>

²⁰¹ http://www.nytimes.com/2016/09/10/technology/apple-is-said-to-be-rethinking-strategy-on-self-driving-cars.html?_r=0

²⁰² <https://www.theguardian.com/technology/2015/jun/10/baidu-could-beat-google-self-driving-car-bmw>

²⁰³ <https://www.wired.com/2016/06/chinas-plan-first-country-self-driving-cars/>

²⁰⁴ <http://fortune.com/2016/01/25/baidu-driverless-vehicle/?iid=sr-link3>

²⁰⁵ <http://www.marketwired.com/press-release/baidu-announces-new-self-driving-car-team-silicon-valley-plans-grow-100-2016-nasdaq-bidu-2117538.htm>

²⁰⁶ <http://www.theverge.com/2016/9/1/12748992/baidu-self-driving-car-california-dmv-testing-permit-google>

²⁰⁷ <https://www.wired.com/2015/12/baidus-self-driving-car-has-hit-the-road/>

Company	Development Efforts
	<p>According to reports in August 2016, Baidu entered into a joint \$150 million investment with Ford in Velodyne, to accelerate efforts in making Lidar sensors at scale while retaining and increasing quality²⁰⁸.</p> <p>In September 2016, Baidu established a strategic partnership with chipmaker, Nvidia to build an autonomous driving platform on an open platform that can also be available to other carmakers for their own self-driving vehicles²⁰⁹.</p> <p>Targets to have a driverless shuttle service in China by 2018²¹⁰.</p>
Google	<p>Started development on self-driving cars in 2009 using a Toyota Prius on freeways in California. In 2012, Google began testing with Lexus RX450h SUVs. In 2014, Google built its own prototype vehicle. The test environment was also expanded from freeways to city streets. As of August 2016, the test vehicles have driven a combined distance of more than 1.9 million miles in autonomous mode, in the streets of Mountain View, CA, Austin, TX, Kirkland, WA, and Metro Phoenix, AZ. As of August 2016, there are 24 Lexus SUVs and 34 prototype vehicles involved in the trials²¹¹.</p> <p>In 2013, Google Ventures made an investment of \$258 million in Uber²¹².</p> <p>Acquired Waze, a social mapping start-up that features real-time traffic data provided by users to help drivers find the fastest route to a destination, for \$1 billion in 2013²¹³. Began a pilot program near its California headquarters in August 2016 using the Waze app to help commuters join carpools²¹⁴.</p> <p>Switched to a new strategy in 2014 to completely eliminate the human driver (no driver, steering wheel, brake or accelerator pedal). Relied entirely on Google sensors and software for control. Limited to a top speed of 25 miles per hour, intended for driving in urban and suburban settings, but not on highways²¹⁵. Unveiled a custom-designed two-seater prototype in 2014, assembled in Michigan by Roush Enterprises.</p> <p>Reported to have set up its own car company, Google Auto LLC, in 2014, headed by Chris Urmson, the project lead for Google's self-driving car project. According to The Guardian, the company is registered as a passenger vehicle manufacturer, and was licensed in 2014 as a carmaker in California²¹⁶. The</p>

²⁰⁸ <https://techcrunch.com/2016/08/16/ford-and-baidu-put-150m-behind-lidar-for-self-driving-cars/>

²⁰⁹ <http://www.forbes.com/sites/greatspeculations/2016/09/29/baidu-nvidia-to-build-independent-self-driving-car-platform/#2fea615a6339>

²¹⁰ <http://readwrite.com/2016/08/29/baidu-self-driving-car-tl4/>

²¹¹ <https://www.google.com/selfdrivingcar/reports/>

²¹² <https://techcrunch.com/2013/08/22/google-ventures-puts-258m-into-uber-its-largest-deal-ever/>

²¹³ http://bits.blogs.nytimes.com/2013/06/11/google-expands-its-boundaries-buying-waze-for-1-billion/?_r=0

²¹⁴ <http://www.wsj.com/articles/google-takes-on-uber-with-new-ride-share-service-1472584235>

²¹⁵ http://www.nytimes.com/2014/05/28/technology/googles-next-phase-in-driverless-cars-no-brakes-or-steering-wheel.html?_r=3

²¹⁶ <https://www.theguardian.com/technology/2015/aug/01/google-auto-car-making-company>

Company	Development Efforts
	<p>company was reported to be making a few hundred vehicles to “learn how to actually build a self-driving vehicle from the ground-up”²¹⁷.</p> <p>Reported to be focused on car-sharing e.g., self-driving taxis²¹⁸ before expanding the use of its technology to personal cars²¹⁹.</p> <p>Unclear if Google intends to partner with established automotive companies or to build and sell their own self-driving cars, as there have been conflicting reports²²⁰.</p> <p>In 2016, announced its first direct tie-up with a carmaker, Fiat Chrysler Automobiles NV to build a fleet of 100 self-driving cars based on the 2017 Chrysler Pacifica Hybrid minivans²²¹. Also announced that it will open a 53,000-square foot self-driving technology development center in Novi, Michigan.</p> <p>The Google car is currently not equipped with V2V communications capability, though some critics have claimed that the accident involving the Google Lexus RX450h with a California transit bus in February 2016 (Google car drove into the side of a bus at low speed) may have been avoided if both vehicles were equipped with V2V communications²²².</p> <p>In April 2016, formed “the Self-Driving Coalition for Safer Streets” with Ford, Lyft, Uber, and Volvo to lobby for a clear set of federal standards for autonomous vehicles and build support for the technology among businesses and local governments²²³.</p>
Microsoft	<p>Does not intend to build its own autonomous vehicle, but plans to partner with existing carmakers to provide devices and/or services such as potentially integrating an operating system, its Azure cloud services, Cortana voice-based virtual assistant or even the Office 365 productivity suite in future vehicles²²⁴.</p> <p>In 2015, announced its partnership with Volvo to work together in developing driverless vehicle, using the data to create “meaningful services”, machine learning, and how to modernize the car buying process²²⁵.</p> <p>In 2016, Toyota Motor Corp expanded its five-year old partnership with Microsoft to develop new internet-connected vehicle services for owners and</p>

²¹⁷ <https://www.theguardian.com/technology/2015/sep/12/google-self-driving-cars>

²¹⁸ <http://www.bloomberg.com/news/articles/2015-02-02/exclusive-google-and-uber-are-going-to-war-over-taxis>

²¹⁹ <http://www.autonews.com/article/20150929/OEM06/150929779/google-sees-top-tier-oems-as-partners-on-self-driving-cars>

²²⁰ <https://www.theguardian.com/technology/2015/sep/12/google-self-driving-cars>

²²¹ <http://www.forbes.com/sites/davidkiley5/2016/05/03/why-google-is-partnering-with-fca-on-autonomous-driving/#2d0777204f12>

²²² <http://www.forbes.com/sites/samabuelsamid/2016/03/07/the-first-google-self-driving-car-accident-makes-the-case-for-v2v-communications/#5c26155869ce>

²²³ <http://www.reuters.com/investigates/special-report/autos-driverless/>

²²⁴ <http://betanews.com/2016/06/06/microsoft-autonomous-car/>

²²⁵ <http://www.cnbc.com/2015/11/20/microsoft-volvo-strike-deal-to-make-driverless-cars.html>

Company	Development Efforts
	<p>dealers. Microsoft has a 5% stake in the Toyota Connected venture that consolidates its existing connectivity services and serves as Toyota's data science hub²²⁶.</p> <p>Reported to be also interested in providing cloud computing capability to mapping business HERE, a formerly Nokia company, now acquired by a consortium of German carmakers.</p> <p>In September 2016, established a partnership with Renault-Nissan to develop the next generation connected services for cars based on Microsoft's Azure platform, for advanced navigation, predictive maintenance, remote monitoring of car features, and over-the-air updates²²⁷.</p>
Nvidia	<p>Founded in 1993 and is a major player in visual computing. Targets four key markets: (1) gaming, (2) professional visualization, (3) datacenter, and (4) auto. Major customers include Volvo, BMW, Daimler, Ford, and Tesla.</p> <p>At the Consumer Electronics Show 2016, the company announced the Nvidia Drive PX2, essentially a supercomputer for the car that comprises 12 central processing unit cores and four graphics processing units, all liquid-cooled. The system will also come with its deep learning network, DriveNet that teaches the car to detect objects in real time, without relying on cloud processing. It was also reported that Volvo will be the first carmaker to implement Nvidia's autonomous driving platform²²⁸.</p> <p>The Drive PX2, a plug-and-play solution, is claimed to be 10 times the performance of the first generation Drive PX that was used by more than 50 companies in the automotive world²²⁹.</p> <p>Also partnering with New York University's deep learning team on a research collaboration at their new auto tech office in New Jersey²³⁰.</p> <p>Also reported that Nvidia will be supplying its Drive PX2 system to be installed in all the cars in the Roborace Formula E series, an all-robotics, all-electric variant of Formula One that will take place in 2017²³¹.</p>

²²⁶ <http://www.reuters.com/article/us-toyota-connectivity-microsoft-idUSKCN0X11LL>

²²⁷ <http://www.media.blog.alliance-renault-nissan.com/news/renault-nissan-and-microsoft-partner-to-deliver-the-future-of-connected-driving/>

²²⁸ <http://thenextweb.com/gadgets/2016/01/05/nvidia-announces-a-supercomputer-gpu-and-deep-learning-platform-for-self-driving-cars/>

²²⁹ <https://blogs.nvidia.com/blog/2016/01/04/drive-px-ces-recap/>

²³⁰ <https://blogs.nvidia.com/blog/2016/06/10/nyu-nvidia/>

²³¹ <http://spectrum.ieee.org/cars-that-think/transportation/self-driving/nvidia-to-supply-robocar-brains-for-roboration-formula-e-series>

Company	Development Efforts
	<p>In September 2016, announced its new Xavier System-On-Chip, claimed to be the artificial intelligence supercomputer for the future of autonomous vehicles, which is expected to be available in end 2017²³².</p>
Qualcomm	<p>A key player in the telecommunications industry founded in 1985. Positioned itself more as a parts supplier to automotive manufacturers who will design and integrate the parts to their own specifications²³³. Claims that there are more than 20 million vehicles that are installed with its LTE modems.</p> <p>In 2015, acquired Cambridge Silicon Radio, a provider of Bluetooth for cars with two-thirds market share, for \$2.4 billion. Plans to integrate the Bluetooth technology into its chips and build on its customer base.</p> <p>At the Consumer Electronics Show 2016, the company announced the second generation of its automotive grade “system on a chip” with the Snapdragon 820A, claimed to be able to power a car infotainment system with 4K graphics, and will support Qualcomm’s deep learning algorithms “Zeroth”. The system will also be paired with a LTE modem to generate a Wi-Fi hotspot. Its first generation Snapdragon 602A will be used in Audi’s cars in 2017²³⁴.</p> <p>Said to be pioneering the developments in cellular-V2X, that is claimed to have twice the range as compared to direct short-range radio communications, and defined two new transmission modes for automotive use cases: (1) direct communications between vehicles, pedestrians, and road infrastructure using the LTE direct device-to-device communications, even outside of mobile network coverage areas, and (2) using the ubiquitous coverage of existing LTE networks to be alerted of an accidents a few miles ahead or guided to an open parking space, through optimization of LTE broadcast technology for vehicular communications²³⁵.</p> <p>Introduced the Qualcomm Connected Car Reference Platform in June 2016, which aims to accelerate the adoption of advanced and complex connectivity into the next generation of connected cars. The platform is built upon its Snapdragon X12 and X5 LTE modems, and also features in-vehicle networking technologies such as Gigabit Ethernet with automotive audio bus and controller area network interfaces²³⁶.</p>
Samsung	<p>South Korean company and the world’s leading manufacturer of smartphones, televisions, and memory chips.</p>

²³² <http://www.forbes.com/sites/davealtavilla/2016/09/28/nvidia-doubles-down-on-self-driving-cars-with-xavier-ai-chip-and-a-hat-tip-to-next-gen-volta-gpu/#119eec7588d4>

²³³ <http://www.tgdaily.com/web/134726-nvidia-vs-qualcomm-and-self-driving-cars-contrasting-strategies>

²³⁴ <http://www.forbes.com/sites/aarontilley/2016/01/05/along-with-nvidia-new-qualcomm-chip-brings-deep-learning-to-cars/#1de8d3075357>

²³⁵ <https://www.qualcomm.com/news/onq/2016/06/07/path-5g-paving-road-tomorrows-autonomous-vehicles>

²³⁶ <http://telematicswire.net/qualcomm-builds-platform-to-connect-smart-cars-to-everything/>

Company	Development Efforts
	<p>Reported to be the sole provider of electric batteries for BMW's line of hybrid and electric cars²³⁷.</p> <p>Announced in December 2015 that Samsung will establish a new team for the development of the next generation auto parts used in self-driving cars and Internet-connected cars. This announcement is reported to be the company's first official acknowledgement of its interest in the automotive business²³⁸.</p> <p>In June 2016, said that it will invest \$1.2 billion in the US over four years to boost technologies aimed at adding computing power to everyday devices i.e., Internet of things, including digital health, drones, robots, and autonomous vehicles, as well as companies developing software to process massive data produced by these devices²³⁹.</p> <p>In July 2016, Samsung invested \$450 million for a 1.92% stake in Chinese automaker and rechargeable batteries firm BYD Co Ltd²⁴⁰.</p>

²³⁷ <http://www.connectedcar-news.com/news/2016/may/12/samsung-creates-autonomous-car-chip-team/>

²³⁸ <http://www.wsj.com/articles/samsung-electronics-team-to-focus-on-parts-for-self-driving-cars-1449648196>

²³⁹ <http://www.wsj.com/articles/samsung-to-invest-1-2-billion-in-internet-of-things-start-ups-and-research-in-u-s-1466514005>

²⁴⁰ http://www.reuters.com/article/us-byd-samsung-elec-equity-idUSKCN1011GJ?feedType=RSS&feedName=technologyNews&utm_source=twitterfeed&utm_medium=twitter&utm_campaign=Feed%3A+reuters%2FtechnologyNews+%28Reuters+Technology+News%29

Table A-3: Investments by Start-Ups

Company	Development Efforts
Comma.ai	<p>A start-up by George Hotz, known for being the first person to hack Apple's iPhone in 2007, and the Sony's PlayStation 3 in 2010²⁴¹.</p> <p>According to Bloomberg in 2015, Hotz demonstrated self-driving on Interstate 280 highway in San Francisco using a 2016 Acura ILX outfitted with Lidar, cameras and his own developed artificial intelligence software. Claims that he has figured out how to phrase the driving problem in ways compatible with deep learning such that instead of hundreds of thousands of lines of code found in other self-driving vehicles, his code is only about 2,000 lines. Instead of built-in If/Then rules, Hotz programs the software to learn what the human drivers do in various situations and then tries to mimic and perfect the behavior²⁴².</p> <p>Received a 3.1 million investments from venture capitalist, a16z in April 2016²⁴³.</p>
Drive.ai	<p>A deep learning start-up from Stanford University's Artificial Intelligence Laboratory.</p> <p>The 13th company to be granted a license to test autonomous vehicles on public roads in California.</p> <p>Received \$12 million in Series A funding in April 2016²⁴⁴.</p>
Future Mobility	<p>A Chinese start-up in electric vehicles, backed by investors including Tencent Holdings (a Chinese investment holding company, known for social media and online gaming operations), Foxconn Technology (that makes iPhone for Apple Inc.), and China Harmony New Energy Auto Holding Ltd (dealer in luxury cars in China).</p> <p>Reported to have hired 50 engineers from BMW, Mercedes-Benz, Tesla, and Google, and plans to sell highly automated electric cars by 2020²⁴⁵.</p>
Nauto	<p>A start-up co-founded by Stanford professor, Stefan Heck in 2015, and is involved in driver safety assistance systems that can be retrofitted into existing cars, connected vehicles, and data.</p> <p>Uses image sensors found in "prosumer" cameras, motion sensors, GPS, and merged with artificial intelligence to alert the driver on events on the road ahead and within the vehicle. The system is also claimed to be able to automatically understand when a collision is about to happen, and records the scene inside and outside of the car then. Its pilot customers include the City Wide Taxi in San</p>

²⁴¹ <http://www.newyorker.com/magazine/2012/05/07/machine-politics>

²⁴² <http://www.bloomberg.com/features/2015-george-hotz-self-driving-car/>

²⁴³ <https://medium.com/@cdixon/comma-ai-e62eea5fa8d2#.avzj2su8x>

²⁴⁴ <http://spectrum.ieee.org/cars-that-think/transportation/self-driving/driveai-brings-deep-learning-to-selfdriving-cars>

²⁴⁵ <http://www.wsj.com/articles/tencent-backed-company-aims-to-launch-smart-electric-cars-before-2020-1468302895>

Company	Development Efforts
	<p>Francisco, and commercial fleets in 23 cities globally such that they can gather data about driver behavior²⁴⁶.</p> <p>Received \$12 million in Series A funding in April 2016 led by Playground Global with participation from Draper Nexus and Index Ventures²⁴⁷.</p>
nuTonomy	<p>A start-up founded in 2013 by MIT scientists Dr. Karl Iagnemma and Prof. Emilio Frazzoli.</p> <p>Selected by the Land Transport Authority, Singapore to begin trials of an autonomous mobility-on-demand transportation service²⁴⁸.</p> <p>Launched its first public test of a commercial fleet of six fully self-driving vehicles in August, 2016, where a select group of customers can hail using nuTonomy's proprietary ride-hail application²⁴⁹. Plans to deploy a full fleet of at least 1,000 vehicles in Singapore by 2018.</p> <p>Established a partnership with ride-hailing company, Grab in September 2016²⁵⁰.</p>
Otto	<p>Formed by a group of 40 people, including former employees of Google, Apple, Tesla, and Cruise Automation. Plans to develop hardware kits for existing truck models rather than building their own trucks. Initial focus will be on highway driving and is currently testing with the Volvo VNL 780²⁵¹.</p> <p>Acquired by Uber for \$680 million in August 2016 and its co-founder, Anthony Levandowski (also one of the original engineers in Google's self-driving team) has been appointed to lead all of Uber's self-driving efforts. Otto is expected to continue to focus on self-driving trucks and building a logistics platform²⁵².</p>
Quanergy	<p>A Silicon Valley start-up founded in 2012 that develops solid-state Lidar sensors.</p> <p>Obtained Mercedes, Renault-Nissan, and Hyundai as some of its first automotive customers.</p> <p>Delphi bought an undisclosed stake in Quanergy in July 2015 where Quanergy is developing the technology while Delphi is likely to produce it²⁵³.</p>

²⁴⁶ <https://techcrunch.com/2016/04/13/nauto-raises-12-million-for-driverless-car-technology-thats-street-legal-today/>

²⁴⁷ <http://www.recode.net/2016/4/13/11586052/autonomous-car-tech-nauto-funding>

²⁴⁸ <http://www.greencarcongress.com/2016/08/20160801-lta.html>

²⁴⁹ <http://www.recode.net/2016/8/25/12639472/nutonomy-self-driving-taxis-singapore>

²⁵⁰ <http://www.recode.net/2016/9/22/13007836/grab-nutonomy-self-driving-partnership-singapore>

²⁵¹ <http://www.theverge.com/2016/5/17/11686912/otto-self-driving-semi-truck-start-up>

²⁵² <http://www.recode.net/2016/8/18/12540068/uber-paid-680-million-for-self-driving-truck-company-otto-for-the-tech-not-the-trucks>

²⁵³ <http://www.autonews.com/article/20151026/OEM06/310269985/delphi-quanergy-team-up-on-low-cost-lidar>

Company	Development Efforts
	<p>Relatively new player in building Lidar sensors and claims to bring the cost of Lidar sensor down to \$100 by 2018²⁵⁴.</p> <p>Raised \$90 million in August 2016 from investors led by Sensata Technologies, and includes Delphi Automotive, Samsung Ventures, Motus Ventures, and GP Capital²⁵⁵.</p>
Zoox	<p>A Palo Alto-based start-up with a concept electric taxi codenamed L4, with no front or rear end, can drive equally well in either direction, and does not have a steering wheel, brake pedal, and windshields²⁵⁶.</p> <p>Based on a research concept vehicle from KTH Royal Institute of Technology, Stockholm.</p> <p>As of June 2016, Zoox was reported to be raising about \$200 million at a \$1 billion valuation, with investors such as Lux Capital, and DFJ²⁵⁷.</p>

²⁵⁴ <http://www.recode.net/2015/10/27/11620026/meet-the-companies-building-self-driving-cars-for-google-and-tesla>

²⁵⁵ <http://fortune.com/2016/08/22/self-driving-car-quanergy/>

²⁵⁶ <http://velodynelidar.com/docs/news/Meet%20Zoox,%20the%20Robo-Taxi%20Start-up%20Taking%20on%20Google%20and%20Uber%20-%20IEEE%20Spectrum.pdf>

²⁵⁷ <https://techcrunch.com/2016/06/30/zoox-raises-200-million-at-1-billion-valuation-for-its-self-driving-cars/>

Table A-4: Investments by Major Tier-1 and Tier-2 Companies

Company	Development Efforts
Bosch	<p>One of the world's largest Tier 1 supplier, with focus on sensors (Radars, video and ultrasonic sensors), vehicle architecture, actuators, and vehicle integration. In the domain of future mobility, Bosch aspires to develop solutions for connectivity, automation, and electrification²⁵⁸. According to a member of Bosch's board of management, its sales in driver assistance systems are increasing by a third every year and are expected to exceed \$1.09 billion in 2016. As of 2015, Bosch has about 2,000 engineers working on refining its driver assistance systems, a 700-person increase from 2013. Some of its key customers include Google, Tesla, and Porsche²⁵⁹.</p> <p>Was the first company to introduce an electronically-controlled anti-lock braking system in 1978, invented the electronic stability control in 1995, and the Radar-based adaptive cruise control in 2000²⁶⁰.</p> <p>Set up a team to work on automated driving since 2011²⁶¹, and began testing automated driving on public roads since 2013 using modified BMW 325d Touring sedans on freeways (A81 near Stuttgart and I-280 in California).</p> <p>Have two collaborative teams who are developing technologies for future automated vehicles using agile development methods. One is based on the Abstatt facility in Germany, and the other in Palo Alto, California. In 2015, Bosch spent EUR 6.3 billion in R&D.</p> <p>Reported to have spent \$225,000 retrofitting two Tesla Model S vehicles with Radar sensors, inertial sensors, backup braking, electronic control unit, and a custom computer that runs its proprietary high-resolution mapping software. The scope involved about 1,400 man-hours, 50 Bosch components, 0.8 miles of additional wiring, and Lidar sensors from Velodyne. The retrofitted vehicles were said to be tested at the Bosch test track in Boxberg, Germany²⁶².</p> <p>Partnered with TomTom since July 2015 to obtain high-definition maps for its autonomous vehicle testing on roads in California and Germany.</p> <p>Leads the MOVE-UK project with a GBP 5.5 million grant awarded by the InnovateUK government initiative to trial driverless technology on roads in Greenwich, London. Other project partners include the Transport Research Laboratory, Jaguar Land Rover, Direct Line Group, The Flow, and Royal Borough of Greenwich²⁶³.</p>

²⁵⁸ <http://www.driverlesstransportation.com/bosch-getting-autonomous-done-12893>

²⁵⁹ <http://fortune.com/2015/07/16/bosch-self-driving-car/>

²⁶⁰ <http://roboticsandautomationnews.com/2016/04/05/youre-not-the-bosch-of-me-now-humans-tell-driverless-cars-to-take-a-hike/3882/>

²⁶¹ <http://roboticsandautomationnews.com/2016/04/05/youre-not-the-bosch-of-me-now-humans-tell-driverless-cars-to-take-a-hike/3882/>

²⁶² <http://www.forbes.com/sites/dougnewcomb/2015/06/12/forget-auto-pilot-bosch-builds-twin-self-driving-teslas/#6726ffbd3be5>

²⁶³ <http://roboticsandautomationnews.com/2016/02/04/consortium-of-automotive-companies-wins-5-5m-fund-to-trial-driverless-cars-on-uk-roads/2434/>

Company	Development Efforts
	<p>Does not have plans to build an autonomous vehicle, but rather to provide the required hardware and software to carmakers. Plans to make highly automated driving on motorways available in 2020. According to the senior vice president, Arun Srinivasan, Bosch foresees that full autonomous driving and also driving in inner city traffic will probably take at least 10 years from 2016.</p>
Continental AG	<p>A German-based company that manufactures tires, and supplies electronics for advanced driver assistance systems such as automatic emergency braking and auto-steering.</p> <p>In 2012, received approval from Nevada DMV to test its highly automated vehicles on the public roads in Nevada, the first license granted to an automotive supplier. Continental's system uses four short-range Radar sensors, one long-range Radar sensor and a stereo camera, and claims to be capable of cruising an open freeway and negotiating rush hour traffic. Using the sensor fusion technology as part of its ContiGuard safety concept, the vehicle is able to track the objects as they enter the sensors' field-of-view. The object information is processed and passed on to its Motion Domain Controller to control the vehicle's longitudinal and lateral motion via signals to the engine, brakes, and steering system²⁶⁴.</p> <p>As at 2013, the company said that they have about 1,300 researchers working in this technology domain²⁶⁵. Also has autonomous vehicle technology development partnerships with Cisco Systems, BMW, Google²⁶⁶, and IBM²⁶⁷.</p> <p>Producing a combination Lidar-and-camera system for Toyota Motor Corp., which will be installed in the 2016 Toyota RAV4 and Avalon²⁶⁸. The Lidar system has a range of 16.4 yards, and when coupled with the camera, aims to provide obstacle detection at a short range.</p> <p>In 2016, acquired (including hiring of 22 engineers involved in sensor development) Advanced Scientific Concepts Inc. (ASC), a Lidar sensor maker at an undisclosed amount. ASC's sensor has no moving parts and the company has previously supplied sensors to Nissan for its autonomous Leaf electric car to construct a nearly 360-degree field of vision. Similar to Delphi with Quanergy, Continental is also looking to drive down the cost of the Lidar sensor through economies of scale.</p>

²⁶⁴ <http://www.prnewswire.com/news-releases/continental-becomes-first-automotive-supplier-to-receive-nevadas-autonomous-vehicle-testing-license-184141281.html>

²⁶⁵ http://www.continental-corporation.com/www/pressportal.com/en/themes/press_releases/1_topics/automated_driving_en/pr_2013_07_01_vortrag_senger_en.html

²⁶⁶ <http://www.digitaltrends.com/cars/google-and-continental-partner-to-develop-self-driving-cars/>

²⁶⁷ <http://www.autonews.com/article/20130910/OEM10/130919991/continental-to-partner-with-ibm-on-autonomous-driving-systems>

²⁶⁸ <http://www.autonews.com/article/20150912/OEM10/309149956/suppliers-advance-in-mass-market-safety-tech>

Company	Development Efforts
Delphi	<p>A major Tier 1 supplier for the automotive industry, with headquarters in the UK. Pioneered the development of electric starters in 1911, in-dash car radios in 1936, and integrated navigation systems in 1994.</p> <p>Since 1999, Delphi has been working on active safety features such as active lane-keeping and blind spot monitoring. In 2014, these technologies were installed in a 2014 Audi SQ5, known as the Delphi Automated Driving System.</p> <p>Reported to have earned \$1.4 billion in sales for the supply of sensors and cameras used in active safety systems in 2014, and \$3 billion in total from 2012 to 2014²⁶⁹.</p> <p>In 2015, Delphi acquired a stake in Quanergy, a Silicon Valley start-up, to develop a low-cost (less than \$1,000 per car), solid state Lidar sensor system. Also purchased Ottomatika, an autonomous driving software company developed out of Carnegie Mellon University for \$32 million²⁷⁰.</p> <p>Presented an autonomous concept car (Delphi Drive system) at the Consumer Electronics Show 2015 and in April 2015, demonstrated a 3,400-mile highway driving from San Francisco to New York over nine days, with the vehicle in autonomous mode 99% of the time²⁷¹. The human driver took control for about 1% of the driving journey such as when maneuvering construction zone with zig-zag lane lines, and they avoided night driving.</p> <p>The 2014 and 2015 demonstrations are part of Delphi's strategy to develop platforms that allow them to build out different components that are required to make an automated driving system, test²⁷², learn, and improve, so that automotive manufacturers can have the flexibility to either go with the entire package or selected components²⁷³.</p> <p>Showcased a new V2X system and an aftermarket V2V unit at the Consumer Electronics Show in 2016²⁷⁴. GM has decided to include the V2V technology in its 2017 Cadillac CTS²⁷⁵.</p> <p>Selected by the Land Transport Authority, Singapore to provide a fleet of fully autonomous vehicles, develop a cloud-based mobility-on-demand software</p>

²⁶⁹ <http://www.wsj.com/articles/delphi-executive-sees-semi-autonomous-driving-features-spreading-quickly-1426267105>

²⁷⁰ <http://www.wsj.com/articles/car-makers-hunger-for-self-driving-tech-1458811804>

²⁷¹ [http://www.streetinsider.com/Corporate+News/Delphi+Automotive+\(DLPH\)+Acquires+Autonomous+Vehicle+Technology+Firm+Ottomatika/10778487.html](http://www.streetinsider.com/Corporate+News/Delphi+Automotive+(DLPH)+Acquires+Autonomous+Vehicle+Technology+Firm+Ottomatika/10778487.html)

²⁷² https://www.dmv.ca.gov/portal/wcm/connect/851838fb-da8b-45da-bd95-0ae0451de988/2015_Delphi_DMV_Summary.pdf?MOD=AJPERES

²⁷³ <https://www.wired.com/2014/11/delphi-automated-driving-system/>

²⁷⁴ <https://www.wired.com/2016/01/delphis-new-self-driving-car-teaches-us-to-give-up-the-wheel/>

²⁷⁵ <http://www.ibtimes.co.uk/ces-2016-delphi-debuts-futuristic-vehicle-everything-system-make-self-driving-cars-step-1536823>

Company	Development Efforts
	<p>suite and conduct a trial of an urban, point-to-point, low speed, autonomous, mobility-on-demand service at the pilot test site in one-north²⁷⁶.</p> <p>Announced in August 2016, of its partnership with Mobileye to provide self-driving components to automakers by end 2019. Plans to demonstrate an early version of their system at the 2017 International Consumer Electronics Show²⁷⁷.</p>
Mobileye	<p>An Israeli-based company founded in 1999, develops software algorithms and system-on-chips for driver assistance systems that provide warnings for collision prevention and mitigation. Its proprietary EyeQ chip and algorithms have been integrated into new car models since 2007, and the company reported that by 2016, their technology would be selected for implementation in serial production of 237 car models from 20 manufacturers²⁷⁸.</p> <p>Plans to phase-in its semi-autonomous driving system in three parts over the next six years, from highways to country roads, and lastly city streets²⁷⁹.</p> <p>In July 2016, BMW Group, Intel, and Mobileye jointly announced their collaboration on autonomous vehicles, with series production targeted for 2021. Based on an agreed common reference architecture, the partnership plans to demonstrate an autonomous test drive with a highly automated driving prototype in the near term, and extend to fleets with extended autonomous test drives in 2017.</p> <p>Mobileye was the provider of EyeQ3 technology used in the autopilot feature of Tesla cars, including the one that was involved in a fatal crash in May 2016. The Wall Street Journal reported in July 2016 that it will no longer provide its computer chips and algorithms to Tesla after a current contract ends due to disagreements about how the technology was deployed²⁸⁰.</p> <p>Plans to introduce a new system called EyeQ4 in 2018 that will include Lateral Turn Across Path detection capabilities. The current system is only designed for rear-end collision avoidance²⁸¹.</p> <p>Mobileye plans by 2020 to offer a hardware/software system that can gather, fuse, and analyze data from 20 different sensors, including cameras, Lidar and Radar. Claimed that the new EyeQ5 "system on chip" will be a key component</p>

²⁷⁶ <http://www.greencarcongress.com/2016/08/20160801-delphi.html>

²⁷⁷ <http://www.nytimes.com/2016/08/24/business/delphi-and-mobileye-to-produce-system-for-self-driving-cars.html>

²⁷⁸ <http://www.mobileye.com/about/>

²⁷⁹ <http://www.bloomberg.com/news/articles/2015-07-15/mobileye-offers-alternative-route-to-google-s-driverless-future>

²⁸⁰ <http://www.wsj.com/articles/mobileye-ends-partnership-with-tesla-1469544028>

²⁸¹

[http://www.streetinsider.com/Corporate+News/Mobileye+\(MBLY\)+Issues+Statement+on+Fatal+Tesla+\(TSLA\)+Model+S+Autopilot+Crash/11793789.html](http://www.streetinsider.com/Corporate+News/Mobileye+(MBLY)+Issues+Statement+on+Fatal+Tesla+(TSLA)+Model+S+Autopilot+Crash/11793789.html)

Company	Development Efforts
	<p>in a fully autonomous driving system that is being jointly developed with BMW AG and Intel Corp, and is aimed at production in 2021²⁸².</p> <p>Also established partnership with Delphi to provide Central Sensing Localization and Planning self-driving (SAE Level 4) components to automakers by end 2019²⁸³.</p>
Velodyne	<p>A dominant market player and developer of spinning 3D Lidar sensors that are being used by major automotive and technology companies on their self-driving cars for mobile mapping and perception applications. These companies include Toyota, Google²⁸⁴, Ford, GM²⁸⁵, and Nissan.</p> <p>In contrast to most of its competitors whose Lidar sensors have no moving parts, Velodyne’s Lidar is a spinning laser, which it claims to have the advantage of giving a 360-degree view and a 200-meter range that is longer than competing systems. The company is also working on a laser sensor that has no moving parts so as to drive down the cost²⁸⁶.</p> <p>Currently has a range of Lidar products ranging from the 64-beam sensor (~\$85,000) to a lower resolution 16-beam sensor that costs ~\$8,000²⁸⁷. Velodyne sets a target pricing of less than \$500 per unit in automotive mass production quantities²⁸⁸.</p> <p>Has a contract with Caterpillar Inc. for exclusive use of its Lidar sensors on autonomous mining equipment.</p> <p>Encouraged by the strong sales of the VLP-16 “Puck” Lidar sensors, Velodyne announced in September 2015 that the company plans to begin high-volume manufacturing of Lidar sensors, and to develop a new automotive sensor that is currently in the preliminary design concept phase²⁸⁹.</p>

²⁸² <http://www.reuters.com/article/us-autos-selfdriving-investment-idUSKCN0ZS0CQ>

²⁸³ <http://www.theverge.com/2016/8/23/12603624/delphi-mobileye-self-driving-autonomous-car-2019>

²⁸⁴ <http://armdevices.net/2013/01/21/velodyne-lidar-vision-sensor-system-for-the-google-self-driving-car/>

²⁸⁵

<http://velodynelidar.com/docs/news/GM%20to%20unveil%20new%20automated%20driving%20technology%20at%20ITS%20World%20Congress%20-%20Automotive%20Business%20Review.pdf>

²⁸⁶ <http://www.wsj.com/articles/continental-buys-sensor-technology-for-self-driving-cars-1457042039>

²⁸⁷ <http://velodynelidar.com/docs/news/Sensor%20cuts%20self-driving%20car%20costs.pdf>

²⁸⁸ <http://www.prweb.com/releases/2016/01/prweb13149601.htm>

²⁸⁹ <http://www.spar3d.com/spar-3d-news/vol13no35-velodyne-car-lidar-good-news-for-all-their-customers/>

Table A-5: Investments by Ride-Sharing Service Provider

Company	Development Efforts
Uber	<p>In 2015, Uber hired 40 scientists, engineers and professors from the Carnegie Mellon University in Pittsburg to work on its self-driving technologies²⁹⁰. Also hired former Google employees (including former head of Google Maps) and Microsoft’s mapping talent, acquired mapping companies such as deCarta that developed the turn-by-turn direction behind GM’s OnStar software.</p> <p>Forged partnerships with TomTom²⁹¹ (a navigation company) in 2015, and DigitalGlobe²⁹² (a satellite imaging company which provides high-resolution aerial imagery to Apple and Google) in 2016. Was unsuccessful in the earlier \$3 billion bid for Nokia’s HERE.</p> <p>Leased a 53,000-square foot facility in Pittsburg to establish its Uber Advanced Technologies Center in 2015, with primary focus on mapping, vehicle safety, and driverless vehicle technologies²⁹³.</p> <p>Conducted the first public testing of its autonomous car, a modified hybrid Ford Fusion in Pittsburg in May 2016²⁹⁴.</p> <p>Reported to be exploring potential autonomous vehicle partnership with South Korea’s largest carmaker, Hyundai Motor²⁹⁵.</p> <p>In July 2016, the Financial Times reported that Uber is planning to invest \$500 million in an ambitious global mapping project. According to Uber, the existing maps do not provide the granular level of detail that Uber can use, such as traffic patterns, location of doors or other potential pickup locations. The new investment will allow them to build tailored-made maps for their purpose and likely reduce their reliance on Google maps²⁹⁶.</p> <p>Acquired Otto, a driverless truck start-up for \$680 million in August 2016.</p> <p>Established a joint project with Volvo in August 2016 to develop new base vehicles to incorporate the latest developments in autonomous driving technologies, at a combined investment of \$300 million. The base vehicles will be manufactured by Volvo and purchased by Uber. Both companies will use the same base vehicle for the next stage of their own autonomous car strategies²⁹⁷.</p>

²⁹⁰ <http://www.wsj.com/articles/is-uber-a-friend-or-foe-of-carnegie-mellon-in-robotics-1433084582>

²⁹¹ <http://www.theverge.com/2015/11/12/9720780/uber-tomtom-mapping-traffic-partnership>

²⁹² <http://www.theverge.com/2016/7/19/12228988/uber-digitalglobe-satellite-imagery-partnership>

²⁹³ <http://www.bizjournals.com/pittsburgh/news/2015/05/18/exclusive-uber-leases-former-restaurant-depot.html>

²⁹⁴ <http://readwrite.com/2016/05/20/uber-autonomous-car-pittsburgh-tt4/>

²⁹⁵ <http://readwrite.com/2016/06/16/uber-hyundai-talks-collaborate-self-driving-cars-korea-tt4/>

²⁹⁶ http://www.ft.com/cms/s/0%2Fe0dfa45e-5522-11e6-befd-2fc0c26b3c60.html?ft_site=falcon&desktop=true#axzz4G0M5oyu8

²⁹⁷ <https://www.media.volvocars.com/global/en-gb/media/pressreleases/194795/volvo-cars-and-uber-join-forces-to-develop-autonomous-driving-cars>

Company	Development Efforts
	<p>Uber China merged with Didi Chuxing in August 2016²⁹⁸.</p> <p>Launched a limited test of its self-driving cars in Pittsburg in September 2016, using a mixed fleet of modified Volvo XC90 and Ford Fusion sedans²⁹⁹.</p>

²⁹⁸ <https://newsroom.uber.com/uber-china-didi/>

²⁹⁹ <http://www.theverge.com/2016/8/18/12541672/uber-volvo-partnership-autonomous-self-driving-car>

Table A-6: Investments by Testing and Proving Service Providers

Company	Development Efforts
American Center for Mobility	<p>A joint initiative by the Michigan Department of Transportation, Michigan Economic Development Corporation, University of Michigan, Business Leaders for Michigan, and Ann Arbor SPARK.</p> <p>Expected to be completed by 2018-2019 at an estimated cost of \$80 million, the former B-24 manufacturing plant at Willow Run in Ypsilanti Township will be developed into a test facility spanning 335 acres and will include a three-level interchange, a high-speed loop, connected infrastructure, and simulated urban and rural environments for autonomous and connected vehicle testing³⁰⁰.</p>
AstaZero	<p>Opened in August 2014, AstaZero is a proving ground located in the West Sweden automotive cluster for the development, testing, and certification of active safety systems. Comprises different test environments including: rural roads, city area, high-speed area, and multi-lane roads, and allows for testing of V2V and V2I communications. The facility was developed by a consortium of European companies and institutes, and owned by Sweden's SP Technical Research Institute, and the Chalmers University of Technology³⁰¹.</p> <p>Volvo is reported to be one of users of the facility³⁰².</p>
CETTRAN	<p>Will have a 1.8-hectare (~4.4 acres) test circuit at CleanTech Park, jointly developed by the Land Transport Authority and Jurong Town Corporation, Singapore to provide a simulated road environment for industry players to test their self-driving vehicles prior to deployment on public roads. The test circuit is expected to be operational by the second half of 2017 and will be operated by the Nanyang Technological University.</p>
GoMentum Station	<p>One of the largest test facilities in the world; the 5,000-acre facility with a 2,100-acre available test site is located in the decommissioned zone of the Concord Naval Weapons Station in Concord, California, where the Contra Costa Transportation Authority leads and facilitates collaborative partnership with automobile manufacturers, Tier-1 suppliers, communications companies, technology companies, academics, public agencies, and other partners to develop, test, validate, and commercialize connected vehicle applications and autonomous vehicle technologies³⁰³.</p> <p>There is about 20 miles of paved roads, and a cluster of barracks and buildings in the facility that provides an urban-like environment. It is also a secure location where companies can test cars in private.</p>

³⁰⁰ <http://www.dbusiness.com/daily-news/Annual-2016/80M-Autonomous-Vehicle-Test-Site-Planned-for-Willow-Run-Airport/>

³⁰¹ <http://www.gizmag.com/astazero-road-safety-track/33477/>

³⁰² <http://www.autoalliance.org/index.cfm?objectid=02000880-B49C-11E1-B12B000C296BA163>

³⁰³ <http://gomentumstation.net/programs-partnerships/>

Company	Development Efforts
	<p>In June 2016, Honda gave a public demonstration of its self-driving car prototypes at the testing facility at GoMentum Station, using the Acura RLX Sport Hybrid model.</p> <p>There has also been reports that Apple may be interested to use the site for vehicle testing³⁰⁴.</p>
HORIBA MIRA	<p>Developed a UK-based city circuit called ADVANCE, in collaboration with innovITS and the Transport Research Laboratory. Circuit comprises an extensive network of roads, traffic islands, and controlled intersections that replicates most European and US urban environments. Designed with communications suite including Wi-Fi, 5.9GHz for V2I and V2V, GSM/3G cellular network and GPS. Marketed as a proving ground for validating advanced driver assistance systems, cooperative active safety, road sign detection, intersection safety systems, autonomous vehicle systems, and driver behaviors.³⁰⁵</p>
Mcity	<p>A closed facility with 32-acre testing ground with full-scale simulated real world urban environment at the University of Michigan's Mobility Transformation Center that opened in July 2015³⁰⁶.</p> <p>As of June 2016, the following companies were reported to have been using Mcity for their testing: Ford, General Motors, Honda, Toyota, Nissan, Bosch, and Delphi³⁰⁷.</p>

³⁰⁴ <http://www.forbes.com/sites/dougnewcomb/2015/08/18/apple-eyes-use-of-local-track-for-vehicle-testing/#4bf964c62861>

³⁰⁵ <http://www.horiba-mira.com/our-services/city-circuit>

³⁰⁶ <http://www.mtc.umich.edu/test-facility>

³⁰⁷ <http://www.nytimes.com/2016/06/06/business/for-driverless-cars-citylike-test-sites-offer-the-unpredictable.html? r=0>

Table A-7: Investments by Map and Mapping Service Providers

Company	Development Efforts
HERE	<p>A location cloud company that operates a fleet of vehicles equipped with Radars, lasers and cameras to capture 3D street images to make high-definition maps for self-driving vehicles³⁰⁸. Has partnerships to provide maps and connected navigation services to automotive companies such as Toyota, Hyundai, Honda, and Volvo.</p> <p>Provides end-to-end location platform and software development kit for Samsung's Tizen operating system and will further extend its collaboration to Samsung's new connected car ecosystem³⁰⁹.</p> <p>Formerly a Nokia company, HERE was acquired in 2015 by a consortium of German carmakers including BMW, Audi, and Daimler, at a price of \$3.1 billion. Each company has an equal stake in HERE³¹⁰.</p> <p>Initiated the SENSORIS Innovation Platform in June 2015 to drive efforts to define a standardized interface for information exchange between in-vehicle sensors and a dedicated cloud or between clouds. As of June 2016, more than 10 automotive and supplier companies have joined the platform that is being coordinated by the European Road Transport Telematics Implementation Coordination (ERTICO). Submitted the design for a universal data format called SENSORIS to ERTICO in June 2016, hopefully to be evolved into a standardized interface specification for use across the automotive industry³¹¹.</p> <p>In July 2016, launched three new cloud-based information services to provide drivers with pre-departure traffic information, personalized fuel, and parking recommendations based on their preferences and habits, via connected embedded navigation systems³¹².</p> <p>There were also reports suggesting that Amazon and Microsoft are interested to provide cloud computing services to HERE. Reuters also reported that Bosch, Renault, and Continental have also expressed interest to have a stake in HERE³¹³.</p> <p>HERE's mapping approach is to make use of its high-precision GPS receiver to collect the car's latitude, longitude, and elevation every one-tenth of a second, a motion tracking inertial system to record the yaw, pitch, and roll every one-hundredth of a second, and a laser scanner to calculate the distance from</p>

³⁰⁸ <http://photos.mercurynews.com/2015/07/28/photos-here-a-nokia-company-has-global-fleet-of-cars-for-3d-street-mapping/#1>

³⁰⁹ https://its.cms.here.com/static-cloud-content/Newsroom/010316_HERE_strengthens_technology_collaboration_with_Samsung.pdf

³¹⁰ <http://www.wsj.com/articles/bmw-daimler-audi-agree-to-buy-nokias-here-maps-business-1438580698>

³¹¹ https://its.cms.here.com/static-cloud-content/Newsroom/290616_HERE_automotive_companies_move_forward_on_car_to_cloud_data_standard.pdf

³¹² https://its.cms.here.com/static-cloud-content/Company_Site/2015_11/HERE_Personal_Recommendations_Whitepaper.pdf

³¹³ <http://www.theverge.com/2016/4/1/11346710/amazon-microsoft-here-autonomous-car-tech-investment>

Company	Development Efforts
	<p>600,000 different points to create the localization layer necessary for a high-definition map. It then extracts features such as bridges, road signs, and guard rails from the images shot by the mapping vehicle, and compares them to what the car sees through its cameras.</p>
TomTom	<p>An Amsterdam-based navigation company.</p> <p>Inked a deal with Bosch (a Tier 1 supplier) in July 2015 to provide maps for Bosch’s autonomous vehicle testing on roads in California and Germany. Claimed to have started working on maps that self-driving cars need since 2010³¹⁴. Also have partnerships with Apple and Uber for the use of its map data.</p> <p>At the Consumer Electronics Show 2016, TomTom announced the launch of its Highly automated Driving map products for all interstate roads in California and all interstates and freeways in Michigan, which are testing grounds for driverless vehicles. In 2015, TomTom launched similar map products for the Autobahn network in Germany³¹⁵.</p> <p>Plans to create high-resolution maps for all freeways and freeway-like roads in Germany by end 2016, and parts of North America by 2017³¹⁶.</p> <p>Using a different approach from HERE, TomTom captures a “depth map” using its mapping vehicles’ Lidar sensors. The system continuously records the distinctive shapes and distances of roadside scenery, without trying to identify what the individual items are. By considering the whole stretch of road, the system is able to correlate the output from the autonomous vehicle’s Lidar with the pattern of the depth map and calculate its own location. This is similar to how Google builds its localization layer for its self-driving cars³¹⁷.</p>
Zenrin	<p>A Japanese map supplier that is 7.5% owned by Toyota. Current customers include Google and Toyota.</p> <p>Working on a system to translate data gathered from vehicles mounted with cameras and other sensors in real time into three-dimensional maps. Aims to sell maps that enable autonomous driving by 2020³¹⁸.</p>

³¹⁴ <https://www.wired.com/2015/07/tomtom-alive-getting-self-driving-cars/>

³¹⁵ <http://corporate.tomtom.com/releasedetail.cfm?ReleaseID=948890>

³¹⁶ <http://www.theverge.com/2015/7/27/9048027/tomtom-bosch-autonomous-vehicle-mapping>

³¹⁷ <http://www.economist.com/news/science-and-technology/21696925-building-highly-detailed-maps-robotic-vehicles-autonomous-cars-reality>

³¹⁸ <http://www.bloomberg.com/news/articles/2016-03-13/race-to-guide-self-driving-cars-is-getting-another-competitor>

Table A-8: Investments by Driverless Shuttle Developers

Company	Development Efforts
Auro Robotics	<p>Began deployment of driverless shuttles (limited to a top speed of 10 miles per hour) on the campus of Santa Clara University in 2015.</p> <p>Plans to expand to other small, contained environments such as amusement parks and small islands, that are privately controlled and not subjected to the government regulations.</p> <p>Working on two variants of the shuttle system: (1) closed loop route with pre-defined stops, and (2) on-demand to and from any user-defined locations³¹⁹.</p>
EasyMile	<p>A joint partnership of two French firms: vehicle manufacturer Ligier Group and robotics company Robosoft. Have demonstrated their driverless shuttles in Spain, Finland, France, Netherlands, Greece, Italy, Singapore, and Switzerland³²⁰.</p> <p>Designed a fully electric-powered EZ10 that can carry 12 passengers, and designed for last-mile travel and looped routes within confined areas. Has an average cruising speed of 12 miles per hour, and a top speed of 25 miles per hour. Does not require dedicated infrastructure; relies on Lidar, video, differential GPS, and odometry sensors for localization, navigation, and obstacle avoidance.</p> <p>Conducting a pilot program with Contra Costa Transportation Authority to test the shuttles at GoMentum Station test track in summer 2016, with plans to operate the shuttle at Bishop Ranch Business Park in San Ramon, California³²¹.</p> <p>Partnered with Japan's DeNA to launch a shuttle service in a shopping center in Chiba Prefecture near Tokyo in August 2016, using the EZ10 that can carry up to 12 passengers and travel at a top speed of 25 miles per hour³²².</p>
Hi-Tech Robotic Systemz	<p>An India-based company established in 2004 in the field of unmanned systems development, artificial intelligence, and computer vision.</p> <p>Demonstrated the Novus Drive, a 14-seater autonomous vehicle for operation in a controlled environment. Used to ferry visitors between pavilions at the 2016 Auto Expo Motor Show in Delhi, India³²³. Reported to be the first of its kind to be manufactured in India.</p>

³¹⁹ <https://techcrunch.com/2015/08/13/auro-robotics-yc-s15-is-building-a-driverless-shuttle-system-for-college-campuses/>

³²⁰ <http://www.gizmag.com/easymile-ez10-driverless-bus/39891/>

³²¹ http://www.mercurynews.com/bay-area-news/ci_30158944/driverless-shuttles-coming-east-bay-be-tested

³²² <http://www.driverlesstransportation.com/tag/easymile>

³²³ <http://www.prweb.com/releases/2016/07/prweb13548184.htm>

Company	Development Efforts
	Equipped with a 32-channel Velodyne Lidar sensor, stereo vision cameras, GPS, inertial navigation system, and machine-driven algorithms for path planning and obstacle avoidance ³²⁴ .
Local Motors	<p>An Arizona-based company that created the world's first 3D printed car in 2014.</p> <p>Developed a 12-passenger electric powered shuttle known as Olli that is equipped with 30 sensors including Radar, Lidar and cameras, with data processed by IBM's Watson supercomputer. Claimed to provide enhanced passenger experience by tapping on IBM's Watsons' application program interfaces: Speech to Text, Natural Language Classifier, Entity Extraction, and Text to Speech³²⁵.</p>
Navya	<p>A French company specialized in electric, autonomous systems. Claims that it has performed R&D in this area for the past 10 years and have conducted tests in Switzerland, France, US, England, and Singapore.</p> <p>Develops NAYVA ARMA production vehicle that is available for sale since October 2015. The fully electric vehicle can carry up to 15 passengers and travel up to a top speed of 28 miles per hour. The vehicle is equipped with Lidar, stereovision cameras, GPS, inertial measurement unit, and odometry sensors, with current applications confined to closed areas.</p> <p>Secured its first sale of two units of production ARMA vehicles to POSTBUS that are planned to be launched on the open roads in Sion, Switzerland in 2016. Also secured a contract with the Royal Automobile Club in Australia, as well as delivered a fleet of six vehicles to a nuclear power plant in Civaux, France in January 2016³²⁶.</p>
Westfield	<p>Together with a consortium comprising Heathrow Enterprises and Oxbotica, plans to develop the next generation "Ultra PODS" to navigate the streets of Greenwich, UK without the need for dedicated tracks.</p> <p>Westfield will be the vehicle integrator and manufacturer of the pods, responsible for the design and testing of the vehicles and ensuring that, where possible, they are manufactured in accordance with the current type approval requirements. Heathrow Enterprises will be responsible for vehicle software engineering, while Oxbotica will be deploying its vertically integrated autonomy solution, which includes mapping, localization, perception, and trajectory planning, to enable the safe operation of fully driverless shuttles in Greenwich. It will also implement an innovative cloud-based shuttle management system, enabling the shuttles to operate as part of a synchronized, self-governing ecosystem, complete with smartphone booking applications, monitoring, and reporting³²⁷.</p>

³²⁴ <http://www.traffictoday.com/news.php?NewsID=80556>

³²⁵ http://www.gizmag.com/olli-electric-driverless-bus/43901/?li_source=LI&li_medium=default-widget

³²⁶ <http://navya.tech/wp-content/uploads/2014/12/Press-Release.pdf>

³²⁷ <http://www.trl.co.uk/news-hub/trl-press-releases/2016/january/heathrow-shuttles-take-off-from-terminal-5/>

Company	Development Efforts
Varden Labs	A start-up by a group of students from the University of Waterloo, backed by Y-Combinator, a Silicon Valley start-up incubator. The system uses a modified golf cart and can currently only operate at intersection-less freeways and closed campuses. Targets the self-driving shuttle space.
WEpods	WEpod is modified from the EZ10 model from EasyMile. Since September 2015, WEpods has been conducting pilot tests on the public roads in the town of Wageningen, Netherlands. The vehicles are travelling at about 15 miles per hour during the trials, and remotely monitored by humans via the cameras ³²⁸ .
2getthere	Provides Personal Rapid Transit and Group Rapid Transit systems with fully automated operations on a dedicated network of guideways. Developed the ParkShuttle system in 1995 and conducted pilot projects at Amsterdam Schiphol airport in 1997, and Rivium Business Park in 1999. Delivered the Personal Rapid System to Masdar City, Abu Dhabi in 2010 ³²⁹ .

³²⁸ <http://wepods.com/pages/media>

³²⁹ <http://www.2getthere.eu/company/company-profile/>