Driving Changes: Automated Vehicles in Toronto

Discussion Paper

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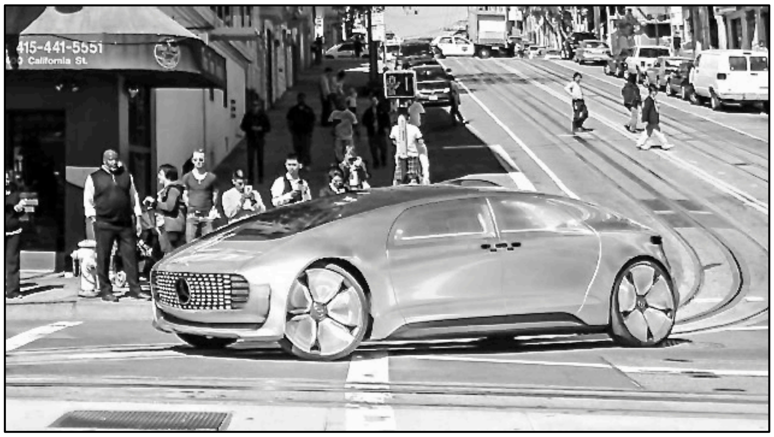

Mercedes-Benz F015 driverless concept car in San Francisco (Jordan 2015)

Yonge Street looking north from Adelaide Street, 1929 (Taylor 2014)

Yonge Street looking north from Adelaide Street, 1900 (Galbraith Photograph Company n.d.)

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1 About this project

This report was commissioned by City of Toronto Transportation Services Division as part of a broader project under the University of Toronto Transportation Research Institute (UTTRI).

The purpose of this report is to equip City of Toronto decision makers with the information they need to identify and evaluate short and medium term policy, planning, and investment options that pertain to the onset of vehicle automation. The report provides independent analysis of statistical and qualitative information, drawing on literature reviews by the author and by UTTRI.

This report and its contents are for discussion purposes only, and do not represent policies or plans of the City of Toronto. The author, David Ticoll (david.ticoll@utoronto.ca), is solely accountable for its contents.

Note to reader: In this report all references to automated vehicles (AV) refer to high or full automation, equivalent to Level 4 and Level 5 in the SAE levels of vehicle automation.

At Level 4, High Automation, the vehicle's system takes full control in specific modes with no driver participation required in those modes. For example, Level 4 AVs could function autonomously on dedicated freight routes, busways, vehicle lanes, and eventually on 400-level highways and major city streets. Once vehicles leave these routes the driver takes control.

At Level 5, Full Automation, the vehicle fully controls all driving modes irrespective of geography, road type, traffic conditions, weather, interactions or events. Steering wheels, floor pedals, and drivers are redundant in Level 5 vehicles because all occupants are passengers.

For more information, please refer to Section 4.2 of this report.

2 Driving Changes: Executive summary

City leaders, researchers and technologists increasingly agree that as vehicle automation transforms public, commercial, and consumer transportation, they will reshape urban life. While the Government of Ontario has just released rules for testing automated vehicles, other leading countries and cities have been preparing for this future for several years. It is neither too soon nor too late for Toronto to be a global leader in this transformation.

What is vehicle automation?

Vehicle automation covers a wide variety of technologies, uses, products and services. Some simple automation features, such as cruise control, are commonplace. Advanced driver assistance systems (ADAS) such as traffic-aware cruise control, lane changing and self-parking, are entering the market. Cars and trucks that drive by themselves are being tested on public roads around the world. They have crossed the United States and traveled long distances on Japanese and European highways. Mines in Canada, Australia and other countries routinely use self-driving loader trucks.

The distinction between ADAS and full or near-full automation is important. We will see many ADAS-equipped cars on Toronto roads in the coming years. They will be new factors in the assessment of traffic violations and accidents. Some advanced driver assistance features can be more risky than full automation because they reduce a driver's attentiveness, situational awareness and responsiveness.

This report uses the term "automated vehicle" (AV) to denote any type of vehicle that is capable of driving without human intervention on most or all road conditions (i.e., SAE Level 4 and Level 5). AVs will also be "connected" with one another (V2V communication) and with transportation infrastructure (V2I). During a lengthy transition period, conventional vehicles – many equipped with ADAS and V2V/V2I – will coexist with AVs.

The rise of AVs

The rush to produce a working automated vehicle (AV) is happening across the automotive and technology sectors. Auto manufacturers with publicly announced programs include:

- US: Ford & General Motors
- Germany: Audi, BMW, Daimler-Benz, Volkswagen
- Japan: Honda, Nissan, Toyota
- Other European: Peugeot, Volvo

Many so-called Tier 1 automotive suppliers are also developing AV technologies. They include Germany's Bosch, Canada's Magna International, and US-based Delphi. Many other technology firms and automotive supply chain participants, such as Canada's Research In Motion, have joined the AV revolution.

In the tech sector the Google Auto self-driving project has received most of the publicity and seems the furthest advanced. Baidu, Google's Chinese counterpart, partnered with BMW on an AV project in April 2014; their joint prototype is due on the streets by the end of 2015. Uber is aggressively pursuing an AV initiative. Apple is also rumored to be in the game.

The auto industry and the tech sector harbor different visions and strategies for AV design and deployment. Most traditional car manufacturers have adopted an incremental approach. They are adding driver assistance features to their respective fleets over time, until eventually their cars achieve fully automation. Tech companies, on the other hand, aim to design, test and sell fully automated vehicles from the very beginning. Consulting firms and market analysts generally predict that AVs will be commercially available around 2020 and commonplace by the late 2020s.

Benefits of AVs

This report provides bottom-up analysis based on Toronto-specific data. The result is a conservative estimate that were AVs to be at a 90% adoption rate in Toronto today, the result would be annual savings of $6 billion, or 4% of the City's $150 billion gross domestic product. This includes $1.2 billion from reduced collisions, $2.7 billion out of congestion costs, $1.6 billion from insurance, and $0.5 billion from parking fees and fines. AVs will provide other quantifiable social and economic benefits that range from fewer deaths and hospitalizations thanks to lower particle emissions, to productivity gains in many business sectors.

Beyond cost savings, benefits include:

- **Safety**. Eventual improvement of 90% or more on today's average of 47 traffic fatalities and 16,200 injuries per year.
- **Equity and accessibility**. Improved access to vehicle mobility for children and youth, seniors, people with disabilities, and low-income groups. For example, in 2030 AVs could significantly improve quality of life for a projected 75,000 seniors with severe or very severe disabilities, who would face challenges in using today's modes of public transit.
- **Environment**. NASA has named road vehicles as "the greatest contributor to atmospheric warming now and in the near term." The Toronto Medical Officer of Health reports that road traffic air emissions contribute "about 280 premature deaths and 1,090 hospitalizations each year." AVs are likely to be small, light, energy efficient, and suited for alternative power sources. A study by the US Lawrence Berkeley National Laboratory projects that electrically powered AVs will eventually reduce emissions by 87-94%.
- **Lower operating costs**. Besides parking and insurance, ownership and fuel costs are likely be a fraction of what they are today. This will particularly apply to Torontonians who forego car ownership in favour of on-demand mobility services.

- **Congestion**. Each of the factors that cause congestion – capacity bottlenecks, traffic incidents, poor signal timing, weather, construction, and uncertain travel times – can be reduced or mitigated by vehicle automation, especially when combined with mass public transit. At the same time, the accessibility and convenience of AVs is likely to stimulate greater use of cars and minibuses.

Policy and planning issues

Besides their many benefits, AVs raise transportation and city planning policy issues as well as various risks and challenges. On balance, the benefits significantly outweigh the costs. Smart, timely and effective AV innovation leadership and transition management have become competitive issues for cities and senior governments around the world.

AVs will affect every aspect of Toronto's transportation demand management framework, as illustrated in Table 1. Specific policies and actions will be necessary to ensure that each objective is optimized in the era of AVs.

Objective	Impact***	Items to address
Foster complete streets	+	Freed-up parking spaces
Increase car occupancy rate	+	Mode mix
Increase multimodal travel	+	Increased access & convenience
Reduce rush-hour congestion	+	Intelligent transportation system
Seamless multimode transportation GTA & beyond	+	Complexity, new market entrants
Strengthen downtown & other hubs	+	AV incentives to sprawl
Environmental sustainability	+	Transition to alternative fuels
Equitable funding & pricing	+	Business models & policies
Improve freight/goods movement roads & curbside	+	Allocation of freed-up parking
Increase road safety for everyone	+	Infrastructure, regulation
Social equity & inclusion	+	Pricing, vehicle tailoring
Foster complete communities	=	New urban design options
Increase fewer & shorter trips	-	Low "time cost" of AV use
Reduce car dependency	-	AV accessibility & convenience
Increase transit use	?	Mode mix & cost
Increase walking & cycling	?	Urban plan/mode mix
Reduce vehicle travel demand	?	Pricing, private vs. public
Shift travel from peak to off-peak periods	?	

Table 1 Impact of AVs on City of Toronto transportation policy objectives. List of objectives based on Official Plan & OPA 274. Highlighted items are from the City's Transportation Demand Management (TDM) framework.

*** Potential net citywide impact of AVs:

+ Positive
= Neutral
- Negative
? Policy dependent

Additional policy-related topics include:

- **Intelligent Transportation Systems**. Governments and industry are collaborating on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies under the rubric of intelligent transportation systems. For example, the US government plans to mandate eventual availability of V2V for new vehicles. It has also granted $42 million to New York City, Tampa and Wyoming for V2V and V2I pilot projects.
- **Public transit**. Industry firms, policy makers and researchers believe that AVs will stimulate the growth of on-demand mobility services. Many believe that AVs in general, and on-demand mobility in particular, will significantly change modality, usage and investment assumptions for public transit. For example, a simulation based on a mid-sized European city found that automated taxis and minibuses in combination with high capacity transit could reduce or eliminate the need for buses and streetcars.
- **Parking**. Mobility services may lead to a dramatic decline in vehicle ownership. Simulation models suggest that most road and off-road parking may eventually disappear.
- **AVs in winter**. Snow conditions present unique challenges for AVs. Some manufacturers have identified this as a design issue.
- **Data policy**. As "big data" and advanced software technologies become key assets in the AV environment, a fundamental change is occurring: the generation and ownership of transportation-related data is shifting from governments to the private sector. The City has an interest in some of this data for transportation planning, management and enforcement. The proprietary nature of vendor applications and data challenge the ability of regulators and consumers to independently assess vehicle safety, emissions, and other compliance issues. Consumers will have concerns about data ownership, privacy and security. The City has an interest in these issues, typically regulated by senior governments, since it must deal with the timeliness, rigor and consequences of regulatory policy.
- **Regulation**. Most AV-related regulation in Canada is the jurisdiction of senior-level governments. However the City has an interest in regulations that enable it to legally host AV innovation and adoption with appropriate rules in place. The Ontario government published official regulations for AV pilots in October 2015. They come into effect January 1, 2016; the government will begin accepting applications for prospective AV pilots in November 2015. City-specific regulation issues may include the transition from taxis and transportation network companies to autonomous mobility services; parking; traffic management; and accident reporting.
- **Fiscal impacts**. The transition to AVs and intelligent transportation systems will require changes in the City's capital and operating budget assumptions and plans. We estimate that the City currently generates about $100 million in net revenues per year from parking and traffic violations. This is about 1% of the City's annual budget, and a fraction of its spending on vehicle road infrastructure and services.

Other levels of government capture significant revenues from a variety of transportation-related sources.

- **Overall economic impact**. AVs will significantly improve business productivity and operating costs across the Toronto and regional economy. The previously mentioned annual cost savings of $6 billion, as well as improved health, safety, and access to transportation will generate economic benefits across a wide variety of private and public industry sectors.
- **Three kinds of sectoral economic impacts**. First, in some specific sectors like construction and technology, AVs will likely foster both business and jobs growth. Second, some Toronto industries such as wholesale and retail trade, transportation and public services, can obtain productivity benefits from AVs, but at the expense of employment. Third are industries that face both business and employment risks. They include motor vehicle manufacturing, distribution and servicing; taxi and limousine services; and insurance.

Three scenarios

We have defined three imagined "end game" scenarios for private vs. shared AVs during the 2030s decade. In the first scenario – **Ownership Leads** – while various shared and public AV mobility services gain market share, privately owned AVs retains a large presence. In the second scenario – **On-Demand Leads** – AV mobility service providers dominate personal transportation. In the third – **Split Outcome** – mobility service providers and sellers of privately owned AVs vie over a market that they share 50-50 plus or minus 10 points of difference.

On-Demand Leads is the most transformative and perhaps the most advantageous scenario. In this model, most Torontonians forego car ownership in favour of active transportation, mass transit, automated taxis (typically "pod-sized" 1-2 person vehicles), and automated minibuses. AV services include specialized vehicles for people with disabilities, families with small children, cargo, and trips to the cottage. In automated busways, individual buses "peel off" to employment hubs. AVs are right-sized, cost effective, and tailored to meet Torontonians' varying day-to-day needs in ways that are impossible today.

International initiatives

Governments and industry in countries around the world are investing, providing facilities and organizational supports, and addressing regulatory needs to foster domestic AV technology innovation and facilitate implementation. Comparing these initiatives, it is difficult to avoid the conclusion that Canada has some catching up to do.

- In October 2015 the **Ontario** government published a regulation that sets rules for AV pilots in the province. It requires a formal application from any company that wishes to test AVs. The government has also offered a cumulative total of $2.95 million in matching funding grants to support AV research, development and commercialization.
- The **US** government is significantly invested in standards creation, technology research, regulatory and policy initiatives. Six US states (California, Florida, Michigan, Nevada, North Dakota and Tennessee) and the District of Columbia have legalized AV trials under various conditions. About 20 other state legislatures are reviewing proposed AV legislation. Among the firms testing AV technologies on California roads are BMW, Bosch, Delphi Automotive, Google, Honda, Mercedes Benz, Nissan, Volkswagen, and Tesla.
- The **German** Ministry of Transportation and Digital Infrastructure released an automated and connected driving strategy, developed in conjunction with industry, in September 2015. It aims to bring highly automated cars to the market by 2020. German car manufacturers and supply chain participants are active in AV development.
- In 2015 the **UK** government published an action plan and a code of practice for AV testing. Several government-supported trials are planned in an effort to kick-start a UK-based AV manufacturing sector.
- In collaboration with legislators and transport authorities, Volvo plans to put end-customers into 100 automated cars in in a 2017 real life pilot at its headquarters city, Gothenburg, **Sweden**. One part of this effort will be to trial AVs for winter driving. By 2017 Gothenburg also intends to have a functioning vehicle-to-infrastructure system that provides alerts about incidents such as lane closures.
- Other countries with significant government supported AV initiatives include **Australia, China, France, Japan, Korea, the Netherlands, and Singapore**.

3 Topics for Consideration

This section (pp. 9-13) provides policy and planning topics for consideration based on findings and conclusions of the research described in this report.

3.1 Strategic pathways

We propose three possible strategic pathways for the City to consider: Prepare the Ground, AV in Toronto, and Showcase. These are not mutually exclusive – rather, they are cumulative. A maximal strategy could include all three. Items listed are illustrative of the type of activity in each pathway.

a) Prepare the Ground

- Develop an overarching vision and point of view on the impact and role of AVs for the City of Toronto.
- Create a cross-functional City working group on vehicle automation.
- Review, prioritize, and timeline the various potential actions that arise from this report, and any others that may be identified.
- Develop comprehensive fiscal, financial, and business tools as a basis for investment decisions related to vehicle automation in the City.
- Review policies and plans for urban planning, transit, and transportation in light of the coming advent of AVs, and consider changes in current assumptions, investments, processes, and decisions.
- Facilitate informed discussion regarding vehicle automation and its implications for Toronto in the community (including specific stakeholder groups), on Council, and among City leaders.
- Assess the impact, desirability, policy and investment implications of the various scenarios described in this report.
- Define City interests and actions to foster provincial and national policy and regulatory changes related to AV testing, licensing, safety, security, liability, data, and other matters.
- Assess the readiness of the City's organizational capabilities and infrastructure for the advent of automated vehicles.

b) AV in Toronto:

- Attract one or more major AV producers to conduct research, development, and trials in Toronto, including a focus on snow conditions.
- Foster use of advanced driver assistance systems to improve vehicle use outcomes by Toronto drivers and in City fleets.
- Conduct a trial of vehicle-to-vehicle, and potentially, vehicle-to-infrastructure communication, by City fleets and a subset of privately owned vehicles.
- Plan a pilot network of automated routes for AV rapid transit.
- Initiate community consultations on the transition to AV-related planning and infrastructure.

c) Showcase

- Incorporate the AV revolution as part of a major showcase event or bid such as Expo 2025 or the Olympics.
- For the event, transform key aspects of the City's transportation and urban design, as a living showcase for 21st century urbanism.
- Proactively address the full breadth of benefits and challenges associated with confronting technological change as a city, as part of the bid and the event itself.

3.2 Transportation planning

AVs will be "rightsized" to meet a variety of needs, including various private vehicles, compact "podcar" taxis for short trips, vehicles adapted to specific accessibility needs, custom-kitted commercial vehicles, and multi-passenger automated minibuses. This has significant implications for transit assumptions, strategies, and plans. Issues for consideration include:

- Public vs. private ownership of various transit modes including automated taxis and automated minibuses.
- Competition (including the question of local ownership), licensing, technology and service standards, data policies, accessibility requirements, safety reporting, insurance, etc.
- Potential automated bus rapid transit projects for completion within the next 3-5 years
- In the short term, use of non-AV transit innovations, such as automated minibuses.

Levels of vehicle automation:

- The traffic management, safety, and liability implications of partial automation for Toronto streets are emerging issues today.
- Conditional automation – where a vehicle functions autonomously most of the time, but the driver is always ready to take over – is likely to be in significant use over the next 2-3 years. It raises several policy issues:
    - In the short term, the City may wish to consider the benefits of encouraging Toronto drivers to select vehicles with conditional automation safety applications.
    - Setting realistic, aggressive targets for requiring conditional automation in vehicles that provide City services might prove beneficial.
    - Toronto has potential shared interests with other urban, provincial, national, and international partners in monitoring and assessing human factors in AVs, such as driver responsiveness and vehicle ergonomics.
- Full vehicle automation has potentially significant implications for public transit, freight transportation support, and congestion mitigation planning frameworks and projects.

Vehicle automation is expected to have a significant impact on the freight sector and freight services. The City has a particular interest in delivery and courier vehicles with respect to their economic, traffic, and curbside impacts.

Given the complexity and variability of the congestion issue, analysis and simulation of various planning options and scenarios would be beneficial.

3.3 City planning

The various scenarios for AV adoption will have significant implications for the City's Official Plan, demographic and economic projections. Achieving best-case outcomes and policy objectives necessitates proactive planning.

Ensuring that AVs advance and extend City equity policy objectives, in particular for seniors, youth, economically disadvantaged, and the mobility-impaired, would likely require targeted policy and regulatory initiatives.

Potential AV-induced sprawl, vehicle usage growth, and impact on active transportation, have implications for Official Plan, urban design, and transportation planning policies and guidelines.

Key issues include:

- Multimodal integration based on AV rightsizing with supports for complete streets/communities & active transportation
- How to use AVs to expand access and affordability
- How various AV modalities and scenarios for privately owned AVs; mobility services employing ATs and AMs; and specialized vehicles might change the shape of the city
- Governance/ownership/financial models for future transportation shared services

The high volumes of parking space likely to be freed up in the coming decades will have significant policy, management and fiscal implications for the City.

The potential decline in demand for parking has implications for City zoning regulations for parking space ratios and occupancy. To the extent that existing parking facilities and spaces are rezoned for development or other uses, a variety of land value capture options will arise.

3.4 Infrastructure & technology

3.4.1 *Road infrastructure*

Toronto may wish follow the lead of US and international cities that are conducting V2V and V2I trials. They are monitoring developments in this domain and implementing strategies to foster use of these technologies (including by their own fleets and transit vehicles) to improve safety and efficiency.

Alternative fuels power provision for AVs would benefit from a plan that is based on international standards such as the City's Sustainable Energy Policy and its Green Fleet Plan. Interested stakeholders would include the automotive/AV sector, the property sector, service station operators, and the Provincial government.

3.4.2 *Information technologies, data & standards*

It will be in the interest of the City and many other stakeholders that the AV sector to use common, open, international standards for data definitions and management.

Tracking, supporting, and learning from the development of pertinent standards would benefit the City's AV-related activities.

A Canada/Ontario policy framework and plan regarding mobility data ownership, use, and protection is needed in order to address the needs and minimize the risks of cities, citizens, and organizational stakeholders. Such a framework might include:

- Policies and mechanisms that address the City's usage needs as well as those of other stakeholders, while adequately protecting the privacy and security of user data
- Access to AV firms' digital maps for City use, whether for urban design and engineering, traffic and street management, or regulatory (including safety and liability management) purposes
- AV user data ownership and control as well as the potential role of Privacy by Design and other frameworks
- Vehicle technology transparency
- Alignment with international emerging and best practices

3.5 Regulation

City-specific regulation issues may include the transition from taxis and transportation network companies to autonomous mobility services; parking; traffic management; and accident reporting.

The City would benefit from a Province-led cross-governmental initiative for AV regulation that draws on international emerging and best practices.

The City has an interest in ensuring that safety evaluation of ADAS technologies, as well as human factors such as "driver situational awareness", be included by the Province for consideration in the assessment, licensing, and regulation of advanced driver assessment systems (ADAS). "Black box" incident recording is a potential requirement.

The City, as well as Provincial licensing authorities, would be well advised to keep a watching brief on the capabilities, limitations, and real world experience of AV safety technologies.

3.6 Economic development

3.6.1 *AV innovation*

It would be in the City's interest to attract and support AV technology innovation and development by startup and established firms in the technology and automotive sectors. A sustained program of AV-connected vehicle trials would be a good signature initiative. Supporting or incenting priority mapping of City streets by AV companies could help attract early deployment.

A potential transition strategy starts with a limited web, or network, of AV capable roads. This network could expand as AV capability is proven, demand increases, and fully automated technologies and business models gain credibility. A stepwise approach might go as follows, over a period of 5-10 years beginning, for example, in 2018 with rapid transit busways:

1. Rapid transit busways for automated buses
2. Automated vehicles including private cars, ATs, and AMs on rapid transit busways and 40x highway HOV lanes
3. Arterial road lanes assigned to AVs
4. Reserve expanding sections of downtown Toronto for highly automated vehicles, freight vehicles, traditional taxis and buses, and active transportation. (This will serve as a proving ground for the presence of fully automated vehicles in Toronto. It requires improved public transit and well managed connection points for people transferring to/from vehicles at the edge of downtown).
5. Expand supports to AVs across the City.

AV navigation and safety in winter conditions is of special interest to the City, the Province, and other Canadian governments.

An AV cluster in Toronto would require collaboration among post-secondary institutions and industry participants.

3.6.2 *Industries & jobs*

Vehicle automation is likely to make profound, systemic economic and fiscal impacts on City government and the City as a whole. While some changes are predictable, others will emerge over time; an AV-related economic planning framework would be useful to help identify opportunities, risks, and necessary actions. Awareness, consultation, and action involving a cross section of City residents, stakeholders and organizations may help identify and address AV-related industry and job opportunities and challenges.

4 Automated Vehicles: a primer for policy makers

4.1 The idea in brief

Vehicle automation covers a wide variety of technologies, uses, products, and services. Some simple automation features, such as cruise control, have already become widely implemented. Advanced driver assistance systems (ADAS), such as pre-collision braking and adaptive cruise control, are now available on mid-market vehicles (Subaru 2015). Near-fully self-driving cars and trucks are being tested on public roads around the world. They have crossed the United States and rolled long distances on Japanese and European highways. Mining operations in Canada, Australia, and other countries routinely depend on automated trucks.

AVs are a breed of advanced robots. They join the emerging Internet of Things, a widely-discussed networking concept for physical devices that combines massive cloud-based computing power, Big Data, and advanced programming methods (including machine learning[1]) (Brynjolfsson and McAfee 2014).

AVs promise improved safety and accessibility, cost savings, and new economic opportunities. Their occupants are "freed" to use their time as they choose. Vehicles will be customized to meet all sorts of needs and desires. New kinds of businesses will emerge. AVs require new approaches to urban and economic planning. They will also disrupt a variety of industries and occupations.

Technology, political, and urban leaders increasingly agree that as AVs transform public, commercial, and consumer transportation, they will reshape urban life. Leading countries and cities are actively preparing for this future. It is neither too soon nor too late for Toronto to be a global leader in this transformation.

4.2 SAE Levels of Automation

Over the coming years, most new vehicles will gain increasing levels of automated driving capability. Industry organizations have created two standards to categorize these levels. This report uses a 6-level model of vehicle automation from SAE International, depicted in Figure 1. The Government of Ontario adopted the SAE model in its AV pilot regulation of October 2015 (Government of Ontario 2015).

A similar model from the US National Highway Traffic Safety Administration (NHTSA) is described in the Appendix. The last 2 columns in Figure 1 map the NHTSA levels to the SAE levels.

[1] Machine learning software applications can "learn" how to build predictions, make decisions and program themselves.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
***Human driver* monitors the driving environment**								
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
***Automated driving system* ("system") monitors the driving environment**								
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

Figure 1: SAE International: six levels of driving automation (SAE International 2014; Center for Internet and Society n.d.)

Nearly every car today has at least one automated feature: cruise control. In the SAE taxonomy, this is at **Level 1**, Driver Assistance, i.e., the automation of either steering or acceleration/deceleration, but not both. Sophisticated Level 1 ADAS include adaptive cruise control, pre-collision braking, and lane departure warning.

At **Level 2**, Partial Automation, the vehicle system takes control of both steering and acceleration/deceleration. In October 2015 Tesla Motors was the first car company to roll out a suite of Level 2 capabilities. The company issued a software update for its Model S cars that are equipped with forward radar, a forward-looking camera, ultrasonic sensors, and digital braking control. The new capabilities can steer within a lane, change lanes, provide "active, traffic-aware cruise control" and collision avoidance, and prevent the car from wandering off the road. The technology can also find a parking spot and parallel park the car. According to the company, the combined hardware and software use "realtime data feedback from the Tesla fleet, ensuring that the system is continually learning and improving upon itself." (Tesla Motors 2015).

Levels 1 and 2 automation technologies perform specific driving tasks and provide warnings in some situations, but the driver retains overall responsibility for monitoring the driving environment. In Levels 3, 4, and 5, automation crosses a critical threshold. Now the technology system takes responsibility for monitoring the driving environment.

At **Level 3**, Conditional Automation, the vehicle system takes full-time control in specific modes only, such as highway driving, dedicated AV lanes, or unobstructed city streets. In these modes, the driver must be able to take control when the system asks him/her to do so. Much AV testing is happening at Level 3 automation, from local trials to transcontinental road trips (Solon 2015; Grobart 2015; Delphi 2015; Audi Corporation 2015). The results suggest that Level 3 automation will be commonplace within a few years. A risk associated with Level 3 automation, that has only seen limited research, is whether drivers, after relinquishing control, can respond in time when asked to take back control. One study found that drivers typically couldn't respond sufficiently to a 2 second emergency. Five seconds is sometimes sufficient, while at 8 seconds results improve significantly. Unfortunately, hazard situations often require responses within five seconds or less (Mok, Johns and et. al. 2015).

At **Level 4**, High Automation, the vehicle's system takes full control in specific modes, as in Level 3. The difference is that no driver participation required in those modes. For example, on dedicated freight routes, busways, or AV car lanes, Level 4 vehicles might run entirely on their own. Once vehicles depart such "modes", or routes, they revert to Level 3 where the vehicle can call on the driver to take over at any time.

With **Level 5**, Full Automation, the vehicle fully controls all driving modes irrespective of geography, road type, traffic conditions, weather, interactions or events. Level 5 vehicles can drive anywhere, though they may need to go slow while learning a new (perhaps off-road) route. Steering wheels, floor pedals, and drivers are redundant in Level 5 vehicles as all occupants are passengers.

NOTE: In this report all references to AVs imply Level 4 or Level 5.

4.3 Competing models of AV deployment

The automotive and technology industries harbour fundamentally different strategies in the race to produce an economically feasible AV. Broadly speaking, auto manufacturers like Ford, General Motors and Mercedes intend to move their fleets from their current Stage 2 automation status to Stages 4 and 5 in a step-by step fashion. Technology firm Google Auto aims directly for Levels 4 and 5, with AVs on the market by 2019 or 2020. Other tech companies, such as Apple and Uber, seem headed in the same direction.

Auto manufacturers with publicly announced AV programs include:

- US: Ford & General Motors
- Germany: BMW, Daimler-Benz, Volkswagen
- Other European: Peugeot, Volvo
- Japan: Honda, Nissan, Toyota

Most auto manufacturers embrace an incremental approach where driver assistance features are added to their respective lineups over time until full automation is achieved in 2-10 years (General Motors 2015; Bunkley 2015; Daimler 2015; Gibbs 2015; Stevens 2014). Mercedes-Benz plans 2016 release of a car with advanced steering assistance for highways and country roads, the ability to adjust speed in accordance with street signs, and the ability to identify pedestrians and objects and stop or swing around them (Behrmann 2015).

We surmise that other manufacturers, such as Ford, Hyundai, Toyota and Volkswagen, may use AV technologies from a Tier 1 supplier such as Delphi Automotive. In April 2015 Delphi announced it had completed the first-ever US coast-to-coast trip by an AV. Over the 3400-mile drive from San Francisco to New York, the car was in autopilot 99% of the time (Delphi 2015). A few manufacturers, notably Fiat Chrysler and Porsche, have expressed scepticism about vehicle automation.

Audi (a Volkswagen subsidiary) and Volvo aim to leapfrog their industry counterparts and quickly move to full autonomy. In early 2015 Volvo announced Autopilot, “a complete production-viable autonomous driving system.” In collaboration with legislators and transport authorities, the company plans to put 100 automated cars in the hands of end-customers in a 2017 real life pilot at its headquarters city, Gothenburg, Sweden (Volvo Car Group 2015). A significant part of this effort is to prepare AVs for winter driving conditions.

Major technology firms have confirmed or rumoured AV initiatives.

- Google Auto’s self-driving project has received most of the publicity on the issue and seems the most advanced.
- Baidu, Google’s Chinese counterpart, has partnered with BMW and announced that a joint prototype will be on the streets by late 2015 (Gibbs 2015).
- Uber is aggressively pursuing an AV initiative with technology teams in several US cities.
- Apple has indicated it is working on an electric vehicle for launch in 2019. It is also rumored to have AV plans.
- A variety of less prominent initiatives are under way. For example, Sony is exploring its options (Inagaki 2015). Navya Technology, a French company, has released a self-driving 10-person shuttle for sale to enclosed campus environments such as industrial sites, airports, and resorts.

As mentioned, technology firms aim to design, test, and sell vehicles that are fully automated from the very beginning. Tech companies will probably outsource manufacturing to auto supply chain players like Delphi, Magna or Robert Bosch. They may even license their technologies to, or partner with, the big car firms. The advantage of this model is its cost-effectiveness.

4.4 Adoption Timing

Auto executives have been quoted on the market availability dates for their presumed Level 4 or 5 offerings (see Table 1) though the dates will likely vary from those promised. In addition, as mentioned, Apple reportedly aims to release an electric car in 2019; its automation level is undefined. Uber's CEO has said he wants the company's fleet to be driverless in 2030.

2017	Audi
2019-2020	Google
2020	Nissan, Tesla, Toyota
2024	Jaguar, Land Rover
2025	Daimler

Table 2: AV mass-market availability by manufacturer (Driverless Car Market Watch 2015).

Consultants and analysts generally predict that AVs will be commonplace in the mid to late 2020s, though others say they will not be in wide use for decades. Technology analyst firm Gartner predicts that by 2030 a quarter of the vehicles in use in mature markets will be AVs (Morgan Stanley 2013; PwC 2015; Levisohn 2015; Bertoncello and Wee 2015; LeBeay 2015; Ross 2014). Table 2 summarizes these predictions.

2015	Morgan Stanley: limited driver substitution begins to roll out
2018	Morgan Stanley: complete autonomous capability begins to roll out
2020	PwC: semi- and full-AVs have 9-10% global share in basic scenario; 12-13% in disruptive scenario[2]
2025	PwC: semi- and full-AVs have 14-16% global share in basic scenario; 19-22% in disruptive scenario Goldman Sachs: Full AVs will be "commonplace"
2028	McKinsey: Consumers begin to adopt AVs
2030	PwC: semi- and full-AVs have 15-18% global share in basic scenario; 28-30% in disruptive scenario Gartner: AVs are 25% of passenger vehicle population in use in mature markets
2035	Morgan Stanley: 100% autonomous penetration
2040-2050	McKinsey: AVs become the primary means of transport

Table 2: Consultant and analyst predictions for AV adoption.

We support the consensus view that AV adoption will accelerate quickly through the 2020s. Lengthier forecasts seem to presume an 8-9 year consumer vehicle replacement rate. We believe that the proliferation of AT and AM services could alter consumer habits, potentially accelerating adoption. Furthermore, the adoption rate for AVs may be more analogous to consumer technology markets rather than cars (see Figure 2).

[2] PwC's basic scenario is that current sales growth and regulations continue. Their disruptive scenario entails less safety regulation and more financial support by governments and a new player (presumably a technology firm) enters the market in mid-2020.

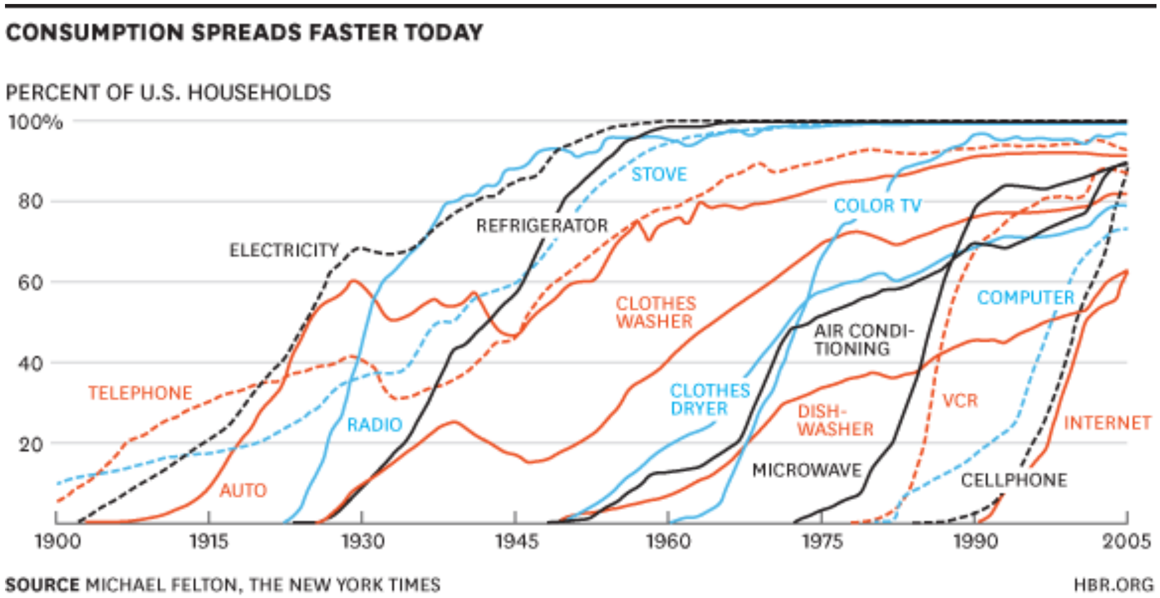

Figure 2: Pace of technology adoption speeding up (McGrath 2013)

The precedent and seed company for applying a technology sector type adoption rate to vehicles is Uber, whose CEO has expressed a goal to be "driverless in 2030" (Kalanick, 2015). We believe the primary limiting factors will be technology capabilities, including the ability to operate in extreme conditions such as winter, and government support including but not limited to regulation. In our view, the forces of competition and innovation will lead industry and governments to solve these and other challenges.

4.5 2030s: Three scenarios

The consensus view described in the previous section is that fully automated vehicles will become the prevailing mode of urban transportation during the 2030s decade. This section forecasts three possible outcomes for Toronto and Torontonians depending on how market dynamics and public policy respond to these changes.

Key questions for the scenario forecast are: Will the current dominant model of private vehicle ownership continue to prevail in the era of AVs? To what extent will people forego car ownership in favour of on-demand mobility services from automated taxis, automated minibuses, mass transit, and the like? [3]

On-demand vehicles, particularly ATs, will be in various shapes and sizes. As AVs become prevalent and accidents decline dramatically, the typical AT will be much smaller and lighter than today's cars ("pod" sized for 1-2 passengers), and electrically powered. Other "rightsized" ATs will be suited for larger groups. Some ATs will have affordances for specific activities (like meetings, eating or sleeping), the mobility-impaired, baggage transport and so on.

We begin by providing some background statistics for our analysis. Toronto residents owned about 1.1 million cars in 2011, with average annual ownership costs of $9,000 (Bateman 2014). A University of Toronto survey found that Toronto residents completed 2.6 million light vehicle trips in a single day, i.e., 2.3 trips per light vehicle per day. In addition, Greater Toronto Hamilton Area (GTHA) residents completed 2.8 million light vehicle trips into the City (Data Management Group 2014). This yields a Toronto/GTHA total of 5.4 million light vehicle trips per day.

Assuming zero AV adoption, we have arbitrarily increased the number of Toronto-owned vehicles by 18% for illustration purposes, to 1.3 million for the early to mid 2030s. A single AT replaces around 10 conventional vehicles (Fagnant and Kockelman 2013). AMs shared by several passengers reduce the number of ATs in each scenario by a ratio of 1:4.

We anticipate new demand for AT and AM travel from segments that have had limited ability to drive traditional cars. These include youth, the elderly, the poor, and the mobility-impaired. A daily vehicle demand projection (120,000 AVs and 30,000 ATs) for these groups has been added to all three scenarios.[4] Not included in this projection is hypothetical AT demand growth due to convenience, cost and similar factors among residents with traditionally high access to transit, including active transportation.

[3] Today's Uberpool service can be viewed as a precursor to automated minibuses (Uber, 2015).
[4] Section 5.5 of this report includes analysis of these new demand segments.

	Ownership leads	On-Demand leads	Split outcome
Automated taxis	22,000	92,000	57,000
Automated minibuses	1,000	3,000	2,000
Private AVs/legacy[5]	1,010,000	260,000	650,000
Toronto light vehicle ownership - total	**1,033,000**	**355,000**	**709,000**
GTHA vehicles entering Toronto (all combined)	1,000,000	350,000	700,000
New 'accessibility' users - -----→Automated taxi	120,000	120,000	120,000
----→Automated minibus	30,000	30,000	30,000
Toronto daily vehicles	**2,183,000**	**855,000**	**1,559,000**

Table 3: Projected number of vehicles in each scenario

In the first 2030s scenario – **Ownership Leads** – Private AV ownership dominates, while mobility services mainly displace taxi and other "shared" transportation services. Specialized ATs somewhat improve access for mobility-disadvantaged Torontonians. AMs have a smaller presence. About one million light vehicles based in Toronto either park all day or service residents. An additional million enter the city each day from other parts of the GTHA. Perhaps 50,000 of the nearly 2.2 million light vehicles on Toronto roads or in parking spots are ATs or AMs.

In the second scenario – **On-Demand Leads** – automated mobility services dominate personal transportation. In this scenario, most parking becomes redundant. The City's total number of vehicles is down to 355,000 or less. Add to this comparable AT/AM adoption across the GTHA and 150,000 more vehicles for 'accessibility' users. Total: the City's transportation infrastructure supports a combined daily base of 855,000 light vehicles.

In the third – **Split Outcome** – mobility services and private ownership vendors vie over a market that they share 50-50 plus or minus 10 percent. The combined Toronto vehicle base is about 1.56 million

To summarize: in Ownership Leads, ATs replace 20% of privately owned AVs and on the roads; in On-Demand Leads, ATs replace 80% of private AVs; in a Split Outcome, ATs replace half.[6]

On-Demand Leads is the most transformative scenario while arguably also the most sensible and advantageous. In this model, Torontonians forego car ownership, opting for combinations of active transportation, mass transit, ATs (typically "pod-sized" 1-2 person vehicles), and AMs. AV services include specialized vehicles for people with accessibility needs, families with small children, grocery shopping, or even trips to the cottage. In automated busways, individual buses can peel off to employment hubs.[7] AVs are right-sized, cost effective, and tailored to meet Torontonians' varying day-to-day needs in fine-grained ways that are impossible today.

[5] A portion of private Toronto-based AVs and legacy vehicles remain parked on a typical day.
[6] AVs in this analysis include automated light vehicles such as small vans and trucks for home-based use. This analysis excludes commercial vehicles, other than those used by the home-based self-employed.
[7] AV controls, enhanced by vehicle-to-vehicle (V2V) communication, will let them follow one another very closely. Dedicated rights of way will further increase efficiency for "platoons" of buses, transport trucks, and other vehicles.

4.6 The transition

Vehicles with varying levels of automation will share roads with traditional vehicles for a long transition period. The average age of light-duty vehicles in the US is 11.4 years.[8] Some drivers will always prefer conventional vehicles. Drivers of conventional vehicles often use eye contact with one another as cues for action (Sivak and Schoettle 2015). How important this feedback is, and how AVs will affect such driving dynamics, is unknown.

Toronto roads will soon host expansion of ADAS (Level 2 and 3) such as adaptive cruise control and lane keeping. These technologies will be new factors in the assessment of traffic violations and accidents. Some advanced driver automation features can reduce a driver's attentiveness, situational awareness, and responsiveness.

But the central issue is how to begin integrating Level 4 and 5 AVs into a big city like Toronto. As mentioned, with Level 4 technology a vehicle's systems take full control. The driver is no longer required – but only in "some" driving modes. For example, dedicated freight routes, busways, or AV car lanes could be made highly efficient for Level 4 "platoons". When a vehicle leaves a platoon or AV lane it reverts to Level 3 or 2. This can provide one foundation for a transition strategy.

4.7 Urban and Social Trends

Toronto, along with many other cities, aims to reduce car ownership and use in favour of active transportation and transit. It invests in complete streets, bicycle lanes, bike rental services, HOV lanes and transit. It supports carsharing services like AutoShare, car2go and Zipcar. The City is considering how to further discourage car use with congestion pricing, toll roads, car-free zones, and other mechanisms. Concurrently, on-demand ride services are on the rise. Growing numbers of citizens embrace these changes as a better way to live.

Some have speculated that the frequent use of car- and ride- "sharing" by Gen Y consumers implies readiness for AV services as an alternative to car ownership (Gill, et al. 2015; Gao, Hensley and Zielke 2014). Others point out that large majorities of Gen Y around the world say they plan to buy cars or have done so, and their numbers are growing (Giffi, et al. 2014; Thompson 2015). For some Gen Y consumers, cost may actually be the main obstacle to car ownership. Nevertheless, for these and other reasons, a historical shift away from car ownership appears to be happening. As Gen Y (and soon Gen Z) take center stage, and older demographics grow in size, they fuel markets for mobility on demand.

Culturally, there is a larger shift toward instantly available, digitally enabled on-demand services, including music and video streaming, social media and self-expression, online purchasing, and work-related applications. We believe that emerging transportation strategies and practices will combine with the rise of digital culture and economics to ready Torontonians for AV services on demand.

Scenario relevance: Cultural trends and various carsharing experiences suggest growing readiness for the On Demand Leads or Split Outcome scenarios.

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[8] "Furthermore the distribution of vehicle age has a very long tail to the right. For example, in 2002, 13.3% of all light trucks sold 25 years earlier were still on the road, with a corresponding percentage for cars of 2.3%." (Sivak & Schoettle, 2015)

5 Benefits of AVs for Toronto

5.1 Safety

5.1.1 *Quantifying the benefits of safety*

The City has moved to align itself with Vision Zero, a project to eliminate traffic fatalities and injuries that has gained commitments across Europe and the United States. The automation of driving is the best way to realize this radical but feasible vision. Human factors are the principal cause of 93% of collisions, even when other factors such as road conditions and mechanical failures are at play (US National Highway Traffic Safety Administration, 2008a). This section describes and quantifies the safety benefits of vehicle automation.

From a 2011 Transport Canada report, unless noted otherwise:

- In 2013 Canada had 1,923 vehicle fatalities and 10,315 serious injuries (Transport Canada 2015).
- In 2008 Canada's accident record ranked fourth from worst among thirteen OECD countries, with 7.2 fatalities per billion vehicle kilometers traveled (VKT). The best-performing country, Great Britain, had 5 fatalities per billion VKT.
- Over 2010-2013, Toronto averaged an annual 46.6 traffic fatalities and 16,198 major and minor traffic injuries (City of Toronto Transportation Services 2014).
- Human factors – choices and/or states of mind or body – account for the vast majority of accident-related deaths and major injuries in Canada (Transport Canada 2011). Primary factors include speeding, driver age, alcohol and/or drug impairment, fatigue, and distraction.

To estimate the economic cost of collisions in Toronto, we apply a model from a 2007 study by Transport Canada for the Ontario Ministry of Transportation (Vodden, et al. 2007). This model accounts for 1) direct collision costs such as property damage, injury-related costs and delays, out-of-pocket expenses, hospital/health care, tow trucks, and police, fire, and ambulance services; 2) discounted future earnings; and 3) willingness-to-pay cost, a socially derived valuation of a statistical life or injury.

We increase this model's results by 16% to account for growth in cost of living to 2012, the most recent year for which Toronto fatal and injury collisions data are available.

City of Toronto cost of fatal & injury collisions $thousands 2012			
	Number	**Cost /collision**	**Total**
Fatal collisions	47	$18,250	$857,750
Injury collisions	16,200	95	1,539,000
Total	16,247		**$2,396,750**

Table 4 City of Toronto cost of fatal and injury collisions in 2012

As Table 4 shows, the presumptive cost of death and injury-related collisions to the Toronto economy in 2012 was $2.4 billion. In addition, we estimate $600 million as a conservative cost of property-damage-only accidents.[9] This yields a 2012 road accident cost of $3 billion.

[9] Property damage only collision data was not readily available.

5.1.2 *Vehicle automation and safety*

Full vehicle automation is not the only technological solution to accident rates. The Insurance Institute for Highway Safety reports that property damage liability claims for cars with automatic braking have already declined by 7-15%. Connectivity for conventional vehicles, including V2V and V2I communications, is expected to make an even bigger impact.[10]

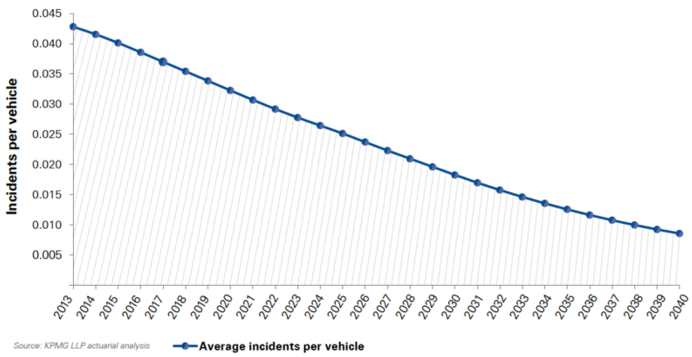

Figure 3 Accident forecast: 80% drop by 2040 (KPMG 2015)

Combining connectivity with automated driving will greatly reduce accidents, fatalities and injuries (US Department of Transportation 2014). Generally the literature predicts 50-90% safety improvement from AVs – rising with the level of adoption. University of Texas researcher James Fagnant projects that 10% market penetration of fully automated vehicles will provide a 50% reduction in crashes and injuries. A 90% market penetration means a 90% reduction.[11]

While trials to date overwhelmingly support the view that automation addresses the human factors in accidents, doubts about safety persist. First, the complexity of AV technologies may limit safe choices by vehicle software. Second, AVs may be unable to match the instinctive knowledge and responses of an experienced, alert driver. And third, pedestrians, assuming AVs will always stop for them, may take dangerous risks (Sivak and Schoettle 2015).

Vehicle accidents have relatively simple causes that technology can address. For example, Google has demonstrated a low cost application that can accurately identify a pedestrian within 0.25 seconds (Harris 2015). While this exceeds the 0.07 seconds required for real time safety identification, performance will likely improve by the time AVs go to market.

We estimate that at 90% AV penetration, the benefit to Toronto is 12,000 fewer road accidents, 38 fewer fatalities and many fewer injuries, with cost savings of $1.2 billion.[12]

Scenario relevance: With respect to safety outcomes, On-Demand Leads will be least costly for the average vehicle user and the economy as a whole. Split Outcome will follow, and Ownership Leads will cost the most.

[10] The US Department of Transportation intends to propose a rule for the provision of V2V communication in new vehicles by the end of 2015 (National Highway Traffic Safety Administration, 2015).
[11] Fagnant's analysis assumes that 10% of AVs are shared and that a single AV serves five times as many trips as a non-shared vehicle.
[12] This assumes safety improvements of 80% and applying an additional 50% discount to costs based on the Transport Canada model.

5.2 Equity and Accessibility

Quality and availability of transit are essential to the standard of living that Toronto strives to provide for its residents. But not only is the City's public transit system overburdened, its insufficiency disproportionately affects marginalized groups. Researchers believe that appropriately designed and managed AVs can transform access to mobility for children and youth, seniors, low income groups and people with disabilities (Bradshaw-Martin and Easton 2014; Anderson, Kalra and Stanley 2014; D. J. Fagnant 2014).

In Toronto (population 2,615,060):

- The population share of seniors will increase by one third from its current level to about 500,000 by 2031.
- 15.6% of the Toronto population consists of youth aged 5-19.
- Toronto's unemployment rate is nearly 9%, with 23% of the population classified as low-income (2014 Q4 data).

Canada-wide statistics suggest the extent to which people with accessibility needs could benefit from improved mobility solutions (Statistics Canada 2015).

- Age 15+ with disability that limits daily activities: 14% of the Canadian population
    - Age 65-75: 26.3%
    - Age 75+: 42.5%
    - Top disabilities among 65+: pain-related, flexibility, mobility (see table 5)

	percent
Pain-related	9.7
Flexibility	7.6
Mobility	7.2
Mental health-related	3.9
Dexterity	3.5
Hearing	3.2
Seeing	2.7
Learning	2.3
Memory	2.3
Developmental	0.6
Unknown	0.3

Table 5: prevalence of disabilities among all Canadians

- Of all Canadians with disabilities: Severe = 23%, Very Severe = 26.6%[13]
- Getting to appointments/running errands: needs help but does not receive it **or** does not receive enough help:
    - People with severe disabilities: 21.3%
    - People with very severe disabilities: 33.8%
- Using public transit: some difficulty or a lot of difficulty[14]
    - People with severe disabilities: 32%

[13] For details on severity scoring in this survey, see (Statistics Canada, 2014).
[14] Toronto has a variety of affordances and services to support people with accessibility needs. However we suggest this number be taken at face value, since it reflects the challenges that result from various levels of needs.

    - People with very severe disabilities: 48.3%
- Median total income of people with disabilities is about two-thirds the $31,160 per year for those without disabilities. For people with severe or very severe disabilities, it is about half.

To illustrate the inclusion opportunities with one example: the rise of AVs coincides with the growth of Toronto's aging population. Based on our analysis of the above data, we project that in 2031 Toronto will have 75,000 senior residents with severe or very severe disabilities who experience challenges in using public transit.

Toronto already has policies and programs to improve accessibility to mobility for underserved groups. AVs present an opportunity to broaden, customize and expand such initiatives to car and minibus travel; indeed, some argue that the exclusion of cars from "design for all" has always been arbitrary and unfair (Bradshaw-Martin and Easton 2014).

Scenario relevance: Demographic segments with access needs will be among the core users of on-demand mobility services that use automated taxis and minibuses. In Ownership Leads they may be a dominant market for these services, while in the other scenarios the "access" market will be one among many.

5.3 Environment

Road vehicles have singularly been named "the greatest contributor to atmospheric warming now and in the near term" (National Aeronautics and Space Administration 2010). The Toronto Medical Officer of Health reports that road traffic air emissions contribute "about 280 premature deaths and 1,090 hospitalizations each year, or about 20% of all premature deaths and 30% of all hospitalizations due to air pollution [from all sources, whether inside or outside Toronto]." Stated differently, more than six times as many Torontonians die prematurely from vehicle air pollution than from traffic accidents. (Annual traffic deaths, as discussed, averaged 44.2 in the years 2010-2013).

Automation is central to the transition to electric vehicle power and other alternative fuels such as hydrogen. Though batteries are much more efficient than petroleum, they are heavy and expensive (NRC 2013a). The battery in the Nissan Leaf, an all-electric conventional car, weighs 600 pounds and takes four to seven hours to recharge (DOE/EPA 2013).

Thanks to the intrinsic safety of AVs, they will shed considerable weight associated with safety features. Their batteries will be small, light, and quick charging, mitigating the main drawback associated with electric vehicles. (Anderson, Kalra, & Stanley, 2014; Hawkins, Gausen, and Strømman, 2012; Michalek et al., 2011; Samaras and Meisterling, 2008).

Vehicle charging itself will be automated. After dropping off a passenger, an electric AV can proceed to the closest available charging station (Shiau et al., 2009). For further convenience, the U.S. Department of Energy and others are developing wireless inductive charging technologies (NRC, 2013b).

Irrespective of fuel source or vehicle design, AVs will be more energy efficient than conventional vehicles. This will be especially true as AVs move into wider use. Platoons of AVs (particularly on dedicated roadways) will move at continuous speeds with little or no stop and go. AVs will have short following distances, reducing fuel consumption by traveling in the slipstream of those ahead; this applies particularly to freight trucks (Folsom 2012). Even in city traffic, AVs will obtain fuel efficiencies from optimal trip routing, smoother acceleration and braking, and parking efficiencies. Even gas-powered AVs will be smaller and lighter than conventional vehicles and will therefore consume less fuel (Morgan Stanley 2013).

A simulation based on a mid-sized US city modeled savings for ATs that are identical to current mid-size sedans in every respect (including size), but drive autonomously (D. J. Fagnant 2014). This scenario projected 12% less total energy use and 19% lower sulphur dioxide emissions from more efficient road performance and the reduction of cold and warm starts.

The US Lawrence Berkeley National Laboratory conducted another simulation, in this case of an electrically powered AV fleet. It found decreased greenhouse gas emissions of 87-94% compared with a 2015 conventional vehicle, and 63-82% compared with a 2030 projected hybrid vehicle (Greenblatt and Saxena 2015).

Scenario relevance: Our hypothesis is that privately owned AVs be somewhat heavier, larger, and therefore consume more energy than ATs, AMs, and other on-demand vehicles. They may also be less likely to convert to from gasoline to electric or alternative fuels. On-demand scenario leads, therefore, in environmental benefit.

5.4 Operating costs

According to Statistics Canada, Canadian household spending on transportation was $11,216 in 2012. This was 20% of all spending and second only to shelter (Gill, et al. 2015). AVs will enable Toronto residents and organizations to cut transportation-related costs, including those from ownership and operation, parking, and insurance. They will also make better use of travel time.

5.4.1 Ownership and Fuel Costs

Will AV features be cost-prohibitive? Today's AV toolkit for a single car certainly is, though it's certainly cheaper than dated reports of up to $70,000. The most critical high-cost component is the lidar, a specialized remote sensor. Lidars have dropped in price by a factor of 10 since their 2007 introduction. This is consistent with cost-performance trends of information technologies, even though demand for the device has been modest to date. The current price of $8,000 for a small-scale lidar "puck" will drop even more as AVs proliferate (Berman, 2015).

We presume that AV technologies will follow the price-performance curve of other information technologies. Though they will be a significant component of future vehicle ownership costs, the total cost of AV ownership (and particularly AV-based mobility services) will be much less than today.

Fewer than 17% of household vehicles in the US are in use at any specific time in a typical day. (D. J. Fagnant 2014, Bhat 2014). Various sources estimate that a typical car is used less than an hour per day. This is at the heart of the case for automated taxis and minibuses that, summoned by mobile phone apps, drive themselves to customers and remain in continuous use. In support of this hypothesis, a large 2008 survey of North American carsharing service users found that 25 had sold their vehicles; another 25% would have considered buying a vehicle if carsharing disappeared (Shaheen and Cohen 2013).

Users who forego ownership in favour of ATs and AMs will enjoy significant cost savings. Most directly, AT users will avoid upfront purchase, financing, and other costs (such as parking) associated with car ownership.

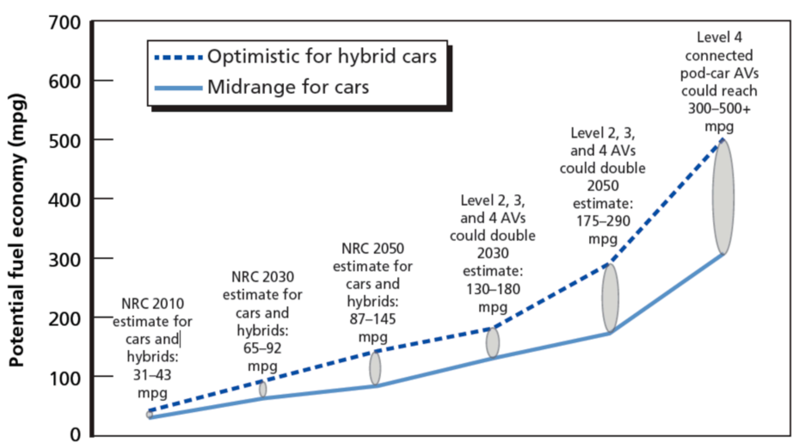

Figure 4 Range of potential fuel economy improvements for conventional, hybrid, and autonomous cars. This graph is based on the US NHTSA 4-Level automation model described in Appendix 1 (Anderson, Kalra and Stanley 2014).

AVs will also be cheaper to use. An analysis cited in a RAND Corporation paper suggests that a networked single-user AT could enable fuel economies of up to 0.25 liters per 100km (Folsom 2012; Anderson, Kalra and Stanley 2014). A RAND graphic (Figure 4) illustrates how even AVs built like today's cars could significantly outperform the fuel efficiency of traditional driver-centric vehicles. The analysis begins with current gasoline and gas/hybrid fuel technologies and moves through alternative fuels like electric and hydrogen.

5.4.2 Parking

Parking will be a big source of cost savings. For those who shift from car ownership to mobility on demand, mass transit and active transportation, parking will become a thing of the past. Meanwhile, private owners will have their AVs self-park in low-cost sites. ATs and AMs will also use low-cost sites during their off-hours. These factors will combine to place downward pressure on the price of parking.

A simulation for the International Transport Forum, an OECD agency, tested several scenarios for AV use. It found that in all cases, self-driving fleets eliminated the need for all on-street parking and up to 80% of off street parking (International Transport Forum 2015).

Reduced street parking will present unprecedented opportunities to turn parking lanes into complete streets features for active transportation, public transportation, public realm, freight, and a variety of social, creative, and economic applications.

Surplus stand-alone parking lots and structures will be redeveloped or turned into public realm. Underground lots will present challenges; some may be repurposed for storage, but others will require creativity. AV mobility services may reduce the value of condominium parking spaces, currently priced at $40-60,000 (Harvey 2013).

Private parking lots will face challenges to their business models. The Toronto Parking Authority (TPA) operates about 17,500 street parking spaces. It also runs 186 off-street parking lots and garages with 37,500 spaces. In 2013 the TPA generated net income of $65 million on gross revenues of $130 million, of which $45 million was conveyed to the City. In addition it paid $18 million to the City in property taxes (Toronto Parking Authority 2014). The City will face decisions about what to do with TPA assets, as well as whether and how to sustain this revenue stream. By the same token the City will likely lose growing portions of parking ticket and traffic citation revenues. In 2014 parking ticket revenue was $105 million.

No statistics are available on the total usage costs of commercial and privately owned parking. We arbitrarily set it at a (very) conservative 2x the $130 gross revenues of the Toronto TPA, i.e., $360 million. Combining these two numbers with the $100 million generated from parking tickets yields annual cash flow parking costs to the City economy of $500 million.

Scenario relevance: Parking demand declines in all scenarios. But the differences are significant. Ownership Leads means about a 10% reduction in the number of vehicles that require private or public parking spaces. Split Outcome cuts demand for parking by 40%, and On-demand Leads by 75%.

5.4.3 Insurance

Other cost savings will come from auto insurance. Accident insurance claims for cars have already declined by 7-15% with advanced Level 1 AV features like automatic braking (KPMG 2015). When AVs are pervasive, accident rates are expected to drop by 80% or more, dramatically reducing insurance costs. Some or all liability for accidents may shift to manufacturers. Automation will make vehicles trackable and capable of being disabled remotely, cutting the insurance cost of auto theft. New risks will be associated with AV cyber-security, but they too may be the responsibility of manufacturers (Yeomans n.d.).

For those who entirely forego auto ownership in favour of mobility on-demand, insurance costs will be embedded in service provider fees. Providers will minimize insurance costs via competitive procurement and/or self-insurance.

According to Kanetix.ca, an online insurance broker, average car insurance premiums in Toronto are $2000 per year (canadianunderwriter.ca 2015). As mentioned, the University of Toronto estimated a count of 1.1 million non-commercial light vehicles resident in the City in 2011. This yields annual Toronto consumer auto insurance costs of $2.2 billion. Industry researcher Celent suggests that consumer premiums could drop by 60% by 2030 due to AVs (Buhayar and Robison 2015); this works out to about $1.3 billion in current dollar savings for Toronto residents. Similarly, the cost of insurance for automated commercial vehicles will drop.

Scenario relevance: Insurance costs are likely to decline sharply for all drivers. It is unclear how liability will work for private owners of AVs. However their costs will likely be higher than the fully amortized insurance costs of on-demand vehicles. Therefore the overall social cost of insurance will be higher for Ownership Leads and Split Outcome.

5.5 Congestion

Congestion is notoriously expensive. The Toronto Region Board of Trade (TRBT) pegged the 2011 cost of congestion at $6 billion per year, rising to $15 billion by 2031 in the absence of remedial actions (Toronto Region Board of Trade 2011). The C.D. Howe Institute argues that congestion additionally constrains urban interactions like job matching, in-person meetings, and business, entertainment and cultural activities. These factors add $1.5 to $5 billion to the TRBT estimate of $6 billion per year (Dachis 2013).

The causes of congestion include physical capacity bottlenecks (40%); traffic incidents (25%); weather (15%); road construction (10%); poor signal timing (5%); and special events/other (5%) (Federal Highway Administration 2004). These factors combine to make travel times unreliable. Unreliability causes people to set out early, further increasing travel duration and the number of vehicles on the road. All these congestion factors can be mitigated – in most cases substantially – by vehicle automation in combination with intelligent transportation systems (ITS) infrastructure.

- **Capacity bottlenecks** – Smaller, more maneuverable vehicles will directly increase capacity per linear roadway meter. It may eventually be feasible to further increase capacity by narrowing highway lanes. Vehicle to vehicle and infrastructure communications will improve throughput. Shortened headroom requirements, platooning, automatic braking, and other changes will reduce bottlenecks and braking-induced shockwave propagation.[15]
- **Traffic incidents** –Half or more of incidents are vehicle accidents, the majority of which will be eliminated with the adoption of AVs (see Section 5.1).
- **Poor signal timing** – This will be greatly offset by better-designed signals that align with V2I communication, along with shorter headways and startup times (D. J. Fagnant 2014). At a more advanced level, V2V and V2I communications may facilitate intersection protocols that manage traffic based on real time vehicle flows.
- **Weather, road construction and special events** – V2V and V2I communication will enable these impacts to be reduced through advance rerouting, as well as better traffic coordination in the presence of these issues.
- **Travel time reliability** – Transportation applications will provide consumers with highly reliable travel time projections.

A simulation study on travel demand management based on the city of Lisbon tested several scenarios including one or more of pod ATs, AMs, and high-capacity public transit. The simulations assumed no presence of vehicles other than those being modeled (International Transport Forum 2015). The study found that nearly the same level of mobility can be achieved with only 10% of the current number of vehicles when AMs are combined with high capacity transit, and 20% of the current vehicle numbers without high capacity transit[16].

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[15] One simulation projects that "cooperative adaptive cruise control (CACC) [that uses vehicle-to-vehicle communication] deployed at 10 percent, 50 percent, and 90 percent market-penetration levels will increase lanes' effective capacities by around 1 percent, 21 percent and 80 percent, respectively ((Shladover, Dongyan Su and Xiao-Yun Lu 2012) cited in (D. J. Fagnant 2014)).

[16] Other important findings from the simulation include that 1) more ATs were needed than AMs; 2) because of the need to reposition vehicles for their next pickups, VKT was higher than traditional usage models, especially during peak periods; 3) high capacity public transit significantly reduced the number of AVs needed; and 4) transition scenarios wherein half the vehicles are traditional cars showed significance increases in VKT, with the exception behind the use of AMs with high capacity public transit during peak hours.

Though automation will mitigate the causes of congestion, AV mobility services are likely to stimulate additional demand for car travel – pushing congestion back up at the expense of other transportation modes. Five factors are likely to increase demand.

- **Growth of new segments** – Governments and parents may allow children and youth to use AVs on their own. Members of the aging population will see AVs as an alternative to car ownership and transit. Governments may mandate that some AVs be customized to meet the needs of those with severe or very severe disabilities who currently have difficulties with public transit. As costs decline, AVs may prove to be a competitive travel option for low-income residents. According to 2011 census data these four demographic groups combined represent nearly 40% of the city's 2,615,060 population. Additional traffic will come from the broader GTHA. Discounting for overlaps and a conservative adoption rate, we suggest that a projection of 250,000 daily additional AT/AM users is realistic. They could, with the support of policy and pricing, be relatively high users of AMs. We project that this additional use could translate into an additional 120,000 ATs and 30,000 AMs on Toronto streets by the 2030s, for a total 150,000 vehicles.

Youth aged 5-17	400,000
Adults 75+	250,000
Severe disabilities + transit difficulties	150,000
Receiving social assistance	235,000
	1,035,000

Table 6 Toronto candidate segments for AV use. Analysis based on 2011 Census data.

- **Convenience**. Individuals outside the above demographics, particularly current active transportation users, may choose AVs for convenience.
- **Cost**. AVs may be sufficiently price competitive to attract users who have similarly convenient but more costly options.
- **Time use/privacy.** Users may choose AVs to increase privacy – whether for productivity, confidentiality (including, for example, business calls), or peace and quiet.
- **More commuting.** Peter Norton suggests that the capacity of AVs to make travel safer and faster "might turn the 50-mile commute of today into the 100-mile commute of tomorrow. Today, people trying to travel by other modes—such as walking or bicycling—must contend with urban sprawl governed [by] drivers' perceptions of distance. How will they reckon with distances that have doubled again? Presumably many of them too will resort to driving". (Norton 2014)

To summarize, automated mobility services may reduce the total number of vehicles in Toronto, but they will not necessarily reduce the number of vehicles on the City's roads. Despite this, we believe that the road efficiencies of vehicle automation will result in a significant net positive impact on congestion in Toronto.

Independent of the potential growth in demand, the driverless nature of AVs means they will extend the workday and/or reduce onsite work time for GTHA commuters. For some, this will mean a shorter overall commute/work day. According to the 2011 Canadian census, more than a quarter of the 1.8 million Toronto CMA commuters spend over 45 minutes travelling to work, with a median time of 33 minutes. Of these commuters, 1.8 million travel by car, truck, or van

(Statistics Canada 2014b; Gallant 2013). Based on median 2013 annual income in the Toronto CMA of $72,830 and 238 working days per year, we estimate the annual value of commuting time per worker as $10,000. Multiplying this by 1.8 million commuters yields a total value of commute time of $18 billion.

We believe it is reasonable to attribute AV-related realizable commuting cost benefit, facilitated by integrated travel demand management policies – in the order of 15% or $2.7 billion for the GTHA.

Scenario relevance: In principle, automation combined with V2V and V2I communication, platooning, and the like, should dramatically improve on congestion regardless of scenario. On the other hand, On-Demand Leads may facilitate the highest road efficiency.

5.6 City Fleet Services

The City of Toronto directly or indirectly manages five significant fleets for the delivery of public services (Brierley 2015):

- Transit (TTC)
- Police
- Fire
- Emergency management
- Fleet Services Division including but not limited to:
  - Refuse collection
  - Street cleaning
  - Parking enforcement
  - Water
  - Unlicensed vehicles such as loaders, bulldozers

As a major owner operator of vehicles, the City of Toronto has a direct interest in leveraging the benefits of automation.

Scenario relevance: On-demand vehicle service models are likely to increase for some City fleets.

6 AV impacts and implementation considerations

6.1 Leadership

With the rise of ADAS and the US government's pending mandate of V2V communication, the transition to AVs has already begun. These technologies will provide early benefits of automation including improved safety, traffic flow, environmental impacts, and driver costs.

On balance, for Toronto – and all major cities – the benefits of AVs will outweigh the risks and costs. Many countries and cities now conduct active, highly visible AV research, development, and trials. Their governments provide substantial financial investments, institutional support, and policy development. Their national conversations about the future role and impact of AVs are increasingly informed by experience. The list includes Australia, Belgium, China, France, Germany, Japan, the Netherlands, Singapore, South Korea, Spain, Sweden, the UK, and the United States.

Neither Canada nor Toronto is on this list. The City of Toronto faces decisions about whether and how to embrace the AV future. It may wish to seek national and international leadership on policy and action – to both achieve the benefits of AVs and address the challenges.

Scenario relevance: Proactive measures will be required to ensure that scenario outcomes align with the City's core policy objectives.

6.2 Transportation planning and urban design

Table 7 summarizes the potential areas of impact of AVs on the City's transportation objectives in areas of planning, urban design, and travel demand management. Please refer to the pertinent sections of this report for details on these topics. Table 8 lists primary benefits and associated challenges that will result from AV deployment.

Objective	Impact***	Items to address
Foster complete streets	+	Freed-up parking spaces
Increase car occupancy rate	+	Mode mix
Increase multimodal travel	+	Increased access & convenience
Reduce rush-hour congestion	+	Intelligent transportation system
Seamless multimode transportation GTA & beyond	+	Complexity, new market entrants
Strengthen downtown & other hubs	+	AV incentives to sprawl
Environmental sustainability	+	Transition to alternative fuels
Equitable funding & pricing	+	Business models & policies
Improve freight/goods movement roads & curbside	+	Allocation of freed-up parking
Increase road safety for everyone	+	Infrastructure, regulation
Social equity & inclusion	+	Pricing, vehicle tailoring
Foster complete communities	=	New urban design options
Increase fewer & shorter trips	-	Low "time cost" of AV use
Reduce car dependency	-	AV accessibility & convenience
Increase transit use	?	Mode mix & cost
Increase walking & cycling	?	Urban plan/mode mix
Reduce vehicle travel demand	?	Pricing, private vs. public
Shift travel from peak to off-peak periods	?	

Table 7 Impact of AVs on City of Toronto transportation policy objectives. List of objectives based on Official Plan & OPA 274. Highlighted items from City Transportation Demand Management (TDM) framework.

***** Potential net citywide impact of AVs:**

+ Positive

= Neutral

- Negative

Key elements of the City's transportation demand management framework are highlighted. Specific policies and actions will be necessary to ensure that *any* objective is achieved in the era of AVs. Where an item has a question mark we believe the outcome will mainly depend on policy-based actions.

Benefits	Challenges
Safety	Transition period: AVs & non-AVs sharing roads
Social equity & inclusion	Vehicle usage and VKT growth
Reduced emissions & GHG consumption	Electric vehicle infrastructure; increased VKT
Road efficiency/reduced congestion	Increased VKT
Rightsized vehicles	Governance, public vs. private business models
Cost savings across City economy	Job losses
Business opportunities, productivity growth	Sector disruptions
Enhanced urban design & available space	Risk of increased sprawl

Table 8 Potential benefits and challenges to Toronto's urban planning priorities from automated vehicles

6.3 Intelligent Transportation Systems

While AVs are individual vehicles, the intelligent transportation system (ITS) is the application of information and communication technologies to components across the transportation system. An ITS joins up a set of applications that enable users to "be better informed and make safer, more coordinated and 'smarter' use of transport networks" (European Parliament and Council 2010).

ITS has yet to achieve its promise. Nevertheless it highlights an important point about what is achievable with networked coordination. The two approaches – AV and ITS – start from different places. To some extent they can be implemented separately. Toronto might be well served (as the US example below illustrates) to identify some ITS-inspired applications for short-medium term implementation, as part of its plans to update and upgrade current transportation infrastructure. Such actions can prepare the ground for AVs while obtaining real benefits in the near future. In any such project it would be advisable to align with international standards that are likely to be forward compatible with AVs.

Questions exist regarding the business case for ITS:

1. Will AVs require big investments in intelligent infrastructure in order to function to a sufficient base level of safety, efficiency, and other criteria? Or will AVs function effectively without such investements?
2. What City investments in ITS infrastructure and applications would provide cost-justifiable improvements in base level safety, efficiency, or other objectives?
3. When and how should the City plan for and implement such investments?

It is reasonable to imagine that a multivendor AV fleet, when equipped with industry standard V2V communications and the requisite software, will readily self-manage for safety and efficiency without the need for an ITS. After all, relatively simple commodity applications like Waze are remarkably effective today at helping drivers avoid congestion.

In an obvious limiting case – a busy intersection – AVs, properly equipped, could conceivably be trusted to stop and go efficiently to the benefit of one another, as well as other sidewalk and road users. Even conventional vehicles equipped with V2V and the requisite software could participate in such self-regulating systems. Research at the University of Texas provides a case for the basic feasibility of such a system (Dresner and Stone 2008; S. Z. Tsz-Chiu Au 2012). The report calls for an external intersection manager to issue reservations that permit vehicles to proceed. But a set of communicating vehicle applications, analogous to what drivers do at a 4-way stop, could perform this task without the need for an external manager.

This line of pure V2V thinking may be too optimistic. We believe that judicious ITS investments are worthy of consideration. V2I is slowly but steadily moving in the US, Europe and elsewhere. V2V is preceded in many vehicles (e.g., General Motors OnStar) with networked communications to the car manufacturer. Once "connected", a vehicle can communicate with a variety of entities, not just urban infrastructure. For example, as a safety measure, pedestrians and cyclists may one day passively announce their presence to connected vehicles via mobile apps or wearable technology.

Even if V2V is technically sufficient for traffic self-management, cities may conclude that they need their own infrastructure communications for verification and enforcement. As costs drop and applications evolve, the case for V2I investment may prove to be compelling.

Torontonians have already experienced simple ITS applications like HOV lane enforcement and red light cameras. The US and other countries, seeing potential benefits, are starting to implement more advanced ITS applications.

The US National Highway Traffic Safety Administration (NHTSA), a division of the Department of Transportation (DOT) with a strong ITS research portfolio, now plans to move to implementation (US Department of Transportation 2014). The NHTSA main focus is on vehicle to vehicle, with some work on vehicle to infrastructure.

The NHTSA has announced its intent to propose a rule by the end of 2015 that will mandate eventual availability of V2V in all new vehicles (National Highway Traffic Safety Administration 2015). The agency is also working with industry and other stakeholders to develop a number of standards, including a connected vehicle reference implementation architecture (Intelligent Transportation Systems Joint Program Office 2015).

In the interim the DOT is investing in V2V/V2I demonstration projects. In September 2015 the department announced $42 million in grants to New York City, Tampa and Wyoming, the outcome of a competitive bidding process. New York City will instal V2V in 10,000 city-owned cars, buses and limousines, as well as V2I on traffic signals on two major roads in Manhattan and throughout Brooklyn. Tampa will also instal V2V with the aim of reducing rush hour congestion. It will also equip pedestrians with a V2P safety-oriented app. Wyoming will use V2V and V2I to improve freight safety and efficiency on a major highway corridor.

Scenario relevance: Scenarios with high private AV ownership (i.e., Ownership Leads and Split Outcome) are likely to have greater variety of vehicles, manufacturers, services, and so on. This will produce greater complexity in technology management of V2V, V2I, and associated protocols.

6.4 Public transit

AVs will improve on today's public transit in several ways:

- A fine-grained spectrum of rightsized on-demand options will include 1-2 person "pod" ATs, larger AMs and buses, and various specialized AVs whether for families with small children, bike users, cargo, or the mobility-impaired.
- Automation and platooning may make bus rapid transit (BRT), operating on busways and high occupancy lanes, competitive with rail. Buses can potentially enter and exit the BRT to serve urban centers and other locations.
- Automation and reduced street parking will improve flow and curbside options for passenger service.
- Driverless operation, safety, congestion management, vehicle intelligence, and rightsizing are likely to increase demand and reduce operating costs.

AT and AM services will challenge bus and mass transit. The International Transport Forum (ITF), a branch of the OECD, has conducted the most pertinent study on this topic. The researchers performed several simulations based on actual traffic patterns at peak and non-peak times in Lisbon, Portugal (International Transport Forum 2015).[17] The simulations focused on universal use of AMs and ATs in combination with high capacity public transport, but no bus service. Top-level findings include the following:

- An AM system combined with high capacity transit used 65% fewer vehicles during peak hours, while increasing VKT (due to the elimination of buses and vehicle repositioning) by 9%. Over all time periods – peak and non-peak – VKT increased 6%.
- An AT system without public transit removed 23% of vehicles during peak hours, with an unmanageable 103% VKT increase. Over all time periods in the simulation, the AT system without public transit increased VKT by 89%.
- In all simulation cases, self-driving fleets removed the need for street parking. This freed up 20% of curb-to-curb street space and an additional 80% of off-street parking.
- High-speed public transit makes a big difference. In its absence, 18% more AMs (5,000 minibuses) and 26% more ATs (12,000 cars) were needed. VKT increased by 13% and 24% respectively.

The researchers also simulated transitional cases where 50% of travel uses AMs and ATs and 50% uses traditional cars. In most scenarios total VKT increased by 30-90%, suggesting a difficult transition. The one exception was use of AMs in the presence of high capacity public transit.

Two striking results arise when AMs combine with mass transit. First, buses become less than necessary. Second, street parking disappears and off-street parking declines dramatically.

The ITF study does not appear to address the projected significant growth in user numbers (youth, seniors, mobility-impaired, and low-income) that we have discussed in Sections 5.2 and 5.5. We hypothesize that the best-case scenarios in the ITF simulations, in conjunction with the benefits listed in Section 5.5, would easily absorb such demand growth. However, as an unknown this points to a need for additional research as well as consequent policy choices.

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[17] The Lisbon Metropolitan Area (3000 km^2) has a population of 2.8 million, of which 565,000 reside in the city proper. The simulations focused on 1.2 million daily trips within the Lisbon administrative boundary.

Furthermore, while this report focuses on AVs, it is noteworthy that precursors to AMs are already changing the transit equation in a number of cities. In addition to Uberpool in San Francisco, Bridj offers pooled minibus services in Boston and Washington, DC (Bridj 2015). Toronto experienced a taste of this with commercial and consumer-based carpooling on HOV lanes during the PanAm Games.

Scenario relevance: Even in the least transformative scenario – Ownership Leads – AVs and mobility services will change many assumptions about transit mix, plans, governance, ownership, and investments. Split Outcome and On-Demand Leads will make an even greater impact.

6.5 Freight

Long distance freight may be among the first beneficiaries of AV technologies (Bertoncello and Wee 2015; Morgan Stanley 2013). Three million heavy-duty trucks deliver 70%, or 9.2 billion tons, of US freight per year (Davies 2015)

Daimler, for one, is now testing freight vehicles capable of operating autonomously on highways under certain conditions in the United States and Germany.

Automated freight trucks are likely to be platooned: spaced, for example, about 4m apart. In one model, a human driver operates the lead vehicle much like a train engineer. Platoons will reduce fuel consumption while increasing speed and road capacity. They may eventually require thicker pavements and other types of new infrastructure (D. J. Fagnant 2014).

Freight AVs can increase road time by 43%, from 14 hours per day (the current daily limit for a human driver in the United States) to 20, with the remaining time being used to load, unload and refuel (Gill, et al. 2015). Current UK tests of under-road electric power sources focus on freight and commercial trucks (Highways England and Jones, M.P. 2015; Highways England 2015).[18]

The City has a particular interest in delivery and courier vehicles with respect to their economic, traffic, and curbside impacts. As street parking becomes freed up, there will be new decisions to be made about access for freight and deliveries. Automation may reduce employment in this sector while increasing the breadth, variety and volume of commercial delivery services.

Scenario relevance: On demand mobility services are likely to significantly change business models and services associated with urban freight.

6.6 Winter conditions

Winter conditions present unique challenges for an AV, well described in the *Toronto Star* (Deschamps 2015):

- Snow can bury sensing devices and render them useless.
- Vehicle systems can interpret a squall as an obstacle and stop driving or try to route around it.
- The infinite variety of snowy streetscapes can confuse vehicle navigation systems.

[18] In addition, a US industry association is promoting an as yet undeveloped proposal for an automated freight corridor from the Manitoba border to Mexico along Highway 83 (Central North American Trade Corridor Association, 2015)

- Sensors, like many human drivers, may not identify or see black ice. Snow may absorb sensor rays rather than reflect them back.

AV trials in California have encountered fog and rain, but not snow. Google developers have said they will run snow trials and Volvo is testing AVs in snowy Sweden. But some researchers believe it will take decades to solve this problem.

Scenario relevance: Minor.

6.7 Data policies

Data generated for and by AVs will be the most valuable asset in tomorrow's intelligent transportation system.

- Detailed maps to 1 cm resolution or better along with real-time situational data will enable every AV to function; vehicles may capture and forward situational changes to the network.
- Vehicles communications with external networks will provide efficient destination routing in the context of current traffic and road conditions.
- V2V communication will include presence, flow, intentions, and behavioral protocols.

Vehicle communication is an emerging domain for the data gathering that has become commonplace in Toronto and the lives of its citizens: mobility data collection, which includes vehicle, foot and cyclist activity, already occurs on a large scale via smartphones.

Two facts are at the heart of the policy issues related to mobility data (OECD International Transport Forum Corporate Partnership Board 2014):

- We are at the beginning of a dramatic expansion in the breadth, volume, and velocity of mobility data collection. This is generating troves of so-called "Big Data".
- Today, governments are the primary sources of the transportation-related data that they need. However as vehicle automation expands, private sector actors will potentially generate and hold the largest, most current, and most complete repositories of mobility data.

These changes raise policy questions related to access, security, privacy and economic policy:

- How will the City obtain access to private sector mobility data for transportation planning and management?
- What should the City do, along with other levels of government and the private sector, to ensure the security of digital mobility data?
- What role should the City play, along with residents, other levels of government and the private sector, in defining and enacting policies to protect the privacy of AV passengers?

The City knows it has an interest in transportation data. Planning for transportation, transit, and broader issues of urban design depend on it, as do everyday functions like operations, safety, congestion, and incident management.

Other levels of government may be responsible for AV data security and privacy policies, rules, and regulation. However as connected and automated vehicles evolve, the City will face such issues every day. For example:

- The City may look to providers for anonymized traffic data, but ensuring anonymity may not be straightforward.
- Pedestrians may object to street surveillance for navigational purposes by private sector AV providers.
- The City will face new issues related to balancing law enforcement with data privacy.

6.7.1 City access to data

An AV is essentially a type of robot – a machine that can sense its environment, assess and plan what to do, act on that plan, and communicate with people and other devices. In every AV, each of these activities requires innovative hardware technologies, massive data resources, advanced software algorithms, and blazing processing speeds.

Sensing alone entails a wide array of views via several kinds of devices. In addition, an AV may exchange digital communications with traffic management infrastructures (V2I), other vehicles (V2V), pedestrians (V2P), and so on. Google's 2013 self-driving car prototype reportedly captured 750 megabytes of sensor data per second (Gross 2013).

At least three AV projects (Google Auto, HERE, Uber) plan to assemble digitizations of urban landscapes to a 1 cm (or better) level of precision (Madrigal 2014; Daimler AG 2015). Google has indicated that it plans to do this for every street where its cars might operate.

Neither Google nor Uber has taken a public position on sharing AV maps with cities or other external stakeholders. On the other hand when BMW, Daimler-Benz and Volkswagen invested in the mapping service called HERE, they promised "to secure the long term availability of HERE's products and services as an open, independent and value creating platform for cloud-based maps and other mobility services accessible to all customers from the automotive industry and other sectors" (Daimler AG 2015).

Municipalities and other levels of government have a substantial interest in AV data assets. Such data can improve traffic operations and management, discrete traffic studies, safety, travel demand management, traveler information services, asset management, and other critical activities (Hong, Wallace and Krueger 2014). It can also inform variable congestion pricing, taxes based on VKT, automated parking payments, dynamic power pricing, and as yet unpredictable innovations (Fagnant and Kockelman 2013; Folsom 2012).

6.7.2 Data ownership, privacy, and security

The basis for a large and lucrative marketplace for transportation data is taking shape. Some key facts about major players and their activities:

- Google, a global leader in capturing and commercially harnessing digital consumer data, is at the forefront of AV research and development.
- AlixPartners, a consulting firm, estimates that connected cars will generate global data-related revenues of $40 billion USD per year by 2018, up from $16 billion in 2013 (Love and Lienert 2015).

- General Motors alone expects to generate $350 million USD in revenue over three years beginning in 2015 from data connections in its cars (ibid.). Most of this revenue draws on pre-AV activity such as in-car Wi-Fi, GM's OnStar service, and third party consumer applications (Fitchard 2015).

The privacy, security, and economic implications of personal data collected through use of AVs have become topics of discussion and debate.

- Regarding privacy, data troves will include passenger identities, personal profiles, origins and destinations, travel dynamics, media use, and so on. Companies, governments, and third parties will have the ability to appropriate ownership of such data and use it to infringe on privacy, safety, economic interests, or other rights – including potential resale or licensing of the data itself.
- Regarding security, the OECD points out that connected mobility services pose "increased cybersecurity risks, especially when network-based systems interact directly or indirectly with primary control systems of vehicles" (OECD International Transport Forum Corporate Partnership Board 2014). Automotive technologies provide "back door" surveillance and tampering opportunities for AV technology firms, car manufacturers, pranksters, government agencies, and cyberwarriors (Geles, Tabuchi and Dolan 2015).

Governments, international organizations and researchers are currently seeking policy strategies that balance innovation and social benefits with privacy, security, and sustainable open markets. For example, the UK Department for Transport code of practice for testing driverless cars, released in 2015, specifies expected actions and practices by AV firms related to data collection, data protection, cybersecurity and software management (UK Department for Transport 2015). Several international organizations, companies, and governments have adopted the Privacy by Design template to address some of these issues (Cavoukian, Privacy by Design: The 7 Foundational Principles 2011).

6.7.3 Software safety and transparency

Vehicle automation is much more difficult than commercial aircraft automation, with low tolerance for error in sensing, reaction time, or cost. The complexity of AV software can result in safety risks due to design mistakes, specification errors or code bugs (Ross 2014).

Not long ago a mechanically inclined person could understand, fix, and modify any part of a car. Consumers, independent researchers and government agencies could reach their own conclusions about, and exercise technical control, over key aspects of vehicle safety, design and performance. This cannot occur if, as is already the case, vehicles rely on proprietary, inaccessible software. As a result, a number of researchers and activists have made a case for vehicle software transparency. Vehicle software, they say, should be open to public scrutiny and verification (Wagner and Koopman 2015; Geles, Tabuchi and Dolan 2015).

The US government protects the nondisclosure of vehicle software under its Digital Millennium Copyright Act. In December 2104, proponents asked the Copyright Office to exempt vehicle code from nondisclosure to let researchers investigate potential security vulnerabilities (Davies 2015). The Alliance of Automobile Manufactures opposes the proposal and the Environmental Protection Agency has also expressed some opposition. The Copyright Office has not yet ruled on this matter.

Concealed vehicle emissions, after the fact safety recalls, and undisclosed surveillance are all too real. They are detrimental to the health and wellbeing of Torontonians and impose costs on the City economy.

The City must embrace innovation and facilitate the use and sharing of mobility data to advance the interests of citizens and the private and public sectors. At the same time today's policies and legislative frameworks should be reviewed in light of the new kinds of risks associated with emerging technologies.

Scenario relevance: It is likely that AV vendors, technology firms, and on-demand service providers will have varying policies and practices related to the use, ownership, and sharing of data and technology information. In general, they will prefer to control information of all sorts. To the extent that the City licenses on-demand services (e.g., On-Demand Leads and Split Outcome), it may have greater ability to require strong privacy, ownership, and transparency practices.

6.8 Regulation

Most AV-related regulation in Canada is the jurisdiction of senior-level governments, whether provincial or federal. The City of Toronto has an interest in regulations that enable it to legally host AV innovation and adoption with appropriate rule in place.

In October 2015 the Ontario Ministry of Transport published Regulation 306/15 under the Highway Traffic Act. The regulation sets rules for AV pilots in the province (Government of Ontario 2015). It requires a formal application from any company that wishes to test AVs. It also requires that a legal driver be capable of taking control of the vehicle at any time. AV owners must deliver collision reports to the motor vehicle registrar. The regulation is the outcome of an extensive Ministry-led stakeholder consultation (Bailey 2015).

Regulation 306/15 comes into effect on January 1, 2016. The Ministry will begin accepting applications for prospective AV pilots in November 2015.

The basic requirements of AV testing are among several regulatory issues. Examples of possible issues are listed below. The first three are based on examples from OECD research (OECD Corporate Partnership Board 2015).

- A Toronto police officer observes a driver operating a vehicle without touching the steering wheel.
- Service Ontario receives a registration application for a vehicle with automation capabilities that have been added by its owner.
- Service Ontario receives a license application from a person with a disability who cannot legally drive under existing laws but who asserts the right to operate an automated vehicle under accommodations legislation.
- A hacker breaks into the records of an automated taxi company and, accusing the firm of privacy violations, threatens to post customer travel histories online.

Other levels of government control most regulatory rules that pertain to AVs. These address driver licensing, vehicle standards, road safety, vehicle liability and insurance (all provincial); manufactured motor vehicle safety and the in-use safety of commercial vehicles (federal); and new AV-related topics like radio frequency allocation and the privacy, ownership, control, and uses of passenger and vehicle data (federal).

Transport Canada participates in the development of a number of international AV standards (Gill, et al. 2015).[19] The Ontario Ministry of Transportation plans to consider other regulatory issues once it has gained experience with intended AV pilots (Bailey 2015). Otherwise to our knowledge no AV-related regulation has been proposed or adopted by any government in Canada.

Additional topics for regulatory consideration of AVs under test include the following:

- AV safety requirements
- Insurance
- Coordination with authorities
- Test drivers: roles, licensing, training, etc.
- Vehicles: technology maturity/verification
- Data recording, data protection/privacy/ownership
- Cyber security, public transparency/accessibility of software code
- Accident protocols including the nature and accessibility of digital vehicle records
- Vehicle to vehicle/infrastructure communications
- Interactions with communities, pedestrians, other vehicles, etc.

Toronto and other Canadian governments can and do learn from and collaborate with many counterparts around the world. Many jurisdictions have adopted AV legislation or are in the process of doing so. Six US states (California, Florida, Michigan, Nevada, North Dakota and Tennessee) and the District of Columbia have legalized AV use under various conditions. Fifteen other states introduced AV statutes in 2015 (National Conference of State Legislators 2015). The UK, France, the Netherlands, and Finland have promulgated rules for AV testing. In other countries – Sweden, Germany, Spain, Singapore, and Japan – AVs are being actively tested with government support and in the absence of specific regulations (OECD Corporate Partnership Board 2015).

The American Association of Motor Vehicle Administrators has an AV regulation best practices working group for North American state and provincial regulators. Participating Canadian provinces include Ontario, British Columbia, Newfoundland, and Quebec (American Association of Motor Vehicle Administrators 2015).

The 1968 Vienna Convention on Road Traffic is an international treaty designed to facilitate international road traffic, which covers 73 nations including European countries, Mexico, Chile, Brazil, and Russia, though not Canada, the United States, Japan or China. It is being amended to permit vehicles to drive themselves, so long as the automation can "be overridden or switched off by the driver."

Scenario relevance: In general, the range of data policy issues applies to all scenarios, whether Ownership Leads, On-Demand Leads or Split Outcome.

[19] Specifically, UNECE WP.29, ISO TC 22 SC39, and ISO TC 204.

6.9 Fiscal impact

As described, in 2013 the Toronto Parking Authority generated a net income of $65 million on gross revenues of $130 million, $45 million of which it conveyed to the City. In addition the TPA paid $18 million to the City in property taxes, for a total transfer of $63 million (Toronto Parking Authority 2014). Parking ticket revenue in 2014 was $105 million and traffic citations yielded additional amounts; however this revenue is offset by enforcement costs. This yields a combined estimate of net vehicle-based revenues in the range of $100 million per year, or about one percent of the City's overall budget.

Other levels of government collect significantly more vehicle-related revenues, including gasoline tax (federal); HST and general tax revenues from gasoline, automotive products, insurance and other services; and fees for driver and vehicle registrations, inspections and the like.

Electrically powered AVs will severely reduce these revenues. A few North American jurisdictions are beginning to address this problem. In 1919 the state of Oregon was the first to introduce a gasoline tax. Now, anticipating the decline of gasoline consumption due to rising efficiency and alternative fuels, Oregon is the first state to pilot a pay-per-mile vehicle tax. (Turpen 2015). This initiative is sign of changes to come.

The foregoing paragraphs are a small part of the fiscal story.

This report provides many example of how AVs will mean a variety of cost savings, revenue losses and opportunities, and new spending imperatives for the City. The City economy itself will change significantly, and the dislocation will require adjustments of some core fiscal assumptions.

Scenario impact: The distribution ratio of AV ownership across service-based and individually owned vehicles will have varying fiscal impacts that would benefit from modeling, assessment, management and monitoring.

6.10 Economic impact

6.10.1 Cost savings

AVs will significantly improve productivity and operating costs across all sectors of the Toronto and regional economy. Based on the results of the analyses in sections 5.1, 5.4, and 5.5 of this report, we estimate that if AVs were pervasive today, reduced collisions, parking, insurance and congestion costs would add up to $6 billion, or 3% of Toronto's $150 billion GDP. Additional savings will result from reduced hospitalizations, fatalities, and ancillary costs due to lower pollution emissions.

Improved accessibility for mobility-impaired, low-income, youth, and older Torontonians will potentially improve labour force participation and increase consumer activity while reducing the costs of social services. These factors will combine to generate new economic opportunities and improve outcomes across a wide variety of private and public industry sectors.

Collisions	$1.2
Commuting	2.7
Insurance	1.6
Parking fees & fines	0.5
	$6.0

Table 9 Some projected Toronto savings due to AVs (current $B)

As driving tasks become less necessary, Torontonians will use AV travel time as they choose, whether for productive work, infotainment, social activity or, for that matter, to sleep. This may increase demand for AV technologies.

Employers will recognize the "freeing up" of this additional time and put it to productive use, depending on the nature of the job. Those who work out of their cars or travel to several locations over the course of a day (e.g., police, home care providers, tradespeople, professional salespeople) can use travel time for administrative tasks.

6.10.2 Industries and jobs

Sectors that innovate for and facilitate emerging AV capabilities – such as technology firms, infrastructure providers, and AV-enabled business innovators from food services to retail – will thrive if they seize the opportunity. Transportation intensive sectors – such as trucking and manufacturing – will enjoy productivity gains and potential business model innovations.

However sectors that depend on current transportation models – including vehicle manufacturing, taxi services and auto insurance – are at risk. Productivity gains and at-risk sectors combined are likely to threaten the sustainability of jobs in a variety of subsectors – including several that are outside the transportation sector.

AVs will create some new jobs, and the estimated $6 billion in savings from collisions, parking, insurance and congestion will create others. However the net job impact from AV could be negative. This is part of a bigger challenge. North American labour markets have already experienced many waves of automation-related job losses from manufacturing workers to radiologists.

Economists and researchers have produced evidence that automation is on balance reducing jobs, and that this problem will increase in the economies of the future. They describe a hollowing-out of the labour market: a structural decline in skilled manual and mid-skilled knowledge-based jobs (Brynjolfsson and McAfee 2014; Ford 2015). As described here, AVs may contribute to this phenomenon.

AV technologies raise additional policy-related issues for the Toronto economy. Information and ideas – typified by software platforms, big data, and patent strategies – have become the most valuable assets, the key building blocks of the digital economy. Some have argued that new kinds of global information-based monopolies are on the rise, resulting in concentration of profits, consumer costs, and the decline of local entrepreneurship (Reich 2015). The arrival of Uber – a global transportation network company that aims to replace its drivers with AVs – exemplifies these issues. With the prospect that global monopolies may leverage technology to displace Toronto's locally owned transportation-related businesses and the jobs they provide, what are the policy considerations?

Across the labour market, some occupations will achieve productivity improvements while others will be eliminated, in either case yielding cost savings for organizations. We see four categories of such occupations:

- Productivity could improve in mobility-intensive jobs (bylaw enforcement, home care, itinerant sales).
- Some full-time driver jobs (e.g., in taxi, bus, truck) could be eliminated.
- AVs with function-specific automation may replace a quantity of jobs in occupations like street cleaning, garbage collection, and courier delivery.
- A number of jobs may become redundant (e.g., parking lot attendants, parking bylaw enforcement officers) due to AVs.

Through analysis of national industry classification data from the 2011 Canadian census we have identified 3 sets of industries likely to be affected by the rise of AVs. For each industry sector or subsector below, we provide a job impact assessment of plus or minus 2-15%, 15-50%, and 50-90% rates of AV-driven job growth or risk relative to total employment in the subsector.

Both business and job growth

- **Construction**. Because AVs will change the shape of the city – including, for example, the conversion of street and off-street parking – growth in construction is likely. (+2-15%)
- **Highway, street, and bridge construction**. More specifically, AVs will foster road redesign, new street infrastructures and road networks. (**+**2-15%)
- **Computer and electronics manufacturing, data processing & related services**. **Telecommunications**. AVs will increase demand for information and communications technology products and services. (**+**2-15%)

Business opportunities, job risks

- **Manufacturing excluding motor vehicle related**. Freight transportation automation will reduce costs and improve productivity. (**-**2-15%)
- **Wholesale trade**. Freight transportation is a significant component of wholesale trade, so automation will have meaningful impact on costs and productivity. Also, AVs will improve

the productivity of itinerant wholesale sales professionals who work out of their vehicles. This may result in some job losses. (-15-50%)

- **Retail trade**. Freight transportation automation will reduce costs and improve productivity. Business innovation in this subsector is likely. For example, mobile in-vehicle retail services may become a way to do business (e.g., for personal care, garment selection/fitting, food/meals). Also, growth in volume and speed of delivery-oriented retail (e.g., Amazon) is likely, with corresponding decline in retail store space. With the decline in personal vehicle parking, space may be allotted to mobile retail services. (-2-15%)
- **Truck transportation**. Automation will transform this subsector and may eliminate many local delivery and driver jobs. (Burns, William and Scarborough 2013). (-15-50%)
- **Urban, interurban, school/employee, charter bus and transit systems**. Automation will improve productivity. Social norms, customer service requirements and expectations may protect many driver jobs. (-2-15%)
- **Waste collection**. Vehicle automation, potentially combined with robotics, will improve productivity. Reduction in street parking will be another supporting factor. Impact on jobs is unclear.
- **Home health care, individual and family services**. AVs will improve the productivity of itinerant home and family workers who work out of their vehicles. This could result in some job losses. (-2-15%)
- **Local, municipal and regional public administration**. As discussed, AVs will potentially result in reduced revenues to the City while also potentially reducing costs in many areas. These include, among others, reduced policing requirements; automated garbage collection, snow removal and street cleaning; and more cost effective fleet management. (-2-15% or -15-50% per functional area)

Both business and job risks

- **Motor vehicle related manufacturing**. The auto industry faces the prospect of significant business model disruption, especially if ATs take hold. A single AT may replace 10 vehicles. It will be likely be much lighter and smaller than current cars, and most of its value will be in ICTs. Due to more intensive use, ATs will have a short life, perhaps 2-3 years, which is good news for manufacturers. Replacement vehicles will depend for their improvement on technology, apps and usability design innovations, passenger amenities and comfort. New kinds of customization for various user classes may be a requirement. If car manufacturing becomes like computer manufacturing, more of it may move offshore. It remains to be seen how Canada's auto sector will participate in this very different market. (-15-50%)
- **Motor vehicle and parts wholesaler-distributors**. **Motor vehicle and part dealers.** Significant market penetration by ATs would be highly disruptive to the vehicle distribution and sales, parts, and aftermarket subsectors. AT service providers are likely to bypass dealer-distributors and buy directly from manufacturers; indeed, some AT providers may themselves be vehicle manufacturers. The consumer aftermarket will be virtually nonexistent for ATs. A likely thriving consumer market for AT-related devices and apps will be a different kind of phenomenon. (-50-90%)
- **Gasoline stations**. Alternative fuels such as electricity and hydrogen may reduce the need for gasoline stations. (-15-50%)
- **Taxi and limousine service**. Transportation network companies like Uber and Lyft have challenged the business models of incumbents in this subsector. Uber aims to replace its drivers with ATs as soon as feasible (Newton 2014). (-50-90%)
- **Insurance carriers and related activities**. AVs will significantly reduce vehicle liability risk as well as the need for personal accident coverage. A significant amount of liability – perhaps

all – may eventually shift from individuals to manufacturers or AV service providers. Such organizations will buy insurance on a wholesale basis or self-insure (OECD Corporate Partnership Board 2015) (Bertoncello and Wee 2015). (-15-50%)

- **Automotive equipment rental and leasing.** As car ownership declines, so will leasing. Many vehicle rental companies have set up or acquired carsharing divisions, which may position them for the AT era. Additionally, customers who normally rely on ATs may, from time to time, wish to "rent" a more specialized vehicle. On the other hand, new players are likely to enter what is today the rental business. Automation will probably eliminate many customer-facing jobs in this subsector. (-50-90%)
- **Automotive repair and maintenance**. Declining accident rates will reduce one revenue and activity source for this subsector. AT providers may use in-house repair shops. (-15-50%)

Scenario relevance: Ownership Leads may or may not support the sustainability of the Ontario auto sector; it will help the Toronto automotive retail, leasing, repair, and aftermarket sectors. For other subsectors and occupational categories, scenario outcomes are likely to have little impact.

7 Government initiatives

7.1 Canada

As described in Section 6.8, the Ontario Ministry of Transport published regulation rules for AV pilots in October 2015, with an eye to having AV pilots on the province's roads in early 2016. In addition, the Government of Ontario Centres of Excellence Connected Vehicle/Automated Vehicle Program has offered a cumulative total of $2.95 million in matching funding grants to support research, development and commercialization.

7.2 United States

US AV-related initiatives are too numerous to list here. We highlight the work of the US Department of Transportation (DOT) and the California nexus of vehicle automation.

The DOT and one of its agencies, the National Highway Transportation Safety Administration (NHTSA), manage national policies and activities pertaining to AVs. These initiatives include:

- A policy on AV development issued in 2013 (NHTSA 2013) that encourages AV research and testing and highlights several states that with enabling legislation. According to a press release, the policy addresses:
    - "An explanation of the many areas of vehicle innovation and types of automation that offer significant potential for enormous reductions in highway crashes and deaths;
    - "A summary of the research NHTSA has planned or has begun to help ensure that all safety issues related to vehicle automation are explored and addressed; and
    - "Recommendations to states that have authorized operation of self-driving vehicles, for test purposes, on how best to ensure safe operation as these new concepts are being tested on highways."
- Research on topics such as advanced emergency braking, human factors (including handoffs from vehicle to human control), and cybersecurity (Beuse 2014).
- Consultations and intention to announce, in 2016, a mandate for availability of V2V communication in new vehicles (National Highway Traffic Safety Administration 2015c).
- Cooperation with SAE International and other organizations on technical and performance standards for AVs.
- Beyond Traffic, a national public consultation to develop a 30 year framework for the future of transportation in the United States (US Department of Transportation 2015a).

As mentioned, six US states (California, Florida, Michigan, Nevada, North Dakota and Tennessee) and the District of Columbia have legalized AV use under various conditions. About 20 other state legislatures are reviewing proposed AV legislation.

Silicon Valley is the centre of AV R&D in the US. In addition to technology-oriented firms (Google, Apple), many car manufacturers (BMW, Ford, General Motors, Honda, Mercedes-Benz, Tesla, Toyota, etc.), and leading Tier 1 automotive suppliers (Bosch, Delphi Automotive) conduct AV development in the area. Other US sites of AV technology development include Detroit (Delphi, Ford, GM), Pittsburgh (Uber), and Tucson (Uber).

AV testing typically occurs initially on the manufacturer's private property. In California (GoMentum Station) and Michigan (Mcity), test sites that simulate urban streets are on offer. However most AV developers seek to conduct tests of sufficiently reliable prototypes on public roads.

As of September 2015 California had issued permits to test AV technologies on public roads to ten companies:

- Car manufacturers: BMW, Honda, Mercedes Benz, Nissan, Volkswagen, Tesla
- Tier 1 suppliers: Bosch, Delphi Automotive
- Technology firm: Google
- Aftermarket vendor: Cruise Automation[20]

7.3 Europe

Several policy and research initiatives are occurring at the level of the European Union. More relevant are the policies and programs of leading countries, including AV initiatives by their home-based domestic and international firms. AV-engaged countries with home-based international car manufacturers are Germany (in particular – with firms such as BMW, Daimler-Benz, Volkswagen and Tier 1 suppliers Bosch, Continental, and ZF), Sweden (Volvo), and France (Renault/Nissan). Other European countries with significant AV projects include UK, Netherlands, Spain and Switzerland (European Road Transport Research Advisory Council 2015; Swisscom 2015).

7.3.1 Germany

The German Ministry of Transportation and Digital Infrastructure released an automated and connected driving strategy in September 2015 (Bird 2015). The strategy was, at least in part, developed by a private-public sector industry roundtable. It aims to bring highly automated (Level 4) cars to the market by 2020, particularly for structured, less complex environments like the Autobahn and for low speed areas like parking lots. It provides regulations that legalize automated driving and address liability and safety. The strategy also addresses security and privacy matters, including encryption, protection against unauthorized access, and several provisions to protect user privacy. The strategy includes a dedicated test track on the Autobahn, focused on automation Levels 4 & 5, V2V and V2I communication, and advanced mapping and sensing.

The German government has funded R&D on a variety of ADAS and cooperative vehicle assistance technologies. It plans to fund additional research on full automation and electric vehicles (European Road Transport Research Advisory Council 2015).

As discussed elsewhere in this report, Germany's leading automotive firms are engaged in AV development. BMW is in a partnership with Chinese company Baidu, with stated intentions to begin trialing an AV in 2016. Daimler-Benz is trialing a Level 4 Freightliner in Arizona. Its CEO has promised a luxury AV and implied that the company will enter the AT marketplace, leveraging the company's car2go carsharing service (Parkinson 2015). Volkswagen subsidiary

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[20] Cruise, a technology startup, sells an aftermarket product for Level 3 automation: lane keeping, adaptive speed control and collision avoidance (Cruise Automation, 2015). At time of writing it was only legal for use in California.

Audi provided the car for Delphi's cross-US automated journey. Google executive chairman Eric Schmidt gave a nod to the country's Tier 1 suppliers (and others) in September 2015, saying, "Germany can lead the world in this. We're working with a whole infrastructure here in Germany" (Boston 2015). Analysts interpreted these comments as a hint that Google may outsource manufacturing of its future AVs to Tier 1 suppliers like Bosch or ZF – or even partner with the likes of BMW or Daimler-Benz.

7.3.2 United Kingdom

In February 2015 the UK Department for Transport published a 40-page report, *The Pathway to Driverless Cars: Summary report and action plan* (UK Department for Transport 2015). The document emphasizes the government's interest in attracting the testing and production of AVs by global businesses. It lists 31 action items for government, many of a technical (though strategically relevant) nature. They include:

- Publish an AV testing code of practice.
- Update the country's legal and regulatory framework to clarify liabilities.
- Amend regulations that pertain to driverless use and vehicle maintenance.
- Strengthen safety and cybersecurity standards.
- Engage the government in planned AV tests on UK roads.
- Press for international regulations and standards.

In July 2015 the UK Department for Transport launched *The Pathway to Driverless Cars: A Code of Practice for Testing*. The document provides detailed safety guidelines and recommendations for public road testing of highly or fully automated vehicles (i.e., Levels 4 & 5), from pods to transport trucks. For example, it requires use of a licensed and trained test driver in every AV under test. It also mandates actions and practices related to data collection, data protection, cybersecurity and software management. Any organization can test AVs on UK roads, without a special permit, on the condition that it follows the code of practice.

The UK government has actively sought out, formed and funded (£40 million to date with requirements for matching private sector investments) AV initiatives and partnerships with the private sector (Gordon-Blomfield 2015).

Several trials are planned in UK cities in an apparent effort to kick-start a UK-based AV manufacturing sector. In Milton Keynes, the first of three UK-designed and built Lutz Pathfinder "pod" cars was presented to the public in September 2015. It will be the first fully automated vehicle to be tested on the country's public pedestrian roads (Catapult Transport Systems 2015). The Pathfinder will also be tested in Coventry in 2016. A UK consortium called Venturer is targeting the start of a 36-month trial of its vehicle in Bristol; it will apparently focus on legal and insurance issues and the public reaction to AVs (University of Bristol (press release) 2015). Another trial, intended to work as a shuttle to and from mass transit, is planned for Greenwich.

7.3.3 Sweden

In collaboration with legislators and transport authorities, Volvo plans to put end-customers into 100 automated cars in in a 2017 real life pilot at its headquarters city, Gothenburg, Sweden (Volvo Car Group 2015). One part of Volvo's effort will be to trial AVs for winter driving.

By 2017 Gothenberg also plans to have a functioning vehicle-to-infrastructure system that alerts cars about incidents such as lane closures so they can safely anticipate and avoid them before they come into view (Stevens 2014).

Volvo has also logged over 10,000 kilometers of autonomously platooned freight vehicles under the SARTRE project in Spain.

7.4 Asia & Australia

Several Asian countries are aggressively pursuing AV strategies. Some examples of Asia activity (Somers and Weeratunga 2015):

Australia. Like Canada, Australia has a significant automotive manufacturing industry, but no international headquarters of major car company. Nonetheless, Australia has made strides toward carving itself a role as an AV leader. As discussed, it is among the first, if not the first, to deploy automated trucks in mining operations. The South Australia government is at the forefront of a project to trial AVs on public roads in November 2015, and other trials are planned across the country. International project partners include Bosch, Volvo, and Carnegie Mellon University. The project coordinator is an independent national road research agency (ARRB Group 2015). The state government introduced enabling legislation for the project in September 2015 (Donellan 2015)

Japan. A cross-ministerial innovation program is pursuing research and innovation in AV technologies with the objective of full deployment between 2020 and 2030. Advanced next generation traffic systems are planned for the 2020 Olympic/Paralympic Games in Tokyo. All Japanese car companies are engaged in AV development.

South Korea. In 2013 the Ministry of Trade, Industry and Energy released a seven-year AV development plan and technology roadmap. South Korea has developed a green intelligent transportation systems (G-ITS) model that emphasizes use of personal wireless devices as enablers of multimodal transportation. Fiber optic cables are being laid in 3500 km of the country's expressways. A university-government consortium has developed a driverless single-seat electric vehicle for the mobility-impaired and the elderly.

Singapore. The Ministry of Transport formed a Committee on Autonomous Travel for Singapore (CARTS) in 2014, mandated to drive research, development and deployment of AV for the city-state. Two working groups have been formed: one will devise a plan for the AV-enabled Singapore of the future, and the other will focus on regulation and implementation. A network of roads has been designated with the intention of conducting AV trials in 2016. A private-public partnership, including the National University of Singapore and MIT, has developed a driverless AT designed to address the 'first and last mile problem' for the aging population.

China. At time of writing we have few specifics on AV-related government initiatives in China. Chinese technology firms Baidu and Tencent (in partnership with contract manufacturer Foxconn) intend to quickly enter the AV market (Cooper 2015).

8 Appendices

8.1 AV technologies and their implications

The urban policy and planning implications of cars and other vehicles can be viewed in three dimensions; first, as an end-user product; second, as a package of underlying technologies; and third, as the avatar of business model innovations (e.g., in freight, personal transportation, and retail). This section focuses on the first two views.

As an end-user product, the 20th century motorcar changed the ways that cities worked, how people moved about and interacted, and how goods and services were transported. To facilitate these changes, governments adopted policies, regulations and investments that – for example – assigned road primacy to motor vehicles, expanded the road network, addressed traffic circulation and safety, regulated driver licensing, and managed the consequences of road accidents.

Karl Benz launched production of a car with a gasoline-powered internal combustion engine in 1885. Since then the gas engine – its mode of propulsion – has been the defining underlying technology of the car. On the face of it, the gas engine has made less impact on policy and planning than has the end-product that it powers. Governments have set zoning regulations for gas stations, rights-of-way and rules for the transportation and storage of fuel, and not much else. Other than efforts around emission standards, until quite recently governments have paid little attention to the externalities of the gas engine: its role in climate change and air pollution.

All this suggests that though the policy implications of underlying technologies may not always be initially apparent, they can have significant unanticipated (or wilfully ignored) consequences.

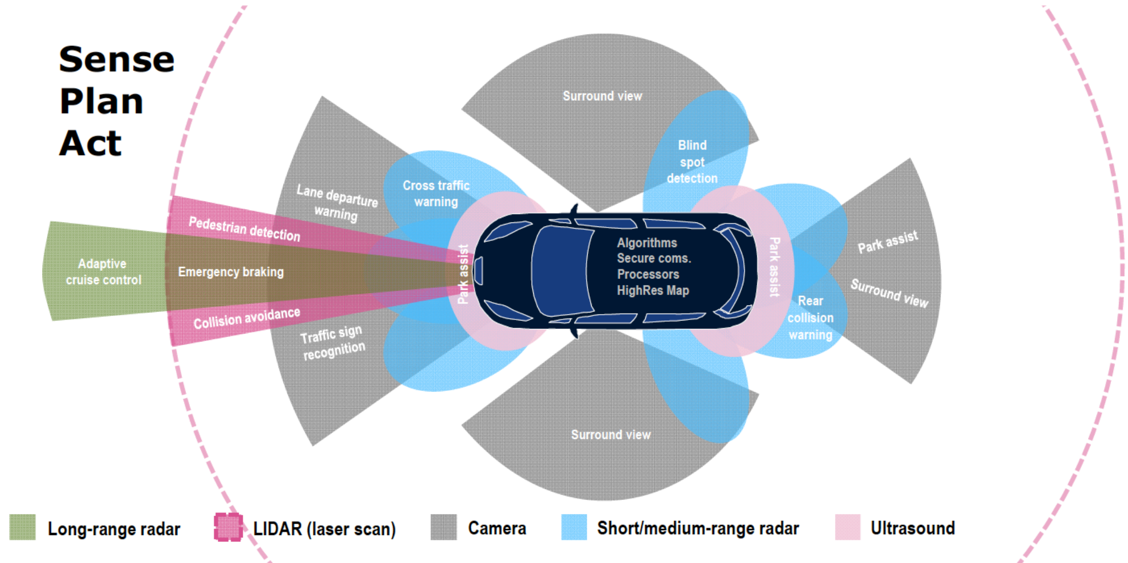
Information and computer technologies (ICT) have played a growing role in human-driven cars for the control and management of core vehicle functions, driver assistance, and external communications. Nevertheless, the human driver and traditional motor vehicle engineering have remained dominant. This is about to change dramatically, and with significant potential implications for urban policies and investments.

Where the internal combustion engine of the 20th century replaced the horse as the mechanism of propulsion, in the 21st century information and communications technologies (ICTs) will replace humans themselves as the mechanism of vehicle control and navigation. Not coincidentally, with a shift to electric power, the source of propulsion is also likely to change.

Certain ICTs – for example, a dashboard animation of traffic-efficient routing – will be part of the "end user" AV experience. Less visible underlying applications – such as (V2V) communications – will support safety and traffic efficiency. To achieve the full potential of AVs and their benefits, cities will implement policies, programs and infrastructures that maximize end user functions, underlying technology capabilities, energy efficiency – and broader social, urban planning and fiscal objectives.

ICTs have already generated policy challenges – notably distracted driving and the "Uber" phenomenon. Some ICT capabilities – such as the collection of data about passengers' travel – raise the potential of new kinds of externalities (e.g., privacy, ownership and uses of personal information). But there is much more to this story. It is important for policymakers to understand key aspects of the nature, capabilities, and implications of the underlying ICTs that will power AVs and ITNs.

An automated vehicle is essentially a type of robot – a machine that can sense its environment, assess and plan what to do, act on that plan, and communicate with people and other devices. In every AV, each of these activities requires a set of innovative physical technologies, massive data resources, advanced algorithms, and blazing processing speeds.

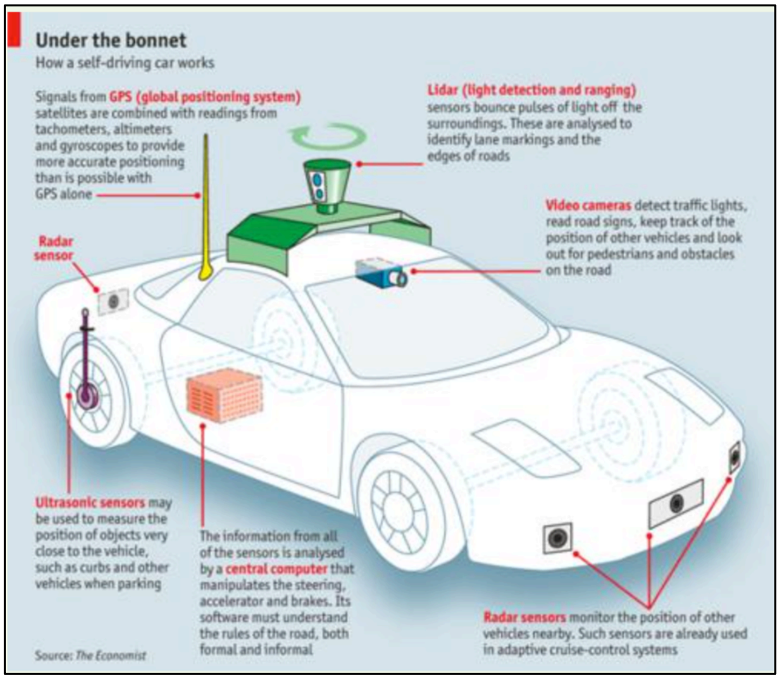


Technologies that allow vehicles to sense the dynamic driving environment (OECD Corporate Partnership Board 2015)

Sensing alone entails a vast array of views, activities and technologies, many of which are illustrated in Figure 5.[21] In addition to these, an AV may exchange digital communications with traffic management infrastructures (V2I), other vehicles (V2V), pedestrians (V2P), and so on. According to one source, Google's 2013 self-driving car prototype captured 750 megabytes of sensor data per second (Gross 2013).

A well-executed sensing capability lets the AV computer continuously "see" its environment as it moves in time through three dimensions; identify special features such as road markings and signage; and notice unexpected events. Most AV sensing technologies, such as radar and cameras, are common and inexpensive. One exception is lidar, a specialized form of radar that uses laser beam reflections to generate accurate 3D snapshots of every object surrounding the vehicle at 30 frames per second day or night, rain or shine from one centimeter away to 100 meters or more (Rechtin 2015). Though the cost has dropped a lot and will continue to do so, a single lidar rooftop "puck" in 2015 is a mass-market prohibitive $8000 US (Berman 2015).)

[21] This graphic from an OECD report originated with a conference presentation by a speaker from AV sensor manufacturer Texas Instruments.



After "sensing", the next phase is to organize and assess what the vehicle's sensors have "seen", heard, or received, compare it with the passenger-assigned destination, and plan the trip's next moves – continually and in fractions of a second. This is the most challenging and critical task of an AV's automated system. Conceptually, there are two possible approaches to this task. A brute force method is for a vehicle to look around itself and assess everything that is going on, almost from scratch. It can consult a generic application like Google Maps, but it must look out for speed bumps and potholes, curb heights, temporary road construction, pedestrians, other vehicles, and so on. This is technologically inefficient (requiring significant in-vehicle sensing and processing power) and risky (as some road features may be hidden or hard to read).

Google Auto's more sophisticated approach greatly expands on Google Maps (Madrigal 2014). The company's teams go outside to map, in minute detail, every road that their cars will travel: "ultra-precise digitizations of the physical world, all the way down to the position and height of every single curb", as well as invisible information like implied speed limits. Google loads a relevant subset of this information from the "cloud" into the memory of a car when it sets out on a trip. Said Andrew Chatham, Google Auto team mapping lead: "We tell it what the world is expected to be like when it is empty.[22] And then the job of the software is to figure out how the world is different from that expectation. This makes the problem a lot simpler."

Aiming to get past brute force navigation, German automakers BMW, Daimler Benz and Volkswagen purchased the HERE mapping unit from Nokia, a Finnish telecommunications company, for 2.8 billion euros in August 2015 (Geiger 2015). Likely for similar reasons, Uber acquired a set of Bing Map technologies and 100 Bing employees from Microsoft in July 2015 (Kokalitecheva 2015).

It is not enough for an AV to "see" moving or new objects. It must also estimate their likely behaviours and integrate that assessment into a response decision. This requires machine

[22] In other words what a street looks like without any people, vehicles and other temporary or passing items.

intelligence: advanced algorithms that learn from experience. Ron Medford of Google Auto states: “With data collected from driving nearly two million miles on public roads, we’ve developed models for identifying objects and predicting what they are likely to do in a given situation. For instance, if a car is approaching a four-way stop at a high speed, there are various probabilities that the other car will stop normally, screech to a stop, or run the stop sign. We then respond accordingly.” (Rechtin 2015)

Communication is another core activity for an AV. Digital communications with other vehicles (V2V) and, potentially, traffic infrastructure (V2I) can improve an AV’s decisions. For example, researchers have designed and simulated infrastructure-based models for AV efficiency in traffic intersections. These include algorithms for managing fully autonomous vehicles (Stone 2010), evasion planning protocols (e. a. Tsz-Chiu Au 2012), and for managing semi-autonomous vehicles (S. Z. Tsz-Chiu Au 2012). All these depend on sending, receiving, processing and acting on digital communications with transportation infrastructure and, potentially, other vehicles.

In summary, an AV decision toolkit will include the following capabilities:

- Consult ultra-precise digitizations of the existing physical world
- Identify and comprehend moving and transitory objects
- Interpret physical and digital communications from other vehicles and traffic management infrastructure
- Predict likely actions of moving and potentially moving objects
- Apply traffic and safety rules and protocols
- Apply the route plan
- Organize all these inputs logically
- Assess alternatives and apply decision rules to choose the vehicle’s actions
- Make decisions regarding communication mechanisms and content with other vehicles, traffic management infrastructure, passengers, pedestrians, etc.
- Identify relevant data (including liability-related) for upload to local and cloud storage
- “Learn” from experience and change decision rules accordingly

The factors listed above make for a complex decision process. And other factors will no doubt appear. For example, one proposal is for 2-way safety-oriented communications with pedestrians (V2P) and other vulnerable road users such as cyclists, motorcyclists, and the mobility-impaired (Jose Javier Anaya 2014).

New planning decisions must be made continuously, in fractions of a second. Yet Google claims that with support from remote servers in the cloud, the processing power in its car is akin to that of a desktop computer (Madrigal 2014).

8.2 NHTSA levels of vehicle automation

As discussed, this paper uses the SAE International model of levels of vehicle automation.

The US National Highway Traffic Safety Administration (NHTSA) proposed a slightly different model in 2013 (National Highway Traffic Safety Administration 2013b). It is the de facto standard in the US.

- **Level 0 – No Automation**. "The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls.
- **Level 1 – Function-specific Automation**. "Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other." Examples include cruise control and advanced driver assistance systems (ADAS) such as automatic braking and lane keeping.
- **Level 2 – Combined Function Automation**. "This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver 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." The driver's hands can be off the wheel and feet off the accelerator at the same time.
- **Level 3 – Limited Self-Driving Automation**. The driver cedes control "of all safety-critical functions under certain traffic or environmental conditions". The vehicle monitors the road and alerts the driver to take action when necessary. The transition to this level of automation is a safety-critical design and regulatory challenge, as it assumes the human driver will competently resume active driving shortly after being notified to do so.
- **Level 4 – Full Self-Driving Automation**. The vehicle performs all safety-critical driving functions and monitors roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

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