UTTRI
Research Report

AUTONOMOUS VEHICLE LITERATURE REVIEW

Alec Knowles, Anton Budnyy, Eric J. Miller and Judy Farvolden

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UNIVERSITY OF TORONTO
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Outline

Alec Knowles
Anton Budnyy
Eric Miller
Judy Farvolden

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University of Toronto Transportation Research Institute

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1 Introduction

This literature review describes the safety, regulatory, financial, energy, environmental, security, and privacy implications of the introduction of Autonomous Vehicles (AVs), including Connected Vehicles (CVs). Specifically, this review is intended to provide background information and context to inform municipal policy- and decision-makers at the City of Toronto, ON, Canada, of ongoing developments and speculations related to AVs and CVs. Discussion of policy and regulatory frameworks introduced or under consideration in other jurisdictions is included where considered to be substantial and relevant. While this paper is intended primarily to inform *municipal* policy, regulation and legislation from all levels of government across Canada and around the world have been incorporated.

The scientific and technological developments facilitating the introduction of these vehicles – i.e., *how* AVs are being introduced – are examined only as and where necessary to provide perspective regarding *what* municipalities should begin to prepare for. Beyond AVs, other forms of intelligent transportation equipment and services (such as drones and wireless communication) are discussed sparingly, and only where considered relevant to municipal services and regulation.

This paper considers peer-reviewed journal articles, newspaper and website articles, academic simulation studies, theses, reports from think tanks, governmental policy analyses, and other diverse sources. As of the time of writing, many of the studies, projects, and developments described are in progress; others are in various planning stages, a handful have been completed, and many are merely speculative.

The umbrella term “AV” is used to refer to any and all autonomous/driverless vehicles, of which connected vehicles are considered to be a subset. In cases where a distinction needs to be drawn between a standalone autonomous vehicle (standalone AV) versus a connected vehicle (CV), that distinction is made explicit.

2 Safety

Virtually every article discussing AVs touches on the potential for improving safety by reducing or eliminating human error, and thus reducing collision rates. Many articles cite the US National Highway Traffic Safety Administration (NHTSA) 2011 statistic that “human causes” are the primary factor responsible in 93% of collisions, and accordingly, many studies estimate a 90% reduction in collision rates following the introduction of fully autonomous vehicles (Articles #1, #2, #5, #6, #13, #19, #32). For context, the US recorded 5.5 million collisions, 2.22 million fatal and injurious collisions, and 32,367 fatal collisions in 2011 (Article #1), while Canada experienced 119,000 fatal and injurious collisions in 2011, leading to 2,000 fatalities and 160,000 injuries (Article #5). Unsurprisingly, in a survey of 1,510 US consumers, the Boston Consulting Group identified “safety” as the top reason consumers are interested in purchasing fully autonomous vehicles, and the number two reason consumers are interested in purchasing partially autonomous vehicles (Article #8).

The majority of articles discussing the safety benefits of AVs refer to future scenarios in which all or virtually all vehicles are fully autonomous. Article #2, however, considers the safety implications at three stages of AV market penetration, predicting that when AVs make up 10% of the total car market share, they will be only half as likely as non-AVs to be involved in a collision; at 50% market share, AVs will be 70% less likely to be involved in a collision; and at 90% market share, AVs will be 90% less likely than non-AVs to be involved in a collision. Further, Article #2 estimates that collision rates of pedestrians and bicycles will drop only half as much as that of AVs, while motorcycles will benefit from a collision rate decline of only 25% relative to AVs.

While no articles anticipate increased collision rates due to the introduction of AVs, Articles #6 and #20 anticipate new causes for collisions will arise, such as system failures, security failures (hacking), increased Vehicle Kilometres Travelled (VKT), and risky behaviour of some drivers due to complacency associated with AV safety benefits (e.g., reduced seatbelt use). Article #6 predicts the majority of safety benefits to materialize only once the vast majority of vehicles are autonomous, likely sometime between during the 2040s to 2060s.

Safety benefits are touted as one of the chief cost-saving benefits of AVs. A Morgan Stanley report estimates annual cost savings of $488 billion (USD, assumed 2013), or 8% of US GDP, due to collision avoidance once the market is fully penetrated by AVs (Article #30). Article #5 applies Morgan Stanley's approach to quantifying safety-related cost-savings to Canada, estimating that $37.4 billion could be saved by eliminating 80% of Canada's annual collision-related fatalities and injuries (all figures 2011 and CAD).

Congestion is also expected to be reduced as a result of declining collision rates. According to Article #1, the US Federal Highway Administration estimates that one quarter of congestion is caused by traffic incidents, of which roughly half are collisions. Congestion mitigation is viewed as another means of generating cost-savings (i.e., beyond savings stemming from reduced fatalities and injuries). Refer to Section 0 for further discussion of congestion costs and impacts.

Concerns exist regarding the safety of AVs which operate autonomously for stretches of time before returning control of the vehicle to a human driver (Articles #3, #7, #22). As most major auto manufacturers continue to introduce individual automated features (such as lane-keeping assist and adaptive cruise control), it is widely speculated that society will undergo a transition period in which vehicles are temporarily capable of operating themselves without driver input. In a study of human reaction times, three groups of participants (each with n = 9) were tested using the Stanford Driving Simulator to imitate a hazardous obstacle emergency (Article #3). The simulated AV provided its driver (i.e., the test subject) with a randomly assigned transition (warning) period of two, five, or eight seconds after which time the vehicle would collide with the obstacle. One-third of participants failed to avoid the obstacle when provided only two seconds of transition time, but all participants successfully avoided the obstacle when provided five or eight seconds of transition time.

AV testing regulations, many of which relate to safe operation of vehicles, are discussed in Section 0.

3 Regulation, Public Trials, and Liability

Article #22 defines two basic types of regulation which can shape the development and operation of AVs: *ex ante* regulation, which refers to standards and conditions which must be met from a legal standpoint (such as conditions of insurance and regulatory performance standards), and *ex post* regulation, which refers to legal claims, investigations, and free-market penalties such as loss of reputation or sales. Section 3.1 describes the *ex ante* regulation in place and under consideration in jurisdictions around the world. Given that AVs have yet to debut commercially (with the exception of a handful of models with a few automated features), the bulk of existing *ex ante* legislation and regulation relates to use of AVs for testing purposes. The status of ongoing AV test projects around the world is thus briefly discussed in Section 3.2.

Very little substantive discussion of *ex post* regulation is evident in current literature, with the exception of the issue of liability, which is addressed in Section 3.3.

3.1 Regulation

Existing regulation of AVs is piecemeal or non-existent within virtually every federal jurisdiction worldwide. In the United States, legislation has been passed in Nevada, California, Florida, Michigan, North Dakota, Tennessee, and Washington, DC, with legislation under consideration in roughly 16 other states (Article #81). France and the Netherlands are in the process of creating regulatory frameworks under which AVs can be tested in public spaces; Finland has amended its Road Traffic Act to allow AVs to operate in restricted public areas for five years beginning in 2015, after which the experimental legislation will be reviewed; and the UK, Sweden, and Germany have reviewed existing traffic legislation and regulation frameworks, concluding that AVs can be tested under existing legislation in specific locations and following strict guidelines, though AVs in Germany require permission on a case-by-case basis (Article #22).

The Department for Transport in the UK has authored a code of practice for testing and a summary action plan (Articles #4, #18) which provide guidelines for meeting existing regulations while testing AVs, stating that existing legislation and regulations in the UK are not a barrier to the AV development and testing. This is in part due to the UK's (arguably prescient) reluctance to ratify the Vienna Convention on Road Traffic, which requires that "every moving vehicle or combination of vehicles shall have a driver", and "every driver shall at all times, be able to control his vehicle" (Article #18). (Canada, the United States, Japan, Australia, and New Zealand are other notable absentees from the list of countries which have signed and ratified the Vienna Convention.) Regardless, the UK government is working to review domestic regulations by 2017 to better accommodate AVs, with the intention of permitting testing of AVs without drivers; promoting AV safety; and improving protection from security issues and cyber threats (Article #18).

In its review of federal legislation, the Swedish Transport Authority has similarly concluded that its laws do not prevent testing of AVs on public roads in Sweden. However, while vehicles with partial autonomy can be operated under current legislation, vehicles which are able to assume full control of the vehicle for any period of time (allowing the driver's attention to wander) will require additional regulation to be created before any commercial launch. The Swedish Transport Authority recommends that new standard regulations, road markings, etc. be implemented internationally within the mandate of the United Nations Economic Commission for Europe (Article #53).

The majority of legislation passed by individual US states includes a definition of AV, including rules for operation, insurance standards, and testing/operating conditions. Some states require human drivers to be prepared to resume full control at a moment's notice of an AV undergoing testing. Legislation from a number of states also includes provisions to limit the liability of Original Equipment Manufacturers (OEMs), i.e., auto manufacturers, in situations where a vehicle has been retrofitted to include after-market third-party AV technology (Article #81). To date, regulators in California have favoured "discretionary" AVs, which allow the user maximum control over when, where, and how AVs operate, rather than "non-discretionary" AVs, which controls the majority of operational decision-making (Article #48). California Vehicle Code 38750(b)(1) (West 2013) requires manufacturers of AV technology installed on a vehicle to provide "written disclosure to the purchaser of an autonomous vehicle that describes what information is collected by the autonomous technology equipped on the vehicle" (Article #48). California also requires the use of Event Data Recorders (EDRs) to provide information to investigators in the event of a collision (Article #48).

While Transport Canada is participating in the development of international AV standards UNECE WP.29, ISO TC 22 SC39, and ISO TC 204 (Article #5), little, if any, regulation has been introduced by municipalities, provinces, or the federal government. However, in December 2013, the Ministry of Transportation in Ontario proposed a five-year pilot project to safely test and evaluate AVs under prescribed conditions before the technology becomes widely available to the public (Article #82). The proposal would restrict AV operation to testing only, to be operated by specifically trained (and ministry-approved) individuals with G-class licenses, third-party liability insurance, and would require EDRs to capture 30 seconds of data leading up to any collision. A public consultation was completed to receive feedback on the pilot framework, but no changes or updates to the pilot proposal have since been announced.

Interestingly, Article #14 points out that if auto manufacturers make Transportation as a Service (TaaS) – envisioned as driverless taxis or short-term car rentals – widely available, it may become economically feasible for manufacturers to produce a huge range of vehicle shapes, sizes, styles, functions, etc., creating the challenging task of regulating such diverse vehicle configurations.

3.2 Public Trials

Several pilot AV projects are being trialed around the world.

In Japan, the first public tests of AVs were completed by Nissan in 2013, and autonomous freight vehicles have since been tested (Article #22). Since then, Toyota, Honda, and Nissan have begun working together to create parts, technology, and an infrastructure strategy for AVs, with the Japanese government committed to providing $83 million in test road funding (Article #45).

The Committee for Autonomous Road Transport in Singapore, or CARTS, was launched in 2014 to study and create test-beds for AVs, as well as developing a legal, regulatory, and liability framework, in addition to developing business opportunities. Singapore has also launched the Singapore Autonomous Vehicle Initiative to help CARTS facilitate public testing (Article #22). Singapore is also in the process of authorizing a trial of on-demand autonomous taxis, in cooperation with researchers from MIT in Boston, MA. One recent simulation project estimated that a fleet of 300,000 “robotaxis” could serve the city’s needs without anyone having to wait more than 15 minutes for a taxi during rush hour, in comparison with 780,000 existing passenger vehicles owned in Singapore as of 2011 (Article #25).

In the UK, AVs are being tested and developed in Bristol, Coventry, Greenwich, and Milton Keynes (Article #49). Funding is coming to three AV consortia (each including a mix of academic institutions, private firms, and municipalities) via Innovate UK, a publicly funded entity which operates at arm's length from the Government (Article #20).

In the United States, Google describes its test AVs as having logged over 1 million miles (1.6 million km), operating in Nevada, California, and Texas. The University of Michigan has built a 32-acre mock city environment, dubbed MCity, for testing AVs (including vehicle-to-vehicle and vehicle-to-infrastructure technology for CVs) in a real-world setting, but without the risks of testing on active public roads (Article #21). The facility is funded by a public-private-academic consortia including Delphi, DENSO, Econolite, Ford, GM, Honda, Iteris, Navistar, Nissan, Qualcomm, Robert Bosch, State Farm Automobile Insurance, Toyota, Verizon, Xerox (Article #21); the breadth of participating parties is indicative of industry interest and the array of technologies likely to be affected and relevant to the development of AVs. In Russia, KAMAZ, an auto manufacturer, has a similar intention of creating a dedicated city for testing AVs (Article #45).

Elsewhere in the United States, Daimler has introduced a vehicle model called the Freightliner Inspiration, an 18-wheeler with limited autonomy. The vehicle is able to operate autonomously on highways, maintaining its distance from other vehicles and remaining in its lane. However, the vehicle will not pass slower vehicles autonomously, and will return control to the driver in situations it is unable to accommodate (inclement weather, exiting the highway, etc.) (Article #32). In Spain, Volvo had logged roughly 10,000 km of autonomously platooned freight vehicle testing by 2012 as part of the SARTRE project, funded by the European Commission (Articles #2, #22).

Article #45, “The Roadmap for Autonomous (Self-Driving) Vehicles in Ontario, Canada”, characterizes Canada’s minimal investment and AV licensing and regulation efforts as lagging behind its counterparts in Europe and the United States. In December 2013, the Ministry of Transportation in Ontario established the “Pilot Project to Safely Test Autonomous Vehicles”, inviting comments from the public until February 2014 before moving to review comments and presumably moving the project forwards (Article #45). Article #45 recommends that Ontario and Canada attempt to leapfrog ahead of other jurisdictions in the AV race by introducing relevant and necessary regulations while developing a unified province- or country-wide test-bed with many "hubs" scattered across municipalities, with each municipality serving a specific testing function: a large city could be used for testing AVs in heavy congestion, while colder cities could be used for testing winter performance, etc. While Suncor has been using autonomous trucks on private roads in the oil sands in Alberta (Article #5), little other action has taken place to date in Canada, with no public road trials to date (to the authors' knowledge).

3.3 Liability

Liability for collisions and system failures is considered one of the most significant non-technological barriers to commercial deployment of AVs (Article #1, #9, #30). The introduction of AVs brings many liability questions not relevant to non-AVs, such as:

- How will the car insurance industry adapt to a possible switch from personal liability to product liability? (Article #8)
- How will liability be assigned and regulated for AVs which assume full control of the vehicle, even temporarily? (Article #53)
- Who is responsible if an AV is involved in a collision during inclement weather?
- Etc.

Safety improvements attributed to AVs are likely to encourage drivers and insurance companies to favour AVs over traditional vehicles. There is wide speculation that manufacturer product liability will increase (Article #1, #8, #9, #22) and personal liability will decrease, or may even disappear altogether. One solution to mitigate possible AV deployment delay would be to integrate cost-benefit analysis into liability standards, and thus find ways to encourage safer technology – in this case, presumed to be AVs – to be introduced even if manufacturers have not yet found a way to reduce their liability, as there will be a net benefit to society from introducing safer technology (Articles #9, #10). For example, governments could create new insurance options for manufacturers if they struggle to find offers of traditional insurance models, or governments could adopt legislation which declares human drivers liable for a vehicle's actions without exception, though these solutions have obvious drawbacks (Article #9). Manufacturers may also be able to limit their liability by offering Transportation as a Service (TaaS), and/or closely monitoring driver behaviour using AV sensors (Article #9, #13, #22). Liability may shift incrementally from drivers to manufacturers as additional autonomous features continue to be released commercially; however, as yet there is no specific framework for accommodating such a transition (Article #22).

The UK has stated it intends to review its legislation by 2017 with the intention of clarifying criminal and civil liabilities, among other questions (Article #18). Currently, UK regulation and practice guidelines stipulate that vehicles must be successfully tested on private tracks before being tested on public roads, and that test drivers must be present and ready to take control of the vehicle at all times during tests (Article #18).

4 Services and Infrastructure

4.1 City Services

Existing literature provides minimal meaningful consideration of AV implications for city services. However, there is general agreement that governments should start anticipating the impacts now, rather than waiting until AVs are entrenched in daily life. For example, Article #5 ("Automated Vehicles: The Coming of the Next Disruptive Technology") poses the following questions:

- How will tolling be managed if platooning is implemented (i.e., if cameras cannot read license plates)?
- How will police stop unoccupied vehicles, or vehicles occupied by sleeping passengers or children? How will tickets for bylaw infringement be assigned and distributed?
- How will automated snowplows affect the need for shoulders on roads and bridges? If snow plows operate more regularly and more efficiently, perhaps there is less need for snow storage along sides of roads.

It could also be that services currently operated by municipalities, such as traffic management, speed limit management and enforcement, and collection of data related to municipal services (such as pothole mapping) could be increasingly managed by vehicle manufacturers; indeed, conflict could arise between manufacturers and municipalities (and other infrastructure providers) over jurisdictional responsibilities. Information related to construction, incidents, congestion, etc. could be collected and relayed by AVs to services responsible for traffic management (Article #14). Reduction of parking spaces could affect postal workers, private couriers, and other delivery services or city services, many of whom may be able to be replaced entirely by AVs (Article #26).

The UK's code of conduct for testing AVs in public spaces recommends that testing firms engage with local emergency services and establish lines of communication, making technical advice available to emergency services proactively to better assist emergency services in the event of a collision or other incident (Article #4). An extended transition period, during which

AVs and non-AVs share the road, will present a challenge to regulators and to city services (Article #38). Refer to Section 11.2 for further discussion of this transition period.

Other technologies, such as autonomous or remotely piloted drones, could be used to improve efficiency and reduce costs of city services. For example, police in York Region, north of Toronto, recently purchased a 2.4 kg drone to help with collision investigations. The drone is equipped to take hundreds of photos of collision sites in 5-10 minutes, and then combine the images into electronic maps and digital renders of the scene. Typically this process takes investigators 8 to 10 hours for serious collisions. The drone in question, a Canadian-made drone designed for use by military and government agencies, can operate in challenging conditions (90 km/h winds, temperatures ranging from -33º to 50º C), and can also be used in search and rescue operations (Article #33).

Refer to Section 5.3 for discussion of public transit (including paratransit) planning and services.

4.2 Infrastructure

A broad cross-section of municipal infrastructure is likely to be impacted by the wide-scale introduction of AVs, and much existing infrastructure may eventually require renewal, replacement, or repurposing. This section considers new types of municipal infrastructure, as well as changes to existing infrastructure, seen as playing a role in a future AV transportation network.

Currently, firms developing AVs are focused on strategies to make use of using existing infrastructure, rather than relying on potential future infrastructure to make AV use feasible, as it will be prohibitively expensive for governments to overhaul existing roads, highways, intersections, etc. in the short term (Articles #5, #14, #19, #24, #51). Sensibly, the UK code of practice for AV testing assumes that no additional infrastructure is required for testing purposes, and where specific infrastructure changes are required, including signage, changes must be agreed with relevant authorities. Sourcing of any data or maps necessary for testing is considered an obligation of the testing party (Article #18). Accordingly, the road network investment policy for the UK is operating on the assumption that the Strategic Road Network is in a transition period, with a clear need to support the arrival of AVs and similar technological advancements (Article #17).

Eventually, it will become necessary for governments to adapt infrastructure investment and needs in order to take advantage of AVs. For example, AVs may prompt (Articles #5, #14, #38):

- Reduced need for highway lanes, due to improve utilization;
- During the AV/non-AV transition period, subdivision of roads into AV and non-AV lanes by restriping roads, or designation of segregated parallel routes;
- Gradual replacement of traffic lights with roundabouts;
- Reduced parking requirements;
- Upgraded electricity generation and distribution infrastructure to accommodate increased electrical demand (assuming a large portion of AVs are powered by electricity), as well as vehicle battery-swap stations;
- Narrower lanes on roads and bridges assuming AVs require less operating tolerance than human-controlled vehicles;
- Etc.

Though it may be many years before infrastructure is upgraded comprehensively to accommodate AVs, governments should consider possible upgrades now to better plan for the future, especially given the relatively long-term planning cycles (i.e., 20-30 years) typically followed by municipal planners (Article #9). Article #14 argues that infrastructure providers (specifically in the United States, though the same can likely be said of Canada and most other countries) such as state highway authorities are not paying due attention to the paradigm shift that AVs will trigger, and are failing to invest in AV technology; for example, the US Department of Transportation does not have a central office devoted to consideration of AVs. That said, it may also be feasible for municipalities which make minimal investments in non-AV or early AV vehicle infrastructure to leapfrog ahead by skipping interim infrastructure technologies and developments in favour of newer technology (Article #9).

Logical, if speculative, early recommendations for infrastructure investment include embedded sensors to provide information such as precise positioning and speed limits; traffic lights capable of transmitting information digitally (as well as visually); AV-only lanes; and communication networks facilitating Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication (Articles #19, #24, #37, #38). The UK is currently completing an 18-month trial of under-road power sources for electric vehicles (EVs), with the intention of enabling vehicles to travel long distances without stopping to charge or refuel (Article #15). Of course, the feasibility of implementing such a system on a large scale is hampered by a chicken-and-egg situation, with vehicle manufacturers unlikely to invest in appropriate vehicle technology prior to construction of the necessary roadways, and vice-versa (Article #16). Interestingly, however, the entity behind the pilot project (Highways England) has suggested that regularly spaced magnetic induction loops embedded within the road could be used by AVs to identify and maintain lane positioning in the face of inclement weather or other obstructive conditions (Article #16).

For further discussion of infrastructure related to information and communication technology, refer to Section 4.3. For discussion of planning issues related to public transit, parking, streets, and urban density, refer to Section 5.

4.3 Information and Communication Technology

The extent and magnitude of Information and Communication Technology (ICT) needs for AVs are not yet clear, and will be governed in large part by the degree to which AVs are designed to be standalone entities capable of operation without external inputs. Various technological paths are plausible: some scenarios describe extensive communication between vehicles and infrastructure, while others describe independent vehicles which rely more heavily on internal sensors, though it should be noted that all scenarios are viewed as relying upon extremely detailed, and possibly three-dimensional, maps (Article #22). Regardless, it is nearly certain that AVs will eventually communicate to some degree with one another and/or infrastructure and/or other devices. Even otherwise-standalone AVs, for example, would benefit greatly from the ability to update software and mapping remotely via cell towers or other wireless infrastructure, even if they do not require a constant network connection (Articles #5, #9). Moreover, AVs largely capable of performing as standalone AVs but equipped to operate as CVs would provide redundancy, and reduce the cost and complexity of developing truly standalone AVs, while minimizing the costs associated with constructing connected infrastructure (Article #7).

Various technologies have been proposed to facilitate communication between vehicles (V2V), between vehicles and infrastructure (V2I), between vehicles and mobile devices (V2D), and between vehicles and retail, such as advertising or commercial vendors (V2R), more generally described as V2X. The most commonly discussed technologies include mobile (i.e., radio tower) connections, wifi, and Dedicated Short-Range Communication (DSRC), which uses radio waves operating at 5.9 GHz. To date, the US federal government has supported the development of DSRC, reserving the 5.9 GHz spectrum exclusively for V2V and V2I applications, though there has been some debate more recently about whether the spectrum should be opened up for uses beyond transportation (Article #9). According to Article #7, DSRC is the only short-range wireless communication to offer all of the following features:

- Fast network acquisition;
- Low latency;
- High reliability;
- Priority for safety applications;
- Interoperability;
- Security and privacy.

DSRC is also capable of communicating with toll systems, navigation systems, and traffic management applications (Article #20).

As with every other aspect of AV technology, the estimated rate of ICT adoption in vehicles is speculative. What is clear is that V2V will require critical mass to be most effective; this may require regulation (Article #7). ABI Research estimates that over 400 million vehicles will be equipped with V2I and V2R equipment by 2030 (Article #42). The availability of infotainment systems may increase the demand for AVs (Article #9), and at least some form of connected car technology is expected to be present in more than 60% of cars [assumed car models, not existing vehicles] worldwide by 2017 (Article #20).

Of course, with any eventual ICT developed for AVs, there will be a need to update distracted driver laws, develop and maintain standards for communication platforms, and manage an extensive array of issues related to data security, ownership, and privacy (Article #9). Refer to Sections 0 and 0 for further discussion of AV security and data privacy.

5 Urban and Transportation Planning

5.1 Parking, Density, and Streets

The average car today sits idle about 95% of the time (Article #36), and parking space is near-universally expected to be a chief casualty of the eventual switch to fully autonomous vehicles (Articles #2, #5, #8, #9, #13, #14, #24, #26, #27, #36, #51, #54AB, #56AB, #58AB). Much of this sentiment is attributable to the prediction that every AV entering operation will replace more than one non-AV, leading to an eventual decline in the number of vehicles registered at a given time (Articles #2, #5, #8, #27, #58AB). (Refer to Section 11.2 for further discussion of possible AV ownership scenarios.) Other studies point to the opportunity to make better use of parking space by returning vehicles to remote locations after dropping passengers at their destination, reducing demand to have high parking capacity in both central business districts (CBDs) and suburban/residential neighbourhoods (Articles # 2, #58AB). Still others estimate that parking spaces could become as much as 15% smaller as passengers will not require access to and from parked AVs (Article #13, #24). Estimates for the current number of parking spots per vehicle in the United States range from two to eight, with a guess that Canada may have similar numbers (Articles #5, #24), equivalent to roughly 5.7 to 7.8 billion square metres of space devoted to parking in the US today (Articles #13, #24, #51). Article #9 quotes Shoup (2005), estimating that 31% of space in the CBDs of 41 major cities is devoted to parking.

Reduced demand for parking will encourage densification of CBDs (Articles #5, #9, #14); densification may also occur around highways and major arterials due to increased capacity (Article #14). A simulation study by the OECD testing various shared AV scenarios in Lisbon, Portugal (with at least half of AVs shared rather than privately owned) found that no roadside parking would be necessary to accommodate AVs, freeing up as much as 20% of space currently devoted to vehicles (Article #54AB). The study further estimated that up to 80% of off-street parking could also be eliminated (Article #54AB). However, densification due to reduced parking and increased road capacity will place additional infrastructure demands on municipalities (Article #14), and parking lots may come to require charging ports for electric vehicles (EVs) (Article #5). Moreover, some studies predict increased suburban sprawl around city peripheries due to decreased travel time and cost (Articles #5, #6, #9, #14, #24). Land values may also be affected by increased tolerance of longer commutes (Article #5).

Studies predicting increased CBD densification and/or suburban sprawl do so on an assumption of increased road capacity, and decreased travel time and cost. From where do these assumptions stem? Some articles cite increased numbers of lanes in existing rights of way due to narrower lanes (or abolishment of lanes altogether) owing to better vehicle control (Articles #5, #14), some cite increased utilization of vehicles through ride-sharing (Articles #2, #5, #8, #11, #39, #50), and some cite better roadway throughput per lane (Article #24). (Refer to Section 0 for discussion of AV ownership and operation cost.)

Increased road capacity may also make it feasible for municipalities to “reclaim” urban road and parking space for parks, restaurants, and other functions (Article #27). Pressure to add lanes and to build new roads and highways will decrease or disappear if road capacity increases sufficiently (Article #14).

5.2 Active Transportation

Active transportation tends not to be covered meaningfully in AV literature. Walkability of streets is expected to improve as streets widen, vehicle exhaust dissipates (following a shift towards EVs), and CBD density increases (Articles #27, 36). Bike paths will become more common; electric bicycles may become even more popular than AVs (Article #27). Beyond this, few details relevant to policy-makers are discussed.

5.3 Public Transit

Virtually all AV literature broaching the topic of public transit agrees that a fundamental shift is coming in what public transit means and how best it can be provided (Article #5, #6, #9, #22, #26, #27, #29, #36, #50). However, while some reports argue that heavy rail in particular will become increasingly important (Articles #5, #27), others advocate for new models and technologies (Articles #26, #29, #50), and still others foresee a deterioration of public support and, accordingly, deterioration of public funding for mass transit systems (Articles #6, #9, #22, #24). Some reports also predict a more nuanced scenario featuring of all of the above (Article #5, #27).

Obvious synergies exist between public transit and AVs. Park-and-ride needs may decrease, and the “last-mile” problem may cease to be an issue (Articles #5, #26). Given that staffing costs tend to represent the largest portion of bus and minibus costs for transit agencies, AVs may offer a much cheaper means of providing paratransit (and typical bus transit) services, thus facilitating improved paratransit and increased social welfare (refer to Section 0 for further discussion of mobility and equity benefits of AVs) (Articles #9, #27). Indeed, AVs may even replace the need for bus feeder lines (Article #27). In South Korea, the Korea Advanced Institute of Science and Technology (KAIST) developed an Online Electric Vehicle (OLEV), a bus which charges while stationary and driving via induction loops embedded under 5-15% of the road surface (Article #29). The system enables vehicles to drive continuously without stopping to recharge. The benefits of having such a bus operate without a driver are self-evident.

Other studies envision more radical changes in the provision of transit services. Article #26, “Energy and Autonomous Urban Land Vehicles”, proposes a fleet of transit agency-operated personal rapid transit vehicles, operating in physically separated AV guideway lanes. Guideways could be covered to protect against inclement weather, and even pressurized in the direction of travel to minimize air resistance. Guideways would always operate at design speed, preventing oversaturation at the source. Alternatively, transit agencies could allow privately owned AVs to use the transit guideways provided that vehicles had passed strict tests confirming successful operation under control of the guideway. Individuals using privately owned AVs could thus address “last-mile” portions of each trip. In this situation, transit may come to resemble a fleet of AV taxis more than traditional mass transit.

Given that transit capital projects take years or decades to plan and execute, and continue to operate for decades, AVs are sure to be deployed within the lifespan of transit projects currently under development (Article #5). Moreover, 90% of people in North America are expected to live in urban areas by 2050, creating a desperate need to reduce road crowding; improved public transit is one of the most viable options for doing so. Generation Y (also known as millennials) have already shown an openness towards car- and ride-sharing, arguably valuing vehicle access over vehicle ownership (Articles #5, #38, #50). With drastic changes to infrastructure, services, and business models of various transportation modes on the horizon, governments may be unable to take sole responsibility for building future transportation systems, potentially leading to increased public-private cooperation and convergence (Article #50).

It is worth noting that autonomous operation of rail transit has been available since at least the 1980s. Both the Skytrain in Vancouver and Lille, France's autonomous commuter rail lines have had an average of 2.8 incidents, 0.0 deaths, and 0.0 injuries per million vehicle revenue km since inception (1986 and 1983, respectively), which is considerably safer than traditional LRT or heavy rail systems (Article #26).

5.4 Auto

As introduced in Section 5.1, many studies predict that AVs will effect an eventual decline in the number of vehicles registered at a given time (Articles #2, #5, #8, #27, #56AB, #58AB), with estimates varying from 2 to 13 non-AVs replaced per shared AV deployed (Articles #2, #5 #27, #56AB, #58AB). Many of the same studies (and others) also predict an accompanying increase in the total number of Vehicle Kilometres Traveled (VKTs). While this may seem counter-intuitive at first glance, there are a number of explanations for such predictions: some studies justify this claim by explaining that unoccupied AVs will drive around in search of customers and parking spaces (Articles #2, #6, #58AB), others describe decreased cost and increased productivity as contributing factors (Articles #1, #5, #9), and others point out that fully autonomous vehicles could be operated by children, seniors, disabled people, and other individuals who are unable or choose not to drive (Articles #5, #9, #18, #47). One estimate for the increase in magnitude of VKTs ranged from 10-26%, depending on the penetration rate of AVs, with roughly 7-11% of VKTs being completed by unoccupied AVs (simulated for a hypothetical US city of 60,000 – 120,000 trips served per day) (Article #2). For perspective, light-duty vehicles in Canada drove roughly 303 billion VKTs in 2009; even assuming all travel occurred at near-free-flow speeds, this represented about 5 billion hours of driving time for drivers (passengers are assumed to be productive or engaged in leisure activities) (Article #5).

AVs may reduce congestion by increasing lane throughput by a factor of 2 or 3, according to Shladover (Article #24). Alternatively, if capacity gains are not equal across highways, arterials, and local roads, new sources of congestion may arise (Article #14). Average vehicle occupancy may fall below 1.0 (Article #24). Vehicles manufactured for shared or public use may be designed to be utilitarian, "vandal-proof" cars, with interiors more closely matching that of current buses than privately owned vehicles (Article #38). Little consensus regarding implications for auto use exists beyond the assumption of increased VKTs.

For discussion of vehicle ownership and use models, refer to Section 11.2. For discussion of economic implications of AVs (including congestion and related issues), refer to Section 0.

5.5 Freight

The freight industry might be one of the first beneficiaries of full AV technology, with commercial release sometime around 2040 (Articles #13, #30). Before 2040, however, freight vehicles are likely to be platooned, reducing fuel consumption (Articles #1, #2, #19). In such cases, a convoy of freight vehicles would closely follow one another (spaced roughly 4m apart), with the lead vehicle operated by a human driver. Freight vehicles capable of operating autonomously on highways under certain conditions are already be tested by Daimler in the United States (Article #32). Eventually, platooning freight vehicles and incorporating autonomous technology may create a need for thicker pavements and other types of new infrastructure (Article #1). Currently, 80%+ of freight traffic (by weight) is moved by road (Article #20), with roughly three million heavy-duty vehicles accounting for 70% (9.2 billion tons) of US freight annually (Article #31).

Eventual replacement of human drivers with freight AVs has the potential to increase vehicle use efficiency 43% from 14 hours per day (the current daily limit for a human driver) to 20 hours per day (Article #5), with the remaining time being used to load and unload the vehicle and refuel. Current tests of under-road power sources for EVs in the UK, intended to enable vehicles to travel long distances without stopping to charge or refuel, are initially focusing on freight/commercial operators as they are considered particularly applicable for preliminary trials of the technology (Articles #15, #16).

Much of the literature addressing freight with respect to AV technology focuses on job loss and cost savings; refer to Section 7.3 for discussion of economic implications of freight AV technology.

6 Mobility, Accessibility, and Equity

Many articles identify improved mobility as an inevitable outcome of widespread AV adoption (Articles #5, #9, #13, #14, #18, #23, #26, #38, #47). New mobility business models, such as pay-per-use car-sharing, peer-to-peer car rentals, and AV taxis are also anticipated, with new entrants to the automotive industry (such as Google and Uber) seen as being likely to try to secure market share by offering alternatives to classic car ownership (Article #13). (Refer to Section 11.2 for further discussion of possible AV ownership and use models.)

Fully autonomous vehicles could be operated by children, seniors, disabled people, and other individuals who are unable or choose not to drive, providing significantly improved mobility and accessibility (social inclusion) for those demographics (Articles #5, #9, #18, #26, #38, #47). The number of people benefitting in this regard is substantial; Article #5 estimates that disabled people make up 14% of the population, and that 25% of people over 65 do not possess a driver's license. Increased accessibility will benefit not only directly affected individuals, but also the public as a whole (Article #9). As discussed in Section 5.3, AVs may offer a much cheaper means of providing paratransit (and typical bus transit) services, thus facilitating improved paratransit and increased social welfare (Articles #9, #27). Traditional school buses may become obsolete (Article #26).

Not all reports predict unambiguous windfalls for accessibility and mobility due to commercial AV release. Depending on privacy legislation and regulations, individuals unable to manually operate a vehicle may find they must choose between taking a vehicle capable of tracking their movements, or potentially even controlling their movements, versus continuing to take a public bus; some individuals have stated a preference for the latter. There is also concern that use of AVs would enable repressive governments or governments with strong central power to control where and when its citizens travel, particularly individuals with reduced personal mobility (Article #47). For example, under the pretence of improving traffic flow, a government could prevent retirees from traveling during rush hour. In response to such concerns, Article #48 ("The Costs of Self-Driving Cars: Reconciling Freedom and Privacy with Tort Liability in Autonomous Vehicle Regulation") proposes that regulators only allow AVs to infringe on the privacy and freedoms of citizens when doing so will move liability from individuals to AV manufacturers, and when the social gains outweigh the social costs.

Finally, it will be important to consider how the introduction of AVs may disparately affect individuals, industries, and other entities. Regulation could be constructed to ensure that some players are not provided anti-competitive or otherwise unfair advantages over others (Article #38). As part of this process, authorities should consider the life-cycle costs and implications of AVs, including the effects of fuel extraction, transmission, emissions, and other externalities which may not be immediately obvious (Article #38).

7 Economic Implications

7.1 General Economy

The economic implications of AVs are many and varied, and tend to be high-level and speculative. There is a general consensus that countries will save tens or hundreds of billions annually following mass adoption of fully autonomous vehicles. Current costs of collisions and congestion are typically used as a starting point for estimating potential savings. For example, according to Article #5, the total direct and indirect cost to the US economy of US road collisions in 2010 was estimated at $871 billion USD ($1.15 trillion CAD), or 6% of US GDP, with direct costs of $277 billion ($367 billion CAD). In Canada, Transport Canada estimated the 2007 costs at $62 billion, or 4.9% of GDP (Article #5).

Article #2 describes a report by Shrank and Lomax (2011) which estimates 8.4 billion wasted hours and $199 billion USD due to congestion alone in the United States by 2020. The costs of congestion, collisions, and environmental damage caused by traffic in Europe in 2012 was estimated at €373 billion ($551 billion CAD) (Article #10), and Article #26 cites M. Delucchi and D. McCubbin ("External costs of transport in the U.S.") as describing the annual externalized cost of driving (including collisions, pollution, congestion, delays, climate change, and noise) as $820 billion USD ($1.09 trillion CAD) in the US.

Estimates of annual savings stemming from widespread AV adoption in the United States range from $450 billion USD ($595 billion CAD as of the time of writing) (Article #1), to $1.3 trillion ($1.72 trillion CAD) (Article #30), to $1.9 trillion ($2.52 trillion CAD) (Article #19). Such values represent sum totals of savings from various corners of the economy: Morgan Stanley's $1.3 trillion savings estimate, for instance, was broken down into $158 billion in fuel savings; a further $11 billion in fuel savings due to congestion avoidance; $488 billion from collision avoidance; $507 billion in productivity gains; and a further $138 billion in productivity gains due to congestion avoidance (all figures USD) (Article #30). In the UK, overall social and economic benefits are estimated to hit £51 billion ($103 billion CAD) in 2030, and £121 billion ($243 billion CAD) annually in 2040 (Article #49). In Canada, the Conference Board of Canada estimated the potential benefit to Canada's economy at $65 billion (in 2013 CAD), broken down into $37.4 billion in collision avoidance; $20 billion in time (productivity) savings; $2.6 billion in fuel savings; and $5 billion in congestion avoidance (Article #5). Relocating parking spots from the CBD to less coveted locations could save $2,000 to $3,000 USD ($2,650 to $4,000 CAD) annually per parking spot (Article #2).

Savings beyond those directly associated with driving will likely appear, such as reduced investment in parking lots and reduced cost of power generation (Articles #5, #10, #26). The Rocky Mountain Institute in the US estimates that oil, coal, and nuclear energy production could cease by 2050 without the need for new inventions, laws, taxes, or subsidies, representing a potential cost savings of $5 trillion USD ($6.63 trillion CAD; estimate assumed to be annual) (Article #26). Lighter materials used for AVs could reduce the cost of vehicle construction, as well as environmental damage (Article #26).

Finally, AV-related economic impacts are expected to extend beyond simple cost mitigation. For better or worse, land values may fluctuate as CBDs become more dense, and suburban sprawl is encouraged by easier and cheaper commuting (Article #5). Annual global digital media revenues could grow €5 billion ($7.4 billion CAD) for every additional minute consumers spend connected to the internet while in cars (Article #13). Generation Y (millennials) has shown itself to be slower to seek driver’s licenses, slower to purchase vehicles, and more likely to participate in the sharing economy, reducing VKTs and arguably boosting GDP accordingly (Article #5). It should be noted that induced negative externalities (such as increased VKT due to cheaper and easier travel) may also result from AV commercial success, though total gains are expected to outweigh total costs (Article #9).

7.2 Individual Citizens

The degree to which benefits accrue to the public as a whole rather than individuals will shape demand for AV technology (Article #9). As with most other predictions regarding the impacts of AVs, anticipated cost implications for individuals vary widely and should be taken with a grain of salt. Transportation as a whole represented the second largest expenditure of Canadian households in 2012, at an average of $11,216 (20% of total expenditures) per household, second only to the cost of shelter (Article #5). Without considering AV-related freight cost savings (which will ultimately be passed on to consumers), Article #5 estimates that once the AV market has matured, average household vehicle expenditures will drop by $1,600 per year per household (assuming that half of households switch to using car-sharing services). When fuel savings and reduced insurance costs are considered, the average Canadian household will save $2,700 per year (in 2012 CAD), even after accounting for a 10% cost increase in vehicle purchase costs and 10% increase in VKTs (Article #5). The Boston Consulting Group estimates that AV features could bring ownership costs down by $2,300 USD ($3,000 CAD) or more over four years, when including fuel and insurance savings (Article #8). In contrast, Article #6 suggests that even once the market has matured, AVs are likely to increase the annualized cost of vehicle ownership by $1,000 to $3,000 (assumed to be AUD), or $920 to $2,760 CAD. Even with 10% savings on fuel and 30% savings on insurance, the resulting savings of $500 (assumed AUD) would not offset the incremental costs (Article #6).

Costs to individuals looking to purchase AVs before the market has matured are expected to pay substantially more. The current cost of the LiDAR equipment (or "light radar", which uses lasers instead of sound to physically map an area) used by Google is roughly $70,000 USD ($93,000 CAD) per vehicle, without taking into consideration costs of any other sensors or the vehicle itself (Article #7). However, the incremental cost of AVs is expected to drop to $7,000 to $10,000 USD ($9,300 to $13,300 CAD) by 2025 (Article #8, #20, #30), and $3,000 USD ($4,000 CAD) by 2035 (Article #20). Interestingly, in a survey of 1,510 American consumers, while more than half of respondents stated that they would be willing to pay more for an AV than an equivalent non-AV counterpart, a third to a half of those willing to pay more were unwilling to pay a premium of $1,000 (USD) or more (Article #8).

Cost savings could also appear in other forms. Time saved per day could be as high as 1 billion man-hours globally, twice the time required to build the pyramid of Giza (Article #13). Article #2 describes a 2013 study by Shaheen and Cohen which found that 27% of car-sharing members reduced their VKTs, while 25% sold a vehicle as a result of joining the car-share service and 25% forwent purchase of a new vehicle. According to a report by the Victoria Transport Policy Institute in Australia, shared AV trips are expected to cost $0.60 to $1.00 per vehicle-mile, with taxi costs closer to $2.00 to $3.00 per vehicle-mile (all figures assumed AUD), or $0.34 to $0.56 (shared AV) and $1.13 to $1.75 (taxi) CAD per vehicle-kilometre (Article #6). General Motors executive Larry Burns, on the other hand, estimates that switching from traditional private car ownership to shared AV use could cut costs from $0.70/mile to $0.15/mile ($0.58/km to $0.13/km CAD) (Article #37).

A study of parking costs at 23 residential developments in Seattle, WA, found that providing abundant "free" parking leads to more expensive rental prices, particularly for individuals with lower incomes (Article #28). An average of 37% of parking spaces were found to be unoccupied overnight (considered the busiest time of day for residential parking). Landlords' life-cycle losses attributable to provision of parking equated to roughly 15% of total rental fees (an average of $246 USD/month), affecting all tenants (not just those making use of parking) (Article #28). Adoption of AVs may thus provide substantial savings for individuals simply through reducing demand for (and construction of) parking facilities.

7.3 Industry

Wide swaths of industry will be affected directly or indirectly by the arrival of AVs. Reports generally agree that there will be both winners and losers. Identification of affected industries and jobs is common in relevant literature; comprehensive, quantitative predictions of impacts to industries or jobs is relatively rare. For example, in Canada, AVs are expected to directly displace transport, truck, and courier drivers (currently 560,000, or 1.5% of the Canadian workforce); taxi/limo drivers (50,000); bus and tow truck drivers; driving instructors; parking attendants; mechanics and autobody shop workers; insurance providers; traffic police; doctors and health staff; and lawyers and legal staff (Article #5). In the United States, there are 240,000 taxi drivers and 1.6 million truck drivers (Article #1), and the automotive industry employs a further 1.7 million, providing $500 billion USD ($664 billion CAD) in annual compensation, which accounts for roughly 3% of US GDP (Article #7). Other articles identify widespread job losses in the taxi, freight, bus, insurance, and other industries as being inevitable (Articles #9, #36).

On the other hand, the economic boost from commercialisation of AVs is expected to be substantial. AV sales could represent 12-13% of the global auto market by 2025, commanding a $42 billion USD ($56 billion CAD) cost premium beyond the base cost of equivalent non-AVs in 2025, and a $77 billion USD ($102 billion CAD) cost premium by 2035 (Article #8). Article #37 ("Realising the Benefits of Autonomous Vehicles in Australia") estimates that the global AV market will be $87 billion USD ($116 billion CAD) by 2020. Increased productivity in the $700 billion USD freight industry in the United States (Article #31) is expected to fall in the range of $100 billion to $300 billion USD ($133 to $400 billion CAD) annually by 2025 (Articles #19, #30); General Motors executive Larry Burns anticipates freight industry costs to drop by roughly 40% (Article #37). At the same time, the American Transportation Research Institute reported in 2014 that fewer individuals are seeking employment as truckers, with a predicted shortfall of 240,000 truck drivers by 2022 (Article #32). Rather than hiring more truckers, concludes Article #32, the better strategy is to phase in AVs to fill the shortage.

Perhaps the industry most discussed with respect to AVs (beyond the automotive manufacturing industry) is insurance. The car insurance industry in the United States is valued at roughly $180 billion annually ($240 billion CAD) (Article #36), and universal assumptions of improved safety due to AVs have led to speculation of collapse or necessary transformation for auto insurance providers (Articles #1, #5, #6, #8, #9, #13, #20, #22, #30, #37). Common ideas include a transfer of liability from individuals to auto manufacturers (Articles #13, #22, #37), including speculation of self-insurance by large manufacturers, and usage-based insurance rates (Article #20). Eventual outcomes are not considered at all clear.

A large and lucrative AV-data industry may also develop. The “big data” market is expected to hit nearly $17 billion USD ($23 billion CAD) by 2015, up from just over $3 billion USD ($4 billion CAD) in 2010, predicts market intelligence provider IDC (Article #7). Capturing, logging, and transmitting data related to V2X communication, as well as transmission of ever-increasing volumes of media will create new opportunities for auto manufacturers, mobile providers, software firms, and others (Articles #37, #46). In early 2015, General Motors stated an aim to generate $350 million USD ($465 million CAD) in revenue over three years as a result of the data connections being installed in its vehicles (Article #46). AlixPartners, a consulting firm, estimates that CVs will generate global revenues of $40 billion USD ($53 billion CAD) annually by 2018, up from $16 billion USD ($21 billion CAD) in 2013 (Article #46).

Other industries might enjoy significant growth due to new revenue streams. There will be new opportunities to deliver media and advertising, especially video, though this may come at the expense of radio and music. CVs could represent a $100 billion USD ($133 billion CAD) market to telecommunication firms, with low churn rates associated with average vehicle lifespans (Article #30). Manufacturers of semiconductors and software developers will find their products are increasingly relevant to auto manufacturers (Article #30). Financial services, energy, and the technology industry generally will also be affected (Article #37). The AV market could create a total of 320,000 jobs in the UK by 2030, of which 25,000 would be in manufacturing (Article #49).

Article #5 provides the following recommendations related to industry in Canada: government should measure the impacts of AVs on Canadian businesses, and encourage a Canadian ecosystem in order to capture a share of the market for AV software, parts, etc.

7.4 Government

All levels of government face myriad economic challenges and opportunities due to the advent of AVs. This section considers only direct implications – such as loss of fuel-tax revenue due to reduced fuel consumption – and ignores implications associated with debt issuance, equity ownership, or erosion and expansion of tax bases due to job churn in local industry.

Opinions differ on whether AVs are likely to strip government budgets of much-needed revenue. Some studies point out that fees for parking, towing vehicles, and distributing tickets for violations of by-laws (running red lights, speeding, parking violations, drinking and driving, etc.) contribute to a significant portion of municipal revenue (Articles #11, #36). Los Angeles, CA, for example, distributed $161 million USD ($215 million CAD) in tickets for parking violations in 2014 alone, and cities in California bring in an average of $40 million USD ($53 million CAD) in towing fees (Article #36). A drop in parking revenue in Washington, D.C. from $90.6 million USD in 2012 to $84.5 million USD in 2013 was attributed to the introduction of smartphone apps enabling customers to top-up parking meters remotely (Article #36). Article 36 (“Local government 2035: Strategic trends and implications of new technologies”) thus argues that once AVs become widespread, these rich sources of government revenue will dry up, leaving governments scrounging.

However, others argue that City revenues are only minimally affected by driving infractions, with only just over 1% of City budgets in Phoenix, AZ and Mesa, AZ coming from such source (Article #11). Further, cities will benefit from cost savings associated with reduced by-law violations (e.g., reduced policing, court costs, etc.). The City of Toronto, ON, recently cancelled 880,000 outstanding low-priority parking tickets issued since 2002 to clear Court Services' backlog (Article #72). While withdrawing these tickets represented roughly $20 million in lost revenue (roughly $23 per ticket), the director of Court Services for Toronto estimated that the cost to process these tickets through the court system would be an average of $26 per ticket, and would thus cost the City more to enforce the tickets than to cancel them (Article #72). Cities also stand to save money from reduced infrastructure spending, if construction or expansion of roads and highways can be supplanted by introduction of vehicles capable of operating at higher capacity; the cost of construction for a new four-lane highway in an urban area in the US in 2012 was estimated to cost $8-12 million USD per mile ($7-10 million CAD per km) (Article #7). Hospital costs attributed to vehicle collisions in the United States are estimated at roughly 1.5% of total hospital/physician costs (Article #30).

Whether from necessity or opportunity, governments will look to profit where possible from new revenue streams offered by AVs. Sensors installed in AVs are likely to facilitate collection of vast quantities of previously inaccessible data (refer to Section 0 for further discussion of AV data and privacy literature). This data could be used to inform dynamic pricing for congestion fees, VKTs, parking, and electricity, potentially replacing existing fuel taxes or other revenue sources (Articles #1, #26). However, such new taxes are often difficult to implement in the face of public and political pressure (Article #36).

Governments around the world have also started committing funding to support local growth and development of AVs. The UK has committed £500 ($1 billion CAD) million over the next five years to support growth in the automotive sector, specifically supporting low-emissions vehicles (Article #15). Japan has committed to providing $83 million USD ($111 million CAD) in funding for road tests of AVs, in cooperation with Toyota, Honda, and Nissan.

8 Energy and Environmental Implications

An assumption of improved energy efficiency per VKT following introduction of AVs is prevalent in the literature. Generally, per capita fuel use and, consequently, emissions, are expected to drop, and there is a strong sense that AVs will ultimately be powered by electricity, though this may not be true exclusively or in the short-term.

Fuel savings per VKT are anticipated due to “right-sizing” of vehicles when car-sharing or using autonomous taxis, and lighter vehicles generally (Articles #9, #14, #26, #39, #50); reduced reliance on private vehicles through increased car-sharing and/or other modes of transportation (Articles #8, #27, #36, #39); smoother acceleration and deceleration, less time spent searching for parking, and reduced congestion and travel time (Articles #1, #2, #7, #8, #30, #45, #56AB); platooning (resulting in drafting), particularly of freight vehicles (Articles #1, #2, #7, #9, #19, #39); alternative fuels, chief among them electricity (Articles #9, #17, #26, #30, #38, #39); and ongoing improved vehicle design (not necessarily related to autonomous features) (Articles #2, #5, #17, #26, #38, #39, #54AB, #56AB).

Vehicle emissions are expected to drop per VKT as a result of reduced cold starts of vehicles (Article #2); lighter vehicles (Article #2); increased fuel efficiency and reduced emissions intensity of electricity, guided by tightened fuel efficiency standards (Articles #10, #17, #26, #36, #39, #50, #56AB); and reduced fuel use, as described above. *Local* emissions are also anticipated to drop due to use of electric vehicles (electricity generation-related emissions are produced remotely) (Articles #5, #26, #39). However, it is widely speculated that introduction of AVs will cause total/per capita VKTs to rise due to easier, cheaper, more accessible car use (Articles #1, #2, #5, #6, #9, #18, #47, #58AB). It is unclear how total fuel use and emissions will change as total VKTs rise, and it is conceivable that total fuel use and emissions will actually rise appreciably despite per VKT reductions (Articles #1, #6).

Many articles describe AVs as having an obvious synergy with electric propulsion (Articles #5, #14, #16, #26, #39). It may be that AVs are actually more likely to mature in the short-to-medium term than electric vehicles (EVs), as mature battery technology fit for mainstream production and consumption continues to prove elusive (Article #30). Widespread use of EVs would require upgraded electricity generation and distribution infrastructure to accommodate increased electrical demand, and possibly vehicle battery-swap stations or similar (Article #5). In urban areas or on major highways, battery swap stations may be supplanted by under-road power sources. The UK is testing under-road power sources on major highways for EVs with the intention of wirelessly power vehicles, enabling long-distance travel using electricity as the fuel; this would require massive infrastructure upgrades and would likely be phased in over many years (Articles #15, #16). The Korea Advanced Institute of Science and Technology (KAIST) developed an electric bus which charges while stationary and driving via induction loops embedded under 5-15% of the road surface (Article #29). The system enables vehicles to drive continuously without stopping to recharge. Extensive displacement of internal combustion engine technology with electric technology is likely to reduce oil use and dependence, though additional electricity demand may lead to increased generation via natural gas or other hydrocarbons (Article #5). Current annual sales of gasoline in Canada top 41 billion litres, of which 85% (35 billion litres) is estimated to be spent on motor vehicle transportation (Article #5).

Article #39 ("Autonomous Taxis Could Greatly Reduce Greenhouse-Gas Emissions of US Light-Duty Vehicles") outlines a variety of vehicle propulsion systems which could be used by AVs (including improved internal combustion engines, hybrid-electric propulsion, hydrogen fuel cell propulsion, and battery-electric propulsion), as well as the relative efficiencies of the different fuel sources. The analysis includes quantitative estimates of emissions and energy use per VKT under different scenarios (car-sharing, ride-sharing, platooned vehicles, etc.). Notably, the article also describes the US Energy Information Administration prediction that greenhouse-gas intensity will decrease by 3.8% for gasoline and 8.5% for electricity between 2014 and 2030 due to increasing availability of renewable sources of energy (Article #39).

9 Security

For the sake of this literature review, a vehicle's "security" is considered to be its ability to resist theft, external tampering, and unwanted remote access to its control systems or data. Protection of privacy and use of personal data for commercial purposes are discussed in Section 0 ("Data and Privacy").

Security is widely recognized as a critical issue for AV technology, and like most other aspects of the technology, its future is highly uncertain. Several potential risks and challenges are cited: possible hazard to personal safety of occupants and other road users (Articles #6, #20); difficulty predicting threats (Articles # 20); limited external connectivity, making updates slow to be received (Articles #20, #43, #44); need to standardize systems, and managing components and systems from different suppliers (Articles #18, #20, #44); challenge of accommodating real-time operation (Articles #20, #42); difficulty of securing important operational data sent and received by CVs (Article #38, #42); and eventual limitations to computational capability, given the relatively long life cycle of vehicles relative to most computers (Article #20). There is widespread agreement that security will be a challenge and must be planned for (Articles #1, #5, #6, #7, #18, #20, #23, #37, #38, #42, #43, #44).

A number of CV and semi-autonomous vehicle security failures have been documented to date. Several researchers have demonstrated the ability to hack into vehicle control systems, either by local or wireless connection, such as a remote attack on a Jeep (Chrysler) using its mobile connection and its infotainment system (Articles #42, #43). Similar attacks have been documented targeting a Tesla, a Toyota Prius, and a Ford Escape (Article #20). Such attacks have shown that virtually all components of a vehicle's control system can be put at risk without appropriate security measures – the scientists remotely attacking the Jeep were able to control its air-conditioning, radio, windshield wipers, display, steering, transmission, and brakes, while disabling the ability of the driver to control the affected components (Article #43). As a result, Chrysler was obliged to recall 1.4 million vehicles using its Uconnect infotainment system in order to update vehicle software to prevent this sort of attack (Article #43). According to Article #20 ("Intelligent Transportation Systems Report for Mobile"), other hackable features in modern cars include self-parking, lane control, cruise control, collision avoidance, remote keyless entry, antitheft, Bluetooth, wifi, and cellular connections.

Few regulations exist mandating security features or targets for vehicles. Foreseeing a need to vastly improve and standardize security features when AVs are commercialized, numerous articles recommend security standards and strategies. These recommendations range from high-level oversight (e.g., produce standards for security, acknowledge safety issues, and work with security researchers, Articles #1, #18, #44) to technology-specific best practice (e.g., use encryption, digital certificates, tamper-proof hardware, real-time constraints, vehicle authentication, Articles #7, #42) to detailed, AV specific suggestions (e.g., use traceable hardware and software supply chains, use adversarial resilience testing, collect and retain data to assist NHTSA investigations, and physically segregate critical systems from non-critical systems, Article #44).

10 Data and Privacy

Management of and access to personal data generated through use of AVs have become major talking points for many articles considering the future of such vehicles. There is an expectation that data pertaining to origins and destinations, time of day, speed, VKT, choice of music, communications, etc. will be generated in volumes far greater and on a much larger scale than at present. While some articles point to the plethora of uses and benefits of such a rich, comprehensive data source, others caution that security will be difficult, and that there will be a temptation for corporations, governments and malicious third parties to use the data in legally and ethically questionable ways (Articles #1, #7, #9, #10, #12, #22, #46, #47, #48).

Corporations (particularly AV manufacturers, software providers, and telecoms) will look to use additional data streams to improve their products and as new sources of revenue (Articles #13, #30, #37, #46). AlixPartners, a consulting firm, estimates that CVs will generate global revenues of $40 billion USD ($53 billion CAD) annually by 2018 (Article #46). CVs could be used to pay for tolls or fuel directly (Article #37); annual global digital media revenues could grow €5 billion ($7.4 billion CAD) for every additional minute consumers spend connected to the internet while in cars (Article #13). Some corporations will treat data as proprietary, refusing to share or minimizing other corporations' access to data sources where possible (Article #46). This competition for data has led to speculation that governments will find it difficult to pry data generated by AVs out of the hands of the private sector (Article #36).

However, municipalities and other levels of government also have much to gain from using AV-related data sources to improve services. AV-related data can be used to inform traffic operations and management, safety applications, performance analysis, travel demand analysis, traveler information systems, new services, asset management, and for other societal benefits (Articles #12, #50). Data could also be used to facilitate a switch from fuel taxes to dynamic pricing for congestion pricing, a VKT tax, parking fees, electricity prices, or similar (Articles #1, #26). Many governments already have in place regulations and policy related to vehicle data. In the United States, 46 states have legislation requiring notification and action if personal data is lost or disclosed during a data breach, and several states (such as Massachusetts) follow their residents' personal information to protect its use, wherever the data is moved geographically (Article #47). California requires that the "manufacturer of the autonomous technology installed on a vehicle shall provide a written disclosure to the purchaser of an autonomous vehicle that describes what information is collected by the autonomous technology equipped on the vehicle" as per the California Vehicle Code 38750(b)(1) (West 2013) (Article #48). Many jurisdictions also require Event Data Recorders (EDRs) to provide data in the event of a collision (Article #47).

Innumerable risks will accompany an increase in data generation and communication. In a survey of 16 major car manufacturers, the staff of US Senator Edward Markey determined that most car manufacturers were unaware of or unable to report on previous hacking incidents involving their models, most do not have an effective means of securing data, and only 2 of the 16 manufacturers provided evidence of the ability to diagnose and respond to real-time invasions (Article #41). Yet, most car manufacturers today sell technology which collects and wirelessly transmits driving history data to local data centres, including data centres operated by third parties (Article #41). Even when data is secured and legally obtained, privacy will suffer, though this may come as a known and accepted trade-off for the societal benefits it can produce (Articles #10, #48). Captive audiences may be unable to avoid unwanted advertising, or be limited in terms of user decision-making and control (route choice, speed, etc.) (Article #47). Many questions related to AV data and privacy have been raised, and most do not yet have answers:

- How can we ensure data security? (Article #38)
- What is a reasonable expectation of privacy? (Article #47)
- Who *owns* the data gathered by AVs? Who has the *right to use* data gathered by AVs? What if a vehicle is leased vs. owned vs. used one time as part of a transportation service? (Article #37)
- Etc.

Though answers to such questions are few and far between, ideas for best practice management of AV-related data have been proposed based on experience with previous industries and technologies. For discussion of best practice, refer to Section 0.

11 Timeframe and Adoption Forecasts (Scenarios)

11.1 Timeframe and Transition

This section discusses the timeframe during which AVs are anticipated to develop and be made commercially available, as well as accompanying predictions of strategies to manage the lengthy transition period which is expected to precede widespread adoption of fully autonomous vehicles. For discussion of adoption forecasts and different AV use and ownership models, refer to Section 11.2. For discussion of the safety implications of time spent by drivers regaining control of an AV switching to manual control (also referred to as transition time), refer to Section 0.

According to Article #5 ("Automated Vehicles: The Coming of the Next Disruptive Technology"), the majority of technology necessary to deploy AVs has already been developed; Mercedes-Benz has test vehicles which are capable of 99% autonomous operation, and commercially available vehicles which are capable of 70% autonomous operation (Article #5). There is expected to be a gradual rollout of AV technology as it becomes mature and affordable (Article #8), and most major auto manufacturers are aiming to release largely autonomous vehicles by 2020; several have indicated they plan to release fully autonomous vehicles by 2025 (Article #5). AVs are thus a matter of *when*, not *if* (Article #5). Other studies echo the year 2020 as a likely commercialization date (Article #1, #13, #37, #52). Article #7 estimates that by 2025, there will be sufficient penetration of built-in AV features and after-market features to support AV operation. Article #8 states that, by 2017, AVs will have traffic jam autopilot and autonomous valet parking; by 2018, highway autopilot with lane changing; and by 2022, urban autopilot with lane changing will be available. The chief executive at ITS Finland predicts that AVs will account for the vast majority of road transportation by 2030 (Article #27).

In a more detailed prediction, Article #13 anticipates three distinct eras of AV deployment:

- **Era 1, "Development"** (between now until the late 2020s)**:** AVs introduced into industrial fleets, with new modes and models of mobility arising;
- **Era 2, "Adoption"** (late 2020s until ~2035)**:** Consumers begin purchasing fully autonomous vehicles, and insurers swap to insuring vehicles rather than individuals;

- **Era 3, “Primary Means of Transport”** (~2035 through 2050)**:** [In the US], AVs become the primary means of transportation, freeing up to 50 minutes per day for drivers, reducing parking space by billions of square metres, collisions are reduced by 90%, etc.

Article #49 (“Connected and Autonomous Vehicles – The UK Economic Opportunity”) estimates the likely timeframe according to standard AV level milestones:

- **Level 2 autonomy** (2018): Driver continuously monitoring driving functions and environment, but not constantly operating the vehicle;
- **Level 3 autonomy** (between 2018 and 2025): Driver must be able to regain control at all times, but is not required to constantly monitor the road;
- **Level 4 autonomy** (between 2025 and 2030): Driver not required for predefined use care;
- **Level 5 autonomy** (after 2030): Full autonomy.

Barring sudden (i.e., legislated) shifts from one technology platform to another, there is expected to be a lengthy transition period during which AVs and non-AVs are obliged to coexist. Two methods of AV introduction and commercialization are often discussed: one method, pursued primarily by existing auto manufacturers, will be to gradually and incrementally add AV features until reaching full autonomous capability; the second method, thought to be pursued primarily by technology firms such as Google, Apple, Baidu, and Uber, will be to research and refine a fully autonomous vehicle until it is ready for public release (Article #52).

Proposed strategies for adapting the existing non-AV paradigm to accommodate the introduction of AVs generally revolve around making changes to infrastructure. Given its position that the transition period is already in effect, Article #5 advises anticipating the impacts of AVs now as we plan infrastructure investments for the next 20-30 years. Though infrastructure needs may not change in the short term, in order to take full advantage of AVs in the long run, society may need to adapt infrastructure as described in Section 4.2, subdividing roads into AV/non-AV lanes, for example (Articles #5, #38). Some believe AVs will trigger minimal change to infrastructure, even if the transition period lasts for decades, due to the prohibitive cost of replacing or upgrading infrastructure (Articles #5, #24, #51). Article #24 describes the creation of communication networks for AVs and nearby infrastructure as the first step in transitioning to AVs.

A number of challenges during the transition period also bear consideration. Governments and industry may experience pushback from unions, suffer from security challenges, and struggle to modernize city services, regulations, insurance and liability standards (Article #5, #38). Safety statistics during the transition period may not be improved beyond current statistics (Articles #6, #51). Beyond this and the challenges described in Sections 0 through 0, little by way of discussion regarding transition-specific challenges exists in literature.

11.2 Adoption Forecasts and Ownership/Use Models (Scenarios)

The rate of adoption of AVs is frequently debated, and estimates vary widely. Estimate parameters also vary from article to article, and are often not directly comparable as a result. For example, one reserved forecast predicts AV sales will represent 2-5% [assumed worldwide] during the 2020s, reaching 40-60% during the 2040s, and only reaching 80-100% of sales by the 2050s (Article #6). Further, Article #6 expects only 20-40% of vehicles in operation to be AVs by the 2040s, and only 40-60% to be AVs by the 2050s. In contrast, Article #8 predicts that 13% of vehicle sales by 2025 will be for partially or fully autonomous vehicles, with AV sales reaching 25% of total vehicle sales by 2035. Article #20 estimates 11.8 million AVs will be sold in 2035, and that by 2050, nearly all vehicles will be AVs. Article #37 estimates that 40% of vehicles in operation could be AVs by the year 2040. Article #30 predicts “full adoption” over the next 20-30 years. Article #49 predicts that over 80% of vehicles manufactured in the UK in 2025 will be Level 3 AVs (refer to Section 11.1 for a description of levels of vehicle autonomy).

Many observers have predicted that AVs will usher in a new era for car ownership and operation. Two primary modes of car ownership/use are expected: private ownership, essentially a continuation of the current popular car ownership model, and Transportation as a Service (TaaS), under which corporations are expected to offer a convergence of autonomous taxi, car-sharing, and short-term car rental services (similar to an AV version of Car2Go’s existing model) (Articles #5, #6, #9, #14, #30, #37, #38, #49, #50, #51, #52, #54AB).

Under a private ownership model, most aspects of current vehicle ownership would be expected to continue. Comfort, privacy, costs, and numbers of car sales would roughly resemble those of today’s vehicles, or continuation of today’s trends. It is expected that this model will appeal more to existing auto manufacturers than new entrants (technology firms) (Article #52).

Alternatively, under a TaaS model, private car ownership would virtually disappear. Corporations would operate a fleet of vehicles, likely taking responsibility for liability (insurance), maintenance, and eventual replacement (Articles #5, #9, #52). Individuals would pay per use (e.g., per vehicle-kilometre), and would likely not require a driver’s license (Articles #6, #39, #51). Vehicles would collect and drop off a passenger before being re-routed to collect another passenger, decreasing the need for parking (Article #5). Cars may become more utilitarian, designed to be “vandal-proof”, and privacy would decrease (Articles #6, #38). TaaS vehicles could also perform as public transit vehicles, possibly as personal rapid transit vehicles, or with smaller AVs linked digitally to form a virtual bus (Articles #26, #49, #51). In a simulation study of Lisbon, Portugal, Article #54AB found that AV taxis and high-capacity public transit could deliver current levels of mobility with only 10% of current car numbers, and no on-street parking. It is expected that TaaS will appeal more to new entrants (technology firms such as Google, Uber, Baidu, and Apple) than to existing auto manufacturers (Article #52).

Realistically, both private car ownership and TaaS will likely be available, to a greater or lesser degree (Article #51). Two-car families may shift to own a single car while relying on TaaS for some needs (Article #51). Private car ownership may be continue to be more practical in rural areas (Article #51). TaaS may be suitable and cost-effective for individuals who drive less than 6,000 miles (9,600 km) annually, but may be less so for those who drive more than 6,000 miles annually, require special accessories, carry tools or equipment, require mobility assistance, place a high value on privacy, etc. (Article #6).

As described in Section 5.4, many studies predict that AVs will cause the total number of vehicles in operation at a given time to decrease drastically (Articles #2, #5, #8, #27, #56AB, #58AB). Estimates vary from 2 to 13 non-AVs replaced per AV deployed (Articles #2, #5 #27, #54AB, #56AB, #58AB). Article #27 predicts as much as a 90% reduction in the total number of vehicles on streets in Helsinki, Finland by 2030. Such predictions are typically based on assumptions of significant TaaS uptake (car- and ride-sharing services), particularly in urban areas, where 90% of North Americans will reside by 2050 (Article #50). Article #50 states that as many as 32 personal vehicles are avoided for every car in the 10 biggest car-sharing markets in the United States. However, car sales are not expected to decrease following AV adoption; though fewer cars may be active simultaneously, each vehicle will be used more frequently, thus requiring more frequent replacement (Article #38). Many studies also consider an increase in the total number of VKTs to be plausible (Articles #1, #5, #6, #9, #38, #39). Refer to Section 5.4 for more information about increased VKTs due to AV implementation.

12 Summary: Government Best Practice

Few studies outlining AV policy recommendations do so for particular levels of government. This appears to be a matter of practicality: different jurisdictions place different responsibilities under different levels of government, but the arrival of AVs is sure to affect all countries and municipalities.

Most of the “best practice” advice contained herein is based on forethought and judgement rather than empirical evidence. Many policy recommendations with respect to AVs exist, but few have been tested, and virtually none can be considered conclusive at this stage. The policy recommendations discussed below have been broken into subsections mirroring Sections 0 through 0.

12.1 Safety

Safety might be considered the primary benefit of AV technology. Improved safety will benefit all road users, not just individuals operating AVs (Article #2). However, few policy recommendations relate to safety matters outside of AV testing guidelines and security matters (refer to Sections 12.2 and 12.8 respectively for discussion of these topics). Perhaps safety is expected to improve as a matter of course, without intensive government intervention; Article #9 states that while the US Federal Motor Vehicle Safety Standards specify performance of safety components, *voluntary* standards are likely to be key for safety and compatibility of AV operation. Given that early generation AVs will not be without flaws, regulators should work with manufacturers to build tools to limit risks posed by legacy AVs, such as monitoring, wireless updates, recalls, or plans for future retrofits (Article #22). Article #41 identifies a need (in the United States) for the National Highway Traffic Safety Administration (NHTSA) to work with the Federal Trade Commission (FTC) to produce standards, particularly relating to data and security, which will have safety implications.

12.2 Regulation, Public Trials, and Liability

Articles #9 and #22 cite a risk of overregulation as being detrimental to the development of AVs, especially if individual jurisdictions create a patchwork of fragmented, region-specific regulations. Article #1 similarly recommends that licensing and regulation be developed primarily at the federal level. Article #22 further suggests creating flexible regulations, perhaps even focusing on adapting existing regulations, to accommodate the uncertainty surrounding AVs and prevent codification of unreasonably high standards. Article #10 recommends preventing standalone AVs (i.e., AVs which do not communicate with other vehicles or infrastructure) from impeding connected AV systems, by providing clear policy direction and by fitting standalone AVs into a cooperative framework (in essence imposing vehicle communication systems so otherwise fully autonomous AVs are connected to the network). Transport Canada is participating in development of international AV standards (UNECE WP.29, ISO TC 22 SC39, and ISO TC 204) (Article #5).

Public trials should be encouraged (Articles #5, #9, #45). Ontario should develop a single connected ecosystem, allowing AV manufacturers to test vehicles across several municipalities under a single regulatory framework, overseen by a central steering committee (Article #45). Test operators should have appropriate driver's licenses and training, should conduct risk analyses for proposed tests, and consider developing a public relations strategy to educate the public (Article #4). Data recording devices should be installed on test vehicles to include whether a vehicle is in automatic or manual mode; speed; steering commands; braking commands; operation of lights and indicators; use of the horn; and sensor data regarding external road users and objects (Article #4). Operating software should be thoroughly tested and documented before beginning public trials (Article #4). Operators should also consult with manufacturers and suppliers to ensure appropriate security measures have been taken to prevent malicious third-party attacks during testing (Article #18).

Article #1 suggests that governments produce standards for liability. Liability is likely to shift to manufacturers, especially those offering Transportation as a Service (TaaS) (Articles #8, #22). Article #9 suggests that policymakers take action to reduce manufacturers' liability by creating insurance options, limiting tort law claims, and possibly adopting a convention making human drivers legally responsible for a vehicle without exception. It may be necessary to expand public insurance schemes, or facilitate greater private insurance opportunities (Article #22). It may also be necessary for governments to audit AV control algorithms, such as algorithms governing decision-making related to collisions (Article #22). Article #10 recommends creating a liability framework to prevent safer technology from being delayed or aborted by manufacturer concerns about increased liability.

12.3 Services and Infrastructure

An extended transition period, during which AVs and non-AVs share the road, will present a challenge to regulators and to city services (Article #38). Article #4 recommends that testing firms establish lines of communication with local emergency services to make technical advice available proactively prior to occurrence of a collision or other incident. No other noteworthy policy recommendations relevant to government services were described in the literature.

Article #5 recommends that all major transportation infrastructure projects in Canada be obliged to participate in an AV audit, ensuring that long-term projects are not planned without due consideration for AVs and associated changes. However, the UK's guidelines for testing AVs assume that no additional infrastructure is required for manufacturers to test vehicles, placing the onus on manufacturers to inform and coordinate with authorities if special infrastructure requirements (including signage) are necessary (Article #18). Though CVs would require increased construction of infrastructure beyond that which would be required for standalone AVs (Article #22), a report by the Rathenau Instituut recommends that the Dutch government prevent standalone AVs from impeding or trumping CV systems, as CV systems are thought to provide more efficient use of road space, better safety outcomes, and a more sustainable transportation network (Article #10). Nevertheless, Article #5 cautions that it will be prohibitively expensive for governments to replace urban roads, highways, and intersections to accommodate AVs. Electricity generation and distribution infrastructure will need to be upgraded if a substantial number of AVs are electrically powered, and parking lots may come to require charging ports for electric vehicles (EVs) (Article #5). A gradual replacement of traffic lights with roundabouts is anticipated as studies in the US have shown roundabouts to be more efficient for AVs (Article #5). Article #14 recommends that traffic lights communicate red light warnings to approaching traffic, and that infrastructure be made more visible to vehicles and include electronic identification tags; for example, lane markings may be improved to better assist AVs. Platooned freight vehicles may require roads be equipped with ticker pavements (Article #1).

12.4 Urban and Transportation Planning

Article #5 describes Canada's priority (with regards to AV introduction) as increasing political leadership at all levels of government, specifically advising municipal governments to focus efforts on planning (including transit) and infrastructure projects. Many studies anticipate a drastic reduction in the need for parking space, with some advising an elimination of most or all roadside parking (Articles #1, #2, #5, #8, #9, #27, #54AB). Some studies warn that while density in central business districts (CBDs) and around highways and major arterials may increase as a result of reduced parking needs and ease of AV travel (Articles #5, #9, #14), and densification will place additional infrastructure demands on municipalities (Article #14). Suburban sprawl may be also encouraged by ease and affordability of AV travel (Articles #5, #6, #9, #14, #24).

Traditional forms of high-capacity public transit (e.g., heavy rail) will continue to be important (Articles #5, #27). Yet other forms of traditional public transit systems may benefit from a conversion to AVs; personal rapid transit vehicles or small, linked AVs could become viable forms of public transit (Articles #26, #51). Given that transit projects take years to plan and should last for decades, AVs will be deployed within the planned lifetime of transit, and municipalities should plan accordingly (Article #5).

Municipalities should determine how to assist the rollout of AV technology, and determine which information they wish to send to and receive from AVs; perhaps municipalities could use AVs to identify infrastructure maintenance concerns, or collect incident and congestion information and relay this wirelessly to other the municipality or other AVs (Article #14).

12.5 Mobility, Accessibility, and Equity

Fully autonomous vehicles could be operated by children, seniors, disabled people, and other individuals who are unable or choose not to drive, providing significantly improved mobility and accessibility (social inclusion) for those demographics (Articles #5, #9, #18, #26, #38, #47). AVs may offer municipalities a cheaper means of providing paratransit and typical bus transit services, thus providing an opportunity for improved transit and social welfare (Articles #9, #27).

It will be important to consider how AVs may disparately affect individuals, industries, and other entities. Regulation should be constructed such that anti-competitive or other unfair advantages are prevented from accruing to specific parties (Article #38). Authorities should consider life-cycle costs and implications of AVs, including the effects of fuel extraction, transmission, emissions, and other externalities which may not be immediately obvious (Article #38).

12.6 Economic Implications

The degree to which benefits accrue to the public rather than individuals will shape economic demand for AV technology, and negative externalities (like increased VKT) may also result (Article #9). Municipalities or other levels of government could use subsidies and taxes to internalize true costs of AV use (i.e., internalize externalities) (Article #9). Article #5 expects AVs in Canada to displace transport, truck, and courier drivers; taxi/limo drivers; bus and tow truck drivers; driving instructors; parking attendants; mechanics and autobody shop workers; insurance providers; traffic police; doctors and health staff; and lawyers and legal staff. Article #5 further provides the following recommendations to Canadian governments: measure the impacts of AVs on Canadian businesses, and encourage a Canadian ecosystem in order to capture a share of the market for AV software, parts, and other components and services.

12.7 Energy and Environmental Implications

Fuel savings per VKT are anticipated due to "right-sizing" of vehicles and lighter vehicles generally, reduced reliance on private vehicles, increased car-sharing and/or other modes of transportation, smoother acceleration and deceleration, less time spent searching for parking, and reduced congestion and travel time, platooning, alternative fuels (primarily electricity), and ongoing improved vehicle design (not necessarily related to autonomous features) (Articles #1, #2, #5, #8, #9, #14, #17, #26, #27, #30, #36, #38, #39, #50 #54AB, #56AB).

Vehicle emissions are predicted to drop per VKT due to reduced fuel use, reduced cold starts, lighter vehicles, and increased fuel efficiency guided by tightened fuel efficiency standards (Articles #2, #10, #17, #26, #36, #39, #50, #56AB). Local emissions are expected to drop due to use of electric vehicles (Articles #5, #26, #39). However, VKTs are expected to rise per capita due to easier, cheaper, more accessible car travel (Articles #1, #2, #5, #6, #9, #18, #47, #58AB). It is thus unclear how total fuel use and emissions will change as a result of AV commercialization (Articles #1, #6).

12.8 Security

Security is considered a critical issue for AV technology, and its future is highly uncertain. There is widespread agreement that security will be a challenge that must be carefully planned for (Articles #1, #5, #6, #7, #18, #20, #23, #37, #38, #42, #43, #44). Security challenges include difficulty predicting threats, slow delivery of software updates, need to standardize systems, management of components and systems from different suppliers, provision of security during real-time operation, securing important operational data sent and received by CVs, and eventual limitations to computational capability given the long life cycle of vehicles relative to most computers (Articles #6, #18, #20, #38, #43, #44).

Few regulations exist mandating security features or targets for vehicles, but studies predict a need to vastly improve and standardize security features when AVs are commercialized. Recommendations include increasing high-level oversight (producing security standards, Articles #1, #18, #44), incorporating technology-specific best practice (e.g., using encryption, digital certificates, tamper-proof hardware, real-time constraints, and vehicle authentication, Articles #7, #42) and use of traceable hardware and software supply chains, adversarial resilience testing, collection and retention of data to assist NHTSA investigations, and physical segregation of critical systems from non-critical systems (Article #44).

12.9 Data and Privacy

Four types of privacy are relevant to AV deployment: an individual's ability to control a vehicle, an individual's ability to make choices related to vehicle operation, protection against intrusions, and anonymity of operation (Article #47). Regulations in California require manufacturers of AV technology to "provide a written disclosure to the purchaser of an autonomous vehicle that describes what information is collected by the autonomous technology" (California Vehicle Code 38750(b)(1) (West 2013) (Article #48). Article #47 quotes Ontario's recent Privacy Commissioner, Anne Cavoukian, emphasizing privacy by design, stating that privacy must become a default mode of operation, and that "forfeiting privacy in favour of security not only represents flawed logic, but is unnecessary."

Article #4 recommends testing to ensure personal data is kept only where necessary and for no longer than necessary. Standards need to be produced for data privacy, with laws and regulations updated accordingly (Articles #1, #41). Article #48 recommends that regulators prevent AVs from infringing on the privacy and freedoms of citizens unless, in doing so, the social gains outweigh the social costs. Finally, Article #47 recommends ensuring CVs are protected against hacking, validating security systems with penetration testing, developing real-time response mechanisms to address hacking attacks, mandating driver awareness of data collection, transmission, and use, providing drivers the option to opt out of data collection and transfer, and requiring removal of personally identifying information where possible and where requested by the user.