Planning for automated vehicles in Edmonton *Final report*

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EXECUTIVE SUMMARY

This report summarizes key results from work that was conducted for the City of Edmonton Department of Sustainable Development. The views expressed in this report are those of the consultant and do not necessarily represent those of the City of Edmonton.

Some vehicle automation technologies, such as adaptive cruise control, are already available on the market, while significantly more advanced technologies are being developed. Vehicles that can drive themselves in any situation with no human intervention may be decades away, but they could emerge sooner, and less advanced but still powerful technologies will emerge in the very near term. All of these technologies could produce significant impacts on travel and land use in Edmonton.

Automation in private light-duty vehicles and taxis could make travel faster and easier, increase road capacity on some roads, and reduce parking demand. However, automated cars have the potential to also produce negative impacts, such as increased vehicle travel due to induced demand, increased congestion on city streets, and a tendency toward more spatially dispersed development. In addition, some benefits, such as increased freeway capacity, may manifest slowly, since they are dependent on high levels of adoption of highly advanced technologies. In contrast, if automation is applied to public transit buses, the frequency and capacity of transit could be significantly improved. This could lead to increased mode share, thus mitigating the tendency toward increased vehicle travel and supporting more spatially compact, resource-efficient development. Importantly, many of these benefits could begin to materialize in the near term.

Levels of vehicle automation

In the taxonomy of vehicle automation developed by the Society of Automotive Engineers (SAE), Level 1 describes systems where either steering or speed control may be automated, but not both simultaneously. In Level 2, the system controls both steering and speed simultaneously, but the human driver must continuously monitor the vehicle's performance and must be available to take control with no notice. In Level 3, the driver need not monitor but must be available to take control within a short time when requested by the system. Level 4 refers to a vehicle that can drive itself without any need for human intervention, but that can only do so in specific situations. This includes automated vehicles that may not be highly sophisticated but that nevertheless can operate without human intervention while in controlled environments. Such environments could include specified roads such as freeways, lanes that are dedicated exclusively for the use of automated vehicles, or private zones such as campuses. In Level 5, the system can drive itself in any situation without any need for a

human to monitor or be available to take over. Level 5 would make possible applications such as self-driving private vehicles and driverless taxis.

Automation technologies: state of the art

Vehicle automation technologies use information provided by a variety of sensors, including radar, LIDAR (a remote sensing technology that detects objects via reflected laser light), cameras, infrared cameras, ultrasound, GPS (Global Positioning System), accelerometers, and others. Automated vehicles can also use information provided via wireless communications with other equipped vehicles or entities in the environment – this is referred to as V2V (vehicle to vehicle), V2I (vehicle to infrastructure), or more generally as V2X (vehicle to vehicle, infrastructure, or other entities).

Level 1 technologies are currently available in a number of vehicles on the market. Lanekeeping technologies use cameras, radar, and other sensors to detect the position of a vehicle relative to lane markings and/or the vehicle ahead to maintain its position in the lane. Adaptive cruise control maintains the vehicle's speed at a desired level while adjusting speed as necessary to safely follow the vehicle ahead according to distance and speed data provided by radar. Cooperative adaptive cruise control is a related technology that uses V2V to detect the movements of other vehicles; this technology has been tested but is not available on the market.

Level 2 technologies, which simultaneously control steering and speed, are beginning to emerge onto the market. For example, Mercedes and Tesla have introduced such technologies into some of their vehicles.

Several projects to develop higher levels of automation are underway. Google is developing automated light-duty vehicles, and is also developing a Level 4, lightweight, two-passenger low-speed automated vehicle that would travel at a maximum of 40 km/h. Google's vehicles rely especially on a rooftop LIDAR (a sensor that scans the environment with laser light) that develops a detailed 3D map of the environment, which is compared against a map that was developed beforehand while manually driving the route. While Google's fleet has been test-driven over long distances, the vehicles are continuously monitored by test drivers who take over control when situations arise that may be beyond the capability of the automated system.

Other projects, such as the CityMobil2 project in Europe, also aim to automate low-speed operation of lightweight vehicles. This approach greatly reduces the technical challenges involved in achieving full automation. These vehicles have been tested in cities in Italy, France, Greece, Finland, and other countries. Such vehicles could operate in restricted areas, such as university and business campuses, retirement communities, hospital sites, and pedestrian areas, and could provide "first and last mile" access to and from public transit routes.

Automation applied to transit buses can enable operation in narrow rights-of-way, precise docking at bus stations, bus platooning, and fully automated driving. Many of these applications were demonstrated as far back as 2003 by PATH (Partners for Advanced Transportation Technology) in California, and various forms of bus automation have been implemented in locations in Europe, Japan, and the US.

Challenges in developing higher levels of automation

In order to attain higher levels of automation, such as Level 5, several issues must be resolved.

There are major technical challenges. Sensors currently do not function reliably in certain weather conditions, such as rain and snow. Automated systems have difficulties in interpreting sensed data in complex, unstructured, highly dynamic environments, which are common in cities. Map-based systems, such as that used by Google, can become confused when their reference maps have not been updated to reflect changes in the environment. It is also difficult for automated systems to predict the behaviour of vehicles, pedestrians, and other objects. Another problem is to determine how automated vehicles should drive in situations where human drivers rely on eye contact or otherwise communicate with other road users.

A related problem is that in order to ensure public acceptance of the technologies, the vehicles will likely need to be capable of driving more safely than humans; to ensure this level of safety, extensive testing will be necessary.

In addition, the technologies are currently expensive – for example, it has been reported that the LIDAR used in Google's test vehicles costs \$75,000. It is anticipated that costs of sensors and other components will drop substantially, though it is uncertain when and to what degree this will happen.

Programming an automated vehicle also raises ethical challenges, as some driving situations may require choosing between alternatives that impose different levels of risk on different road users.

Legal issues must be addressed. While several jurisdictions, including the province of Ontario, have legalized the testing of automated vehicles with human monitors on public roads, before the public can use Level 3, 4, or 5 vehicles, where the vehicle need not be continuously monitored by a human, it will be necessary to clarify the legality of the operation of such vehicles.

Liability must also be clarified: if an automated system is driving, blame for a crash may be distributed among various parties, such as an auto manufacturer, a designer of system

components, or a computer programmer. The need to resolve human factors issues – such as ensuring that human drivers perform monitoring or backup tasks as required – could slow the emergence of Level 2 and 3 systems in particular.

Security and privacy are also concerns, especially for systems equipped with V2X. Hackers could cause vehicles to crash or otherwise cause problems. Privacy advocates are also concerned about protecting the data on the movements of vehicle users.

Timelines of emergence of higher levels of automation

There is a general consensus that Level 3 systems will emerge by 2020 to 2025. Estimates regarding when Level 5 vehicles will be available on the market vary widely – some commentators suggest that Level 5 will emerge as early as 2017, while others contend that it will emerge several decades in the future.

While it is highly uncertain when Level 5 will emerge, several factors suggest that it may emerge further in the future than the more optimistic estimates suggest. Most importantly, there are technical problems to solve, such as the challenges mentioned above. In addition, the level of technological advancement achieved to date is often overstated. For example, while it is often reported that Google's test fleet has driven large distances in automated mode without having caused collisions, it is important to recognize that the testing takes place in favourable weather conditions and less challenging road environments, and under continuous human monitoring, and the frequency and nature of interventions by the test drivers has not been made clear. Therefore, it is not possible to make a meaningful assessment of the capability of their vehicles.

Impacts on road safety

It is uncertain what degree of safety benefits that high levels of automation would produce, though there is a large theoretical potential if automated systems perform with a high level of reliability, since human error causes 75 to 95 percent of crashes.

Safety improvements can be achieved with less advanced forms of automation. For example, according to some reports, automatic emergency braking systems could reduce crashes by 27 percent.

The safety impacts of Level 1, 2, and 3 systems are highly uncertain, due to the novel "human factors" risks resulting from the sharing of responsibility for driving between human and machine. There is a risk that the human driver will fail to properly perform their driving, monitoring, or backup driver tasks. For Level 2, a driver may not monitor the system and may fail to take over immediately, while in Level 3, a driver may fail to safely take over control of

the vehicle in a timely manner when requested by the system. Therefore, it is possible that while these technologies might prevent some crashes, new crashes might also be caused. To date, there has been one known fatal crash involving a Tesla car where the Level 2 automated system was in operation. There is insufficient data currently to conclude whether this particular Level 2 system improves or worsens safety.

In the case of Level 4 vehicles where full automation is achieved by controlling the environment in particular, safety will depend in part on how effectively the environment is controlled. For example, in the case of protected lanes, safety would depend on how effectively potential hazards, such as unauthorized vehicles, or pedestrians and cyclists, are excluded from the lane.

As Level 5 technologies do not exist yet, their safety impacts are inherently highly uncertain. Some early studies have attempted to compare the safety record of automated test vehicles, especially those of Google, with the safety record of human drivers; however, available data does not support any useful conclusions at this time.

Impacts on the efficiency of use of transportation infrastructure

An automated system capable of controlling a vehicle more precisely and with a shorter reaction time than a human makes it possible to safely follow a preceding vehicle at a closer distance, thus increasing lane capacity by 50 to 100 percent. The shorter reaction time would also make traffic flows more stable, reducing the shock waves that lead to "stop and go" traffic.

To enable these increases in capacity, vehicles would drive in groups or "platoons" of several vehicles – in the range of four to twenty vehicles is commonly proposed. The vehicles in each platoon follow each other closely, for example, at distances of one to four metres. The platoons are separated from each other by larger gaps to minimize the risk of collision if a leading platoon were to suddenly stop. Meanwhile, the small gaps between the vehicles in each platoon mean that even sudden stops would produce small speed differences between vehicles, so any impacts would be of low severity.

Large capacity increases would require V2V combined with automation. V2V can provide information on the movements of other vehicles with shorter time delays than on-board sensors; it can even provide information about the manoeuvres other vehicles plan to execute before they are executed. In addition, V2V can provide information on vehicles that are beyond the line of sight of on-board sensors.

Capacity would increase little until a large proportion of vehicles on the road are capable of platooning. Large capacity increases require high levels of adoption, when the proportion of equipped vehicles exceeds 60 to 85 percent.

The capacity benefits of platooning can be realized while adoption levels are still low by enabling platooning-capable vehicles to cluster together into dedicated lanes. Unfortunately, such dedicated lanes suffer from a "chicken and egg" problem, where individuals are motivated to acquire platooning-capable technology only if they perceive a benefit, such as reduced travel time or reduced workload, while infrastructure providers are unlikely to provide dedicated lanes before a demand exists.

Because vehicles entering into and exiting from platoons would significantly reduce lane capacity, capacity increases would occur mainly on freeways where entrance and exit ramps are widely separated.

The capacity benefits of automation would be limited on city streets, since the complex movements of city traffic would diminish the capacity increases that platooning can provide.

Platooning would be most useful for longer trips and would provide limited benefits where traffic flows are complex, such as on freeways with closely spaced interchanges.

Capacity increases from platooning on freeways would attract traffic from other roads, thus potentially reducing congestion on arterials in some areas, but could also lead to congestion near freeway entrances and exits where platooning produces minimal capacity increases. This would limit capacity increases for the overall network.

Platooning would provide significant benefits only to those trips that use freeways for a significant portion of the trip. In addition, if many vehicles take short trips on freeways, their frequent manoeuvring into and out of platoons will limit capacity.

For platooning to benefit a large proportion of trips in a city, a large proportion of origins and destinations must be close to freeways, such as in a city where development is focused along freeway corridors, or with an extensive freeway network.

Capacity increases would be limited where there is significant truck traffic – heavy trucks must follow at longer headways due to their poorer braking capabilities.

Automation is not likely to result in significant increases in lateral road capacity. The potential gains from narrower lanes are small compared to the potential gains from shorter headways – while only around 11 percent of the length of the lane is used by manually driven vehicles, around half of the width of the lane is used.

Automation combined with V2X could improve traffic flow at intersections. It has been proposed that intersections would have no need for signals or signs; instead, cars equipped with V2X would be assigned time and space slots in which to move through the intersection. This could substantially reduce delays, though the magnitude of reduction would depend on high levels of adoption of V2X-equipped automated vehicles, and would also depend on the presence of few pedestrians or cyclists.

Automation in transit buses can facilitate operation in narrow rights-of-way, precision docking, bus platooning, and full automation. These applications can increase speeds, reduce dwell times, increase passenger comfort, reduce labour costs, and facilitate increased capacities and frequencies.

With their high steering precision, automated buses can drive safely in narrower lanes than human operators can, and at higher speeds. This is a useful application for bus rapid transit (BRT) service, since narrower busways reduce land and construction costs, especially where tunnels or bridges are required.

Precise steering also allows precision docking, where buses quickly and reliably pull in very close to the boarding platform, thus providing easier and faster access for passengers with limited physical mobility, as well as for other passengers. This reduces station dwell time and increases schedule reliability.

Platooning of buses would increase capacity, reduce labour costs, and enable buses to provide service similar to trains without the need for rail infrastructure. A bus platoon could operate with a driver in the lead bus and with the following buses operating without drivers, or an entire platoon could operate without drivers. Unlike trains, the buses could operate on the larger road network, enabling "dual mode" operation, where a bus could operate manually on uncontrolled roads for a portion of its service and join a platoon on a protected busway for another portion of its service.

Full automation in buses would also enable reduced labour costs, and would also make it possible to provide higher frequency service with smaller vehicles.

Automation could facilitate a shift toward significantly smaller and lighter vehicle designs, but such a shift is unlikely until very advanced automation is very widely adopted. It has been argued that crashworthy vehicle design would be unnecessary for automated vehicles because their crash avoidance capabilities would be superior to those of humans; vehicles could then be built much smaller and lighter. However, especially while some vehicles are still being driven by humans, small, light automated vehicles would be vulnerable in collisions with large and heavy vehicles; in such crashes, crashworthiness will still be necessary.

Automation could improve safety and thus reduce non-recurrent congestion due to crashes. Level 5 in particular could reduce non-recurrent congestion on all roads; however, there is greater uncertainty regarding the safety impacts of Level 2 and 3.

With Level 5 vehicles, a shift in parking locations could result. Level 4 vehicles could drive themselves to park at remote locations: for example, a commuter could travel to work and then send their car back home to park. This could reduce the demand for parking in areas of high intensity land uses, such as downtown areas, where parking is expensive or difficult. In addition, remote parking could generate additional traffic.

Driverless taxis could reduce demand for parking. The magnitude of this effect would depend on the proportion of trips taken by driverless taxi rather than by private light-duty vehicle, and on the temporal peaking in demand for driverless taxi trips.

Some studies examining the potential impacts of driverless taxis appear to suggest that driverless taxis would dramatically reduce or even eliminate the need for transit provided by vehicles with high passenger capacities; however, when the assumptions in the models used in these studies are critically assessed, these studies are more reasonably interpreted as indicating that driverless taxis could supersede buses and trains where there is substantial unused road capacity. For example, some models assume that roads in the network have large amounts of unused capacity at peak travel periods, and others assume that automation would hugely increase capacities for all roads in the network, to double or triple current levels. Based on these points, it is more likely that driverless taxis could provide useful service in areas of lower population density and during periods of lighter travel, whether serving complete trips or feeding into bus and train networks.

Environmental impacts of automation

Automation, especially when combined with V2V, could enable smoother, more efficient driving, with smoother speed profiles. Platooning could improve aerodynamic efficiency, especially for heavy-duty vehicles such as trucks and buses, which could benefit from significant energy savings. In addition, if vehicles become lighter and smaller, energy consumption would be reduced. This would also facilitate a shift to electric power.

Adoption

For both private vehicle owners and fleet owners, the prospect for automation to reduce or eliminate driving labour would be a significant attraction. Automation would reduce driving stresses, freeing up the traveler's time to perform other activities, and reducing labour costs for fleet owners. Fully automated vehicles could allow for greater independent mobility for

those less able or unable to drive, such as elderly people, children and adolescents, and people with reduced physical mobility.

Though it is not certain how rapidly automated vehicles will be adopted, simple models based on Edmonton vehicle statistics suggest that if adoption is extremely rapid, Level 5 light-duty vehicles would make up a large majority of the overall fleet of light-duty vehicles on the road within 15 to 20 years after their emergence onto the market; while if the pace of adoption is more moderate, it could take 30 years or more for Level 5 vehicles to become a large majority of the overall light-duty fleet on the roads. These points are important to consider, since many of the impacts of automated light-duty vehicles would only become significant at higher levels of diffusion.

Level 5 vehicles could be rapidly adopted by taxi fleet owners, especially to cut labour costs. This would enable low taxi fares – perhaps a third of present levels, according to one estimate – increasing demand for travel by driverless taxi and stimulating more rapid adoption. Adoption could also be more rapid in taxi fleets than for private individuals because fleet owners could leverage economies of scale and purchase large numbers of vehicles at lower costs. Adoption in taxi fleets could also be accelerated because taxis are more intensively used than private vehicles, so fleets are refreshed more rapidly than the general fleet of vehicles owned by private individuals.

Driverless taxis could provide convenient, comfortable, private travel, with lower fares than today, thanks to the elimination of labour costs for human drivers. This would reduce incentives for people to own their own private vehicles. In addition, since each driverless taxi would provide many trips to many individuals over the day, a relatively small fleet could serve a population, and parking demand would also drop. However, studies have generally suggested that widespread use of automated taxis could result in large increases in vehicle kilometres traveled, particularly due to empty taxis traveling from one passenger to the next. In general, when road capacity limits are taken into account, driverless taxis would be most useful in areas of lower population density, while higher passenger-capacity vehicles like buses and trains will still be needed in areas with dense spatio-temporal clustering of trips.

Automation could provide substantial labour and other operating cost savings for bus transit fleet operators, since buses are used intensively and have high operating costs. Because the absolute cost of automation technologies would be similar for light-duty vehicles and buses, the technologies would make up a smaller fraction of the total vehicle cost for buses. In addition, buses are more intensively used, so the cost would be amortized more quickly. Fleet owners could also benefit from economies of scale by purchasing numerous vehicles at reduced costs.

Lower levels of automation are more likely to be useful for buses than for private vehicles. In controlled environments such as protected lanes, less advanced automated systems can

drive with reduced need, or no need, for human intervention. Since bus networks occupy a small fraction of the total road network, automated buses could derive large benefits by using a network of protected lanes that similarly occupy a small fraction of the total road network, in contrast with private vehicles, which would generally derive smaller benefits from a limited network.

Travel and land use impacts

Due to the effects described above, vehicle automation will tend to result in increased travel and dispersed development, unless appropriate policy measures are taken.

While automation would improve road capacity, the surplus capacity would be taken up in the long run by induced demand.

Users of automated vehicles, especially Level 5 vehicles, will benefit from reduced cost of travel time per unit time. In addition, some users of automated vehicles may benefit from reduced delays. The resulting reduction in generalized travel cost for these individuals will induce some drivers to change their routes, especially to freeways from arterials and other roads; it would attract some users of other modes, such as transit, to travel by car; it would attract some drivers to travel during peak rather than off-peak times; it would encourage drivers to take longer trips; it would generate new freeway trips and reduce incentives for trip chaining; and car ownership would be encouraged – both automated and non-automated – which in turn would encourage more car trips.

Automation in private vehicles would tend to result in mode shifts to private vehicles, mostly from longer public transit trips. Driverless taxis would shift trips away from transit and private vehicles, if fares drop sufficiently.

Partial automation, platooning, or full automation, would enable increases in capacity and/or frequency with minimal increases, or even decreases in labour costs. Improvements in transit service enabled by automation would support increased ridership, especially for trips originating or ending in or near heavily travelled corridors, where transit service is most likely to be sufficiently frequent and rapid to compete with other modes, especially if dedicated busways are provided.

Drivers of Level 2 and 3 vehicles would tend to use freeways or highways more often, especially where dedicated lanes for automated vehicles are provided.

Travelers in automated vehicles would shift some trips to peak periods, even where delays are not reduced, due to the reduced cost of travel time per unit time. Where delays are reduced, travelers in both automated and non-automated vehicles would travel more during peak periods.

Vehicle automation would tend to generate longer trips, especially for trips that make use of freeways or highways. The increase in trip lengths would be largest for Level 4 vehicles, but could also be large for Level 3 vehicles, especially where these vehicles make trips that make extensive use of freeways and dedicated lanes. Automation in transit could also result in the generation of longer trips, where service improvements reduce the generalized cost of travel.

A reduction in the generalized cost of travel would lead to the generation of new trips, and would also lead to more unchained trips.

Level 5 would enable remote parking and lead to more trips to destinations where parking is expensive or in short supply. "Cruising for parking" would diminish, but trips to remote parking locations would be generated.

Driverless taxis would reduce the need for parking, and would generate increased vehicle travel as taxis drive from one passenger to the next.

Many individuals would be attracted to purchase automated vehicles, especially with Level 4. However, as driverless taxis become common and as fares decrease, some individuals would opt to use taxis rather than own vehicles.

Users of privately owned automated vehicles and driverless taxis would experience incentives to choose residential locations that are more distant from their jobs or other activities, and that are particularly accessible by freeway. Where dedicated lanes are provided, users of automated vehicles would experience an incentive to choose residential locations that are more accessible by dedicated lanes. Users of improved transit services would be incentivized to choose residential locations accessible by these services, which would likely be in heavily travelled corridors. Automation would provide firms an incentive to choose locations more distant from their customers, employees, or other firms they do business with.

With Level 2 and 3, parking demand would tend to increase. With Level 5 automation, driverless taxis could reduce parking demand, thus freeing up land previously used for parking, while remote parking of private vehicles would tend to lead to a shift of parking from intensely developed areas to less central areas. These changes would allow for infill development, which could encourage more short trips taken by walking and cycling. However, remote parking would also result in land in other neighbourhoods being consumed by new parking facilities.

Once platooning-capable automation is widely adopted, road capacity could increase significantly. This could allow for the removal of freeway lanes. The land could be used for busways or for other modes, or could be used for greenspace or development.

Recommendations

The following preliminary recommendations are proposed.

PUBLIC TRANSIT

- Deploy lane-keeping and precision docking in BRT buses. These applications can at first be used to improve service in partially automated buses where human drivers monitor operation
- Implement protected busways on freeways. These busways can enable fully automated operation, even before the emergence of Level 5 technology
- Implement bus platooning technology to support increased capacity with minimal labour costs
- Consider the use of smaller automated buses and shorter platforms for BRT buses
- Consider automated BRT as an alternative to LRT, in general, and especially where dualmode operation could provide superior service
- Deploy low-speed Level 4 vehicles in lower-density areas
- Provide demand-responsive service in low-density areas with smaller automated buses
- Reduce bus service and encourage use of driverless taxis as transit feeders
- Price transit appropriately to maintain mode share
- Price driverless taxi trips appropriately to incentivize their use as transit feeders
- Provide drop-off/pick-up zones to facilitate transfers to and from first/last mile services

SUPPORT WALKING AND CYCLING IN DENSE AREAS AND NEAR TRANSIT STATIONS

- Provide suitable infrastructure to support walking and cycling, especially in dense areas and near transit stations
- Deploy and price low-speed vehicles and taxis strategically to minimize reduction of active transportation mode share

ROADS

- Consider reducing speed limits on local streets
- Consider dedicated lanes for automated light-duty vehicles when adoption levels are sufficiently high
- Implement lane conversions/road diets where opportunities exist
- Price roads to mitigate increases in VKT and congestion on streets
- Incentivize adoption of platooning-capable technology with lower road pricing

PARKING

- Price parking to mitigate demand increases that would result from increased travel with Level 2 and 3 automation
- When Level 5 emerges and adoption levels become significant, price parking appropriately in areas used for remote parking to limit traffic associated with remote parking and to encourage transit or driverless taxi use
- Reduce minimum parking requirements and convert park-and-rides

LAND USE

- Internalize the costs of infrastructure and services, via development charges, for example, to discourage excessively dispersed development and to minimize the associated external costs of transportation and costs of other infrastructure and services
- Support development near BRT and other higher-order transit services
- Encourage the redevelopment of land formerly used for parking in intensely developed areas, such as in downtown areas, or at park-and-ride facilities at transit stations
- Convert roadside parking spaces to pedestrian and cycle facilities or greenspace

PILOT DEPLOYMENTS

Prior to any large-scale deployments of automation in public transit, deploy existing Level
1, 2, and/or 4 automation in small-scale pilot projects. Deployments could include Level 4
low-speed vehicles serving short routes in areas such as university campuses, business
parks, airports, and multi-use paths, ideally where the service would not compete
inappropriately with active modes of transportation; deployments could also include Level
1 and 2 technology in BRT with protected busways

NEXT STEPS

- Conduct focused research on priority areas, including modeling of travel and land use impacts of various forms of vehicle automation, planning pilot deployments of automated vehicles, conducting a feasibility study of broader deployments of automation in bus transit, reviewing labour issues related to vehicle automation, and studying issues related to vehicle automation and goods movement in Edmonton
- Create automated vehicles issues working group with internal and external stakeholders
- Develop comprehensive vision and strategy to guide city's approach to automated vehicles
- Develop strategy to educate Edmontonians about automated vehicles and to communicate on the City's related initiatives
- Expand, refine, and update the analysis provided in this brief report on a frequent and regular basis to inform optimal policy approaches

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1. Introduction

This report summarizes key results from work that was conducted for the City of Edmonton Department of Sustainable Development. The views expressed in this report are those of the consultant and do not necessarily represent those of the City of Edmonton.

As progressively more advanced vehicle automation technologies continue to emerge, they will produce significant impacts on urban mobility and land use. In order for Edmonton to effectively plan to maximize the benefits and minimize the negative impacts of vehicle automation, it is necessary to have a sound understanding of the technologies, their capabilities and limitations, their potential applications, their likely timelines of emergence and adoption, and the range of potential impacts in the near term to long term. This report provides an overview of key issues related to the travel and land use impacts of automated vehicles that the City of Edmonton, and the Department of Sustainable Development in particular, should consider when planning for the future.

Recently, there has been increasing interest in and speculation on the benefits that fully automated vehicles could bring; however, critical analysis is needed to support a well-informed understanding of the range of potential impacts. In particular, it is important to better understand at what date various forms of automation are likely to emerge, the scale of benefits they are likely to bring, the negative impacts they could create, and the impacts that would arise while vehicle automation is in the earlier stages of development and adoption. This latter point is critical, since this transition period could be lengthy. In addition, it is important to consider the potential for application of advanced automation to buses in public transit. This report provides a critical overview of issues relevant to the future impacts of automated vehicles. The report also provides preliminary recommendations on appropriate policy approaches to maximize benefits and minimize negative impacts in Edmonton. The report can be considered as a first step toward Edmonton positioning itself as a leader in preparing for emerging automation technologies and strategically exploiting them.

A range of driver assistance technologies, such as lane-keeping assist and adaptive cruise control, are entering the automotive market, and more advanced technologies, including vehicles capable of driving themselves without the intervention of a human driver, are being developed. Many observers anticipate the widespread adoption of such highly advanced technologies in the coming years and decades. This report investigates when various vehicle automation technologies are likely to emerge onto the market, how rapidly they may be adopted, how they could affect the ease of travel, how they could affect urban travel which roads and parking infrastructure are used, and how they are likely to affect urban travel and land use patterns. In brief, this report finds that automated vehicles could significantly

alter travel and land use patterns in Edmonton. Automation in private light-duty vehicles, taxis, and car-share vehicles could result in benefits such as increased capacities on some roads and easier motor vehicle travel. However, there could also be negative impacts, such as increased congestion on city streets, increased vehicle travel, and an increased tendency toward dispersed development. In addition, road capacity improvements from automated light-duty vehicles may be slow to emerge, since they are dependent on high levels of adoption and high levels of automation. In contrast, if public transit buses are automated, transit service could be improved, thus mitigating increases in vehicle travel, road congestion, and inefficient dispersed urban development.

The key questions that will be answered in this report are:

- How are road vehicle automation technologies likely to impact passenger travel and land use in Edmonton in the coming decades?
- When are advanced vehicle automation technologies likely to emerge onto the market?
- How are automated vehicles likely to affect the efficiency with which roads and parking infrastructure are used?
- How are vehicle automation technologies likely to affect the ease of travel by motor vehicle?
- How will the effects of automation on ease of travel and efficiency of infrastructure use impact travel and land use patterns?
- What travel and land use policies would maximize the benefits and minimize the negative impacts of vehicle automation?

This report focuses on examining the impacts of road vehicle automation on passenger travel and land use. Other relevant issues were not within the scope of the current project; these include the impacts of automation on goods movement, environmental impacts, social equity impacts, labour impacts, and the impact on intercity travel.

Categories of vehicle automation and relevant terms are explained in Section 2. The various technologies that are on the market and that are in development are reviewed in Section 3. Likely timelines of emergence and adoption of the technologies are discussed in Section 4. Section 5 provides a discussion of the impacts of automation on safety. Section 6 explains how automation can affect the efficiency with which road and parking infrastructure is used. In Section 7, the potential environmental impacts are briefly addressed. In Section 8, adoption rates are discussed. In Section 9, the likely travel and land use impacts of automation are examined. In Section 10, recent, ongoing, and planned activities relating to vehicle automation technologies in selected cities are reviewed. In Section 11, a number of preliminary policy recommendations are proposed. In a supplementary section at the end of the document, a brief discussion of existing shared mobility modes, with a focus on ridesourcing and carsharing, is provided.

2. Terms and taxonomy

In this section, key terms and concepts are clarified and taxonomies of vehicle automation technologies are reviewed.

2.1 "Automated" vs. "autonomous"

The term "autonomous" has been commonly used in discussions of vehicle automation technologies, and has also been used in legislation and regulation. However, the term "autonomous" is ambiguous and is often used in two different senses in discussions of vehicle technologies (Smith, 2012a). "Autonomous" is sometimes used in a first sense, to describe a vehicle that can drive itself with no need – or reduced need – for intervention from a human driver. The vehicle possesses sufficient intelligence to analyze the information it collects regarding the environment and then plan and execute manoeuvres and thus, drive itself, at least in certain situations, with little or no intervention from a human driver. The vehicle is considered self-sufficient, or autonomous, in its intelligence. "Autonomous" is also used in a second sense, to describe a vehicle that is not in wireless communication with other vehicles or other entities – it relies only on the information provided by its on-board sensors. The vehicle is considered self-sufficient, or autonomous, in its sensing of the environment.

The term "automated" avoids this ambiguity. It refers particularly to the capability of a vehicle to drive itself. An automated vehicle may or may not be in communication with other vehicles or devices. Experts such as the SAE (the Society of Automotive Engineers) specifically recommend "automated" and deprecate "autonomous" (SAE On-Road Automated Vehicle Standards Committee and others, 2014). In this report, the term "automated" is used accordingly.

2.2 Automation vs. vehicle communication technologies

Though vehicle automation technologies are sometimes conflated with vehicle communications technologies, they are distinct (Shladover, 2009a). Vehicle communications technologies provide information that can be used either by a human driver or by an automated system. An automated vehicle may or may not be capable of communicating wirelessly with other vehicles or entities, and similarly, a non-automated vehicle may or may not be capable of communicating wirelessly.

2.3 Vehicle communication technologies

Vehicle communication technologies – referred to as V2V (vehicle to vehicle communication), V2I (vehicle to infrastructure), or V2X (vehicle to vehicle or to infrastructure or any other equipped entity, including cyclists and so on) – can provide valuable information about the driving environment, much of which on-board sensors are unable to detect. For example, while most sensors can only detect objects within their line of sight, a communicating vehicle can receive information from vehicles or infrastructure obstructed by hills, curves, other vehicles, and so on.



Figure 1. Conceptualization of V2V and V2I communications. Image source: Traffic Technology Today

2.4 Taxonomies of automation

A number of taxonomies of vehicle automation have been developed to distinguish different technologies (e.g, see Gasser and Westhoff, 2012). The two most well-known are those

developed by NHTSA (the US National Highway Traffic Safety Administration) and the SAE (the Society of Automobile Engineers).

NHTSA TAXONOMY OF VEHICLE AUTOMATION

NHTSA categorizes four levels of vehicle automation, in addition to a base level of no automation (Maddox, 2013; Medford, 2012; National Highway Traffic Safety Administration, 2013). The taxonomy is only briefly described here, as the taxonomy developed by the SAE is preferred.

Level 0 describes non-automated systems. Level 1 describes systems where either steering or speed control may be automated, but not both simultaneously. In Level 2, the system controls both steering and speed simultaneously, but the human driver must continuously monitor the vehicle's performance and must be available to take control with no notice. In Level 3, the driver need not monitor but must be available to take control within a short time when requested by the system. In Level 4, the system can drive itself in any situation without any need for a human to monitor or be available to take over.

SAE TAXONOMY OF VEHICLE AUTOMATION

The Society of Automotive Engineers (SAE) has developed a more comprehensive and precise taxonomy of vehicle automation (SAE, 2013; Shladover et al., 2013). The SAE categorizes automation in levels from 0 to 5. Levels 0 through 3 of the SAE taxonomy correspond closely with Levels 0 through 3 of the NHTSA taxonomy. Level 5 of the SAE taxonomy corresponds with Level 4 of the NHTSA taxonomy, where the vehicle can drive itself in any situation with no need for any human intervention. In addition, the SAE taxonomy introduces a distinct new category: Level 4 refers to a vehicle that can drive itself without any need for human intervention, but that can only do so in specific situations. This includes automated vehicles with relatively low levels of capability but that nevertheless can operate without human intervention while in controlled environments. Such environments could include specified roads such as freeways, lanes that are dedicated exclusively for the use of automated vehicles, or private zones such as campuses. In this report, the SAE taxonomy is used.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Huma	an driver monit	ors the driving environment				
0	No Automation	the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the <i>driving mode-specific</i> execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	Partiai Automation	the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving fask	System	Human driver	Human driver	Some driving modes
Auto	mated driving s	ystem ("system") monitors the driving environment	1			
3	Conditional Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	System	Some driving modes
5	Fuil Automation	the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	All driving modes

Figure 2. Summary of SAE taxonomy of vehicle automation. (SAE International, 2014)

Level 0: Non-automated

The human driver performs all driving tasks. Level 0 captures technologies that simply provide warnings and other information to a human driver to act on.

Level 1: Assisted

Either longitudinal or lateral control, that is, either steering or speed, is automated, but not both simultaneously. The human driver continually monitors the system's driving performance and must be available to intervene with no notice. The system can operate only in specific "driving modes", which are specific situations, such as cruising at speed on a freeway, or driving at low speeds in traffic jams.

Level 2: Partial automation

Steering and acceleration/deceleration are automated. The human driver must continuously monitor the system's driving performance and must be available to intervene with no notice. The system can operate only in specific situations.

Level 3: Conditional Automation

The vehicle performs all driving tasks. The human driver need not monitor the system's driving performance, but must be available to intervene, with some advance notice, within a certain transition time, if requested by the system. The system can operate only in specific situations.

Level 4: High Automation

Level 4 is called "high automation" but also encompasses fully automated operation in restricted conditions. The vehicle performs all driving tasks. The human driver need not monitor the system's driving performance, but may be requested to intervene; however, if the driver fails to intervene, the system can move itself to a safe location, pulled over to the side, for example. The system can operate only in specific situations.

Level 5: Full Automation

The vehicle performs all driving tasks. The human driver need not monitor the system's driving performance, nor will the driver be requested to intervene. The vehicle can drive itself in any situation without any involvement from a human driver.

LEVEL 4: FULLY AUTOMATED OPERATION IN LIMITED RISK CONDITIONS

Level 4 includes vehicles that, despite lacking the more advanced capabilities of Level 5 vehicles, can nevertheless drive themselves without any need for intervention from a human driver, provided risk is limited in some way.

Limiting risk reduces the technical challenges involved in achieving full automation. For example, if a hazardous situation emerges suddenly when driving at high speed, a vehicle may need to quickly plan and execute a complex series of evasive manoeuvres. At lower speeds, simpler manoeuvres, including simple stops, are more likely to suffice, and more time is available for the system to plan appropriate actions. In addition, while stopping in mid-lane on a regular road would obstruct traffic, this behaviour is less problematic in some of the areas where the use of Level 4 vehicles is contemplated. Finally, if a collision does occur, there is a reduced potential for injury to occupants and other road users at low speed.

Risk can be limited by controlling the environment or driving in a risk-averse fashion.

Controlled environments that can facilitate fully automated operation include:

- specified roads such as freeways, or certain rural highways
- lanes isolated by medians, vegetation, concrete barriers, or fences
- roads where pavement conditions, lane markings, signage, and other features meet a high standard
- private zones such as campuses
- parking facilities
- controlled areas with low-speed automated vehicles only low speed shuttles

Driving in a risk-averse fashion includes:

- driving at low speed
- slowing down or pulling over in risky situations
- allowing larger following gaps, etc.

Level 4 vehicles are not necessarily more advanced than Level 3 vehicles. The key point here is that full automation can be facilitated by limiting the difficulty of the driving task.



Figure 3. Example of an exclusive protected roadway used in a pilot deployment of Level 4 low-speed vehicles in Vantaa, Finland. Image source: CityMobil2.

3. Current and future vehicle automation technologies

3.1 Current vehicle automation technologies

A number of vehicle automation technologies are already available on the market. Examples of these are discussed below.

LEVEL 0

Examples of technologies that provide information or warnings to the driver include collision warning, lane departure warning, and blind spot monitoring (Bishop, 2005). Such technologies are offered by numerous manufacturers. These are not automation technologies – control of the vehicle is left up to the human driver.

ACTIVE SAFETY TECHNOLOGIES

Several manufacturers offer active safety technologies. These automated systems are not included in the SAE taxonomy – the SAE calls them "momentary intervention" technologies, since they only become active in emergency situations. These include collision avoidance technologies, such as automatic emergency braking. For example, Volvo's Pedestrian Detection technology uses radar to detect pedestrians. The driver is first given a warning, and if the driver does not react, the vehicle automatically brakes. Collisions can be avoided at speeds up to 35 km/h; at higher speeds, the technology reduces the severity of impact (Volvo, 2012). Mercedes, Lexus, and other manufacturers also offer collision avoidance technologies (Jaynes, 2013).

LEVEL 1

Level 1 technologies are widely available.

Adaptive cruise control (ACC), like regular cruise control, maintains the vehicle's speed at a desired level, but also uses radar or other sensors to detect the vehicle immediately in front; speed is automatically adjusted to follow at a safe distance (Baskar et al., 2011). ACC systems are available from many manufacturers, including Toyota, Nissan, Ford, BMW, and

Mercedes-Benz. Basic ACC technologies are generally capable of operating only at highway speeds, since low-speed driving situations are generally more complex and require a higher level of system intelligence to decide whether the vehicle should change speed or stop. More advanced low-speed ACC technologies have been developed that can control the speed of a vehicle at lower speeds and in congested stop-and-go traffic (van Driel, 2007; Hounsell et al., 2009; Volvo, 2012). Manufacturers such as Nissan, Toyota, and others offer this type of low-speed ACC.

Cooperative adaptive cruise control (CACC) is a related technology, where rather than using on-board sensors alone to detect the immediately preceding vehicle, V2V is used to detect the movements of preceding vehicles. This technology has been tested but is not available on the market.

Lane-keeping technologies use cameras, radar, and other sensors to detect the position of a vehicle relative to lane markings and/or the vehicle ahead; steering is adjusted to keep the vehicle in the lane. These technologies generally provide assistance to the driver rather than providing full control. For example, if the vehicle is drifting out of position, Volvo's Lane Keeping Aid "applies gentle steering wheel torque to help the driver steer back onto the intended course", and if the vehicle ends up leaving the lane, the driver is warned via a vibration in the steering wheel (Volvo, 2012). With the Steering Assist feature in Mercedes vehicles, if the driver is not holding the steering wheel, the driver is warned and then the Steering Assist function is deactivated (Vijayenthiran, 2012).

Automated steering control has also been implemented in buses, with some technologies based on optical sensing, and others based on other kinds of sensing, such as sensing of magnets embedded in the roadway. For example, a BRT system in Las Vegas used optical guidance to facilitate precise docking at bus platforms (Hardy, 2005), and a system piloted on a BRT route in Eugene, Oregon from 2013 to 2015 used magnetic guidance (Huang and Tan, 2016).

A number of manufacturers, such as Volkswagen, Volvo, Lexus, BMW, and Ford, have developed technologies to assist drivers in parking. Volvo's Park Assist Pilot aids parallel parking by controlling the vehicle's steering while instructing the driver to control the vehicle's speed. Ford and Toyota's automated parking technologies similarly leave brake and throttle control to the driver.

LEVEL 2

Level 2 technologies, which simultaneously control steering and speed, have emerged onto the market. Mercedes was the first to offer such a technology, in their S-Class vehicles. Mercedes' system provides a warning to the driver and then deactivates itself if the driver removes their hands from the steering wheel for more than a few seconds. Tesla also recently introduced Level 2 functionality (Ross, 2015). Other manufacturers, such as BMW, Audi, Volvo, Volkswagen, and Cadillac, are developing such technologies.

Similar technologies have been tested in buses. As far back as 2003, PATH (Partners for Advanced Transportation Technology) in California demonstrated automated bus driving while a driver monitored operation (Shladover, 2003). The bus guidance system used magnetic sensors to detect magnets embedded in the road. Recently, in 2015, the Chinese bus manufacturer Yutong demonstrated Level 2 driving over a trip of approximately 30 km. The vehicle reportedly "drove the entire route in regular traffic without human assistance", and reached "a top speed of 68 km/h, passed 26 traffic lights and was able to change lanes without any problem" (Crowe, 2015).



Figure 4. Automated bus platooning. Image source: California PATH

In 2016, Mercedes-Benz tested their "CityPilot" automated bus technology over a BRT route approximately 20 km in length that links Amsterdam's Schiphol airport with the town of Haarlem. The bus has a top speed of 70 km/h, and is equipped to communicate with infrastructure such as traffic signals (Vincent, 2016)(Thomas).



Figure 5. Mercedes-Benz automated bus. Image source: AUTOSEITUNG

LEVEL 4

Level 3 vehicles are not yet available, but some Level 4 vehicles are – as discussed above, Level 4 technology is not necessarily more advanced than Level 3, since Level 4 includes vehicles that can operate without a human driver, but only in specific conditions.

Several groups are developing low-speed, relatively lightweight, automated, electric vehicles. In 2014, the French company Induct began selling the Navia, an eight-passenger shuttle with a maximum speed of 20 km/h, and no steering wheel, for \$250,000 (Associated Press, 2014). These shuttles have been tested in Singapore on a 2 km route between a university and a business park (Sunderland, 2013). Newer versions of these vehicles, branded as Navya Arma, carry up to 15 passengers. Arma vehicles are being tested in other locations, such as Lyon,

France, where they are providing free service along a 1.3 km, 10-minute route on public roads (Connexion, 2016).

The CityMobil2 project in Europe has been developing small vehicles that carry between 4 and 20 passengers, sometimes referred to as cybercars, to operate in fully automated mode at low speeds in uncontrolled environments and at higher speeds in more protected environments (CityMobil2, 2013). These vehicles are similar to PRT (personal rapid transit) vehicles, such as those in operation at London's Heathrow airport, but do not require dedicated guideways (Parent and Fortelle, 2005). Examples of vehicles tested in this project included two 12-passenger buses, limited to 10 km/h, developed by Robosoft, tested on a 1.3 km route through a seaside pedestrian route in Oristano, Italy, in 2014 (CityMobil2, 2014); and six 10-passenger minibuses developed by EasyMile, tested in Vantaa, Finland, in 2015, connecting a railway station with exhibition grounds a kilometer away, at a maximum speed of 15 km/h (CityMobil2, 2015). In tests that took place in Helsinki in 2016, the vehicles drove in mixed traffic, at approximately 11 km/h (Yle, 2016)(Ross, 2016a), EasyMile shuttle buses were also tested in Lausanne, Switzerland, connecting a metro station with different areas of a nearby university campus over a 2.3 km route (letemps.ch, 2015). These vehicles were also tested in 2015 in the Greek city of Trikala on a 2.4 km route in the centre of the city (Associated Press, 2015), and have also been tested in other cities, such as La Rochelle, France (Genet, 2014). Similar vehicles transported members of the public in a test along a one-mile path inside a Singapore park (Hamblen, 2016). 11-passenger shuttle buses are also undergoing testing in Sion, Switzerland, over a 1.5 km route, at a maximum speed of 20 km/h. An on-board attendant monitors performance (Hulm, 2016). Auro Robotics has also tested a five-passenger automated shuttle on the campuses of Santa Clara University and California State University Sacramento (Coren, 2016).

The company Local Motors has developed a 12-passenger shuttle bus called "Olli" with a maximum speed of approximately 20 km/h (Miller, 2016). Reportedly, 30 percent of the bus is produced using a 3D printer (Rabb, 2016). They are undergoing testing in the Washington, D.C. area in 2016 (Murphy, 2016b), and will be tested soon in Las Vegas and in Miami-Dade County (Rothberg, 2016), and on public roads in Vesthimmerland, Denmark, in September (Copenhagen Post, 2016).



Figure 6. Olli automated shuttle. Image source: Computer World

Another small, light, low-speed automated vehicle is known as the Lutz Pathfinder. Up to around 40 of these electric-powered two-passenger pods have been undergoing early stages of testing, and will soon be tested further along pedestrian pathways in the UK town of Milton Keynes, connecting a train station to a shopping centre about a mile away (BBC.com, 2015)(OneMK, 2016)

Google is also developing a low-speed automated vehicle. Since early 2014, they have been developing a small two-passenger self-driving vehicle with a maximum speed of 40 km/h (Urmson, 2014). Such low-speed automated vehicles could provide service in retirement communities and industrial and university campuses, resorts, military bases, amusement parks, and so on, or, on speed-restricted roads in lower-density neighbourhoods, they could act as feeders for public transit routes, helping to address the "first and last mile" problem. For example, in Wagenigen, the Netherlands, modified EasyMile minibuses known as WEpods may begin serving a fixed route between a university and a nearby inter-city railway station in 2016, at speeds up to 25 km/h (autoworldnews.com, 2015). While they will operate on public roads, they will not operate in peak traffic periods, in poor weather, or at night, and will be monitored remotely from a control room, as well as by an on-board steward

(CityMobil2, 2016a). In the first test run in early 2016, speed was limited to 8 km/h (Hsu, 2016a).



Figure 7. Low-speed automated vehicle from Google. Image source: Google

Level 4 also includes conventional vehicles that can operate at higher speeds without human oversight, but only when in appropriate situations. Volvo is planning to test such technology on public roads in the DriveMe program beginning in 2017. 100 volunteers in Gothenburg, Sweden, and London will test automated Volvo XC90s (Muoio, 2016)(Volvo, 2016)(Danielle Muoio, 2016). The tests will be restricted to select roads that have been mapped in 3D. If weather conditions become unfavourable, drivers will be prompted to take control. If the driver fails to do so, or if there is a malfunction in the automated system, the car will bring itself to a stop on specially designed turnouts (McGehee et al., 2016).



Figure 8. Navya Arma low-speed automated vehicle. Image source: www.20minutes.fr

Various auto manufacturers are also developing automated valet parking, where the driver exits the vehicle and the vehicle drives itself at low speed in a risk-averse fashion to a parking space. Tesla recently introduced a "Summon" feature that enables car owners to direct their unoccupied vehicles to enter and exit a garage and park (Loizos, 2016).

Automated mining trucks, such as those in use at the West Angelas mine in Australia, are another example of Level 4 (Latimer, 2015). These trucks operate in a highly risk-averse fashion at low speeds in environments with little traffic. If the obstacle detection system detects an obstacle, such as a human, the truck simply slows down and then stops if the obstacle is still there. Suncor Energy may begin operating similar vehicles soon in oil sands mining in Alberta (TTnews.com, 2015).

3.2 Future automation technologies

LEVEL 3

Several projects to develop Level 3 automation are underway. Several manufacturers, such as GM, Mercedes, Tesla, and Nissan, as well as automotive suppliers such as Bosch and Delphi, have announced plans to offer Level 3 technologies by around 2020 (Kilcarr, 2016).

Another Level 3 technology is platooning. SARTRE was a recent project where the platoon, or so-called "road train", consisted of a V2V-equipped lead truck, manually driven by a professional driver, followed by up to eight cars, also equipped with V2V. These platoons were tested on public roads in Spain, travelling at speeds of up to 90 km/h with gaps between vehicles as small as four metres (Bergenheim et al., 2012). The "road trains" are being promoted especially as a way to allow motorists the freedom to perform other activities while travelling; in addition, its touted benefits are energy savings due to improved aerodynamics, improved traffic flow, and improved safety (Fleet News, 2012).

Another demonstration of platooning technology took place in 1997, when the National Automated Highway Systems Consortium demonstrated an eight-car platoon, with vehicles traveling with 6.5 metre inter-vehicle gaps at up to full highway speed (Tan et al., 1998). Magnetic markers were buried in the roadway to enable the vehicles to detect their position in the lanes, as well as to receive information on upcoming curves, exits, and so forth, and the vehicles used V2V to communicate their movements.

LEVEL 5 (OR HIGHLY ADVANCED LEVEL 4)

Several projects to develop highly advanced automation are underway. It is not clear whether these projects are aiming at achieving Level 5 or a highly capable Level 4 system that can operate in a wide but not comprehensive range of situations.

Google

Google's self-driving car project is the most prominent example of a project to develop Level 5, or a highly advanced Level 4. While it is working on a Level 4 low-speed vehicle, it is continuing to work on automating conventional light-duty vehicles. Each test vehicle senses the environment with radar, cameras, GPS, and other sensors, but relies especially on a rooftop LIDAR (a remote sensing technology that scans the environment with laser light) to develop a detailed 3D map of the environment. That map is compared against another map that was developed beforehand while manually driving the route several times (Levy, 2016). Comparing the maps enables the automated system to identify features of the static environment, like traffic lights and crosswalks, as well as moving entities such as other vehicles, pedestrians, and cyclists.

Google has conducted testing primarily in the Mountain View, California area; testing is now also conducted in Austin, Texas; Kirkland, Washington; and Phoenix, Arizona (Shepardson, David, 2016).

More recently, the ridesourcing company Uber has been developing an automated vehicle. Similar to Google, their vehicle also relies on creating detailed 3D maps of an area before driving those roads (Chafkin, 2016) (Aupperlee, 2016). In August of 2016, Uber began providing rides to members of the public in Pittsburgh in their test vehicles. The safety of the vehicle is monitored by a test driver and a copilot observer in the front passenger seat (Grabar, 2016).



Figure 9. One of the light-duty vehicles in Google's fleet of self-driving test cars. The LIDAR is prominently visible on the rooftop. Image source: Google.

While Google's vehicles have cumulatively driven long distances, the vehicles are continuously monitored by test drivers who take over control when situations arise that may be beyond the capability of the automated system; thus, while the precise capabilities of Google's test self-driving vehicles are not clear from publicly available documentation, it is evident that they have not attained Level 5 capabilities. While their fleet of test vehicles has now driven large distances in automated mode with no reports of major safety problems – as of September 2016, Google reported that its fleet of test vehicles had driven over 3 million km in automated mode without having caused any collisions – this is a very limited indicator of

performance. One reason is that testing so far has generally been conducted in favourable conditions, avoiding difficult weather and road environments. Arguably more important is the fact that their vehicles are constantly monitored by human test drivers who take over control if there is any indication that a risky situation is emerging. The nature and frequency of these interventions has not been disclosed, ¹ though Google team members have previously admitted interventions are frequent. In addition, it is interesting to note that Google's monthly reports reveal that their vehicles are often driven in manual mode – approximately 1 km is driven in manual mode for every 4 km in automated mode.

Other projects

The Autonomos team, from Germany, have conducted various tests; most notable is a recent trip of 2400 km trip in Mexico (Mamiit, 2015). A long voyage was also conducted by Delphi earlier in 2015 - their team drove a vehicle from San Francisco to New York "with 99 percent of the drive in fully automated mode" (Prigg, 2015). However, this metric does not make clear the nature and frequency of test driver interventions. In 2010, the VisLab team also conducted a long voyage in their Intercontinental Autonomous Challenge, where two vans were driven over a 13,000 km route from Parma, Italy to Shanghai, China (Bertozzi, 2013). The lead van drove largely in automated mode, though a human driver frequently intervened, while the following van was fully automated and followed the route set by the lead vehicle. The vehicles generally had to be driven manually through cities. These vehicles drove without highly detailed maps of their routes, and primarily used cameras for sensing. In 2013, the VisLab team conducted a test of an automated vehicle on freeways and city streets in Parma, Italy, and negotiated some challenging environments, such as pedestrian crossings and traffic lights. It drove in a particularly risk-averse fashion - for example, coming to a complete stop before entering roundabouts or merging onto other roads (VisLab, 2013). Oxford University is developing a system that, like Google's, depends on pre-developed 3D maps. Unlike Google's system, it does not use GPS, and it uses a less expensive LIDAR system (Arthur, 2013; Lee, 2013). In 2013, Mercedes-Benz tested an automated vehicle, that used 3D maps, over a 103 km route on German highways and city streets (Undercoffler, 2013).

¹ In late 2015, Google provided a report to the California Department of Motor Vehicles that enumerated selected incidents where its test drivers intervened in the operation of its vehicles; however, the precise criteria for inclusion in the report were not made clear. (Google, 2015a)



Figure 10. A map of the route taken by the VisLab vehicle on its 13,000 km test drive from Parma to Shanghai. Image source: IEEE Spectrum.

4. Timelines of emergence of future technologies

4.1 Advanced automation technologies: issues to resolve

A number of issues must be resolved before more advanced technologies, including Level 3, Level 5, and Level 4 vehicles that can operate in a wide range of situations, emerge onto the market.

TECHNICAL CHALLENGES

Driving, whether conducted by human or machine, can be understood as comprising three main tasks: situational awareness, decision, and action. Situational awareness consists of sensing and interpreting the environment and the vehicle itself with respect to the environment.

Automated systems generally have good capabilities in the action task, in that they are capable of executing precise and quick control of the steering and speed of a vehicle. For example, after detecting a hazard, an automated system is capable of activating the brakes more quickly than a human. Automated systems have certain strengths in the situational awareness task, but also have several weaknesses. They also have particular challenges in the decision task.

Situational awareness

Some sensors can detect objects humans cannot – for example, an infrared sensor may be able to detect objects in poorly-lit environments where a human would be incapable of seeing. Similarly, an automated system using V2X may have access to ancillary information not detectable by either humans or engineered sensors. In addition, automated systems are not prone to the distraction or fatigue problems humans suffer from.

Different sensors have different strengths, and are not effective in some situations. LIDAR is useful for developing 3D maps and is relatively accurate, but is expensive, and functions poorly in rain and snow. Radar is effective for measuring motion and works in a range of conditions, but has lower accuracy. Cameras are useful for interpreting scenes and are inexpensive, but generate data that is challenging for automated systems to process (Santo, 2016). Rain, snow, dust, and certain light conditions can confuse camera-based sensors
(Young, 2016). Google notes that in heavy rain, their cars "automatically pull over and wait until conditions improve", or test drivers take over (Google, 2015b). It has been reported that water splashing from puddles also poses a problem (Bizjak, 2016), and even exhaust plumes or steam plumes venting from underground infrastructure that are barely visible to the human eye can cause problems for LIDAR (Radecki et al., 2016). Snow can obscure lane markings, road edges, or even the sensors themselves. Ford in particular has made early progress in automated driving on snow-covered roads (dailymail.co.uk, 2016)(Wong, 2016b). One approach is to navigate with respect to various objects, such as guardrails or signs (Richardson, 2016). It is not clear from available reports the level of reliability that has been achieved so far, nor is it clear how effective the technology is in falling snow (Davies, 2016). GPS performs poorly around tree canopies, tall buildings, and in tunnels. Radar and LIDAR are vulnerable to interference from other vehicles using the same sensing technologies. Extreme heat and cold can also affect sensors (Fung, 2016).

In addition to improvements in existing sensors, new sensor technologies may help to address challenges in sensing. For example, MIT is developing a ground-penetrating radar that could help vehicles localize themselves on snow-covered roads by mapping features such as rock beds and soil layers underneath roads (Ryan, 2016).

Interpreting sensed data about the environment is a particular challenge for automated systems. Interpretation is difficult in particular where the static environment is complex, cluttered, and not clearly structured – for example, where lane markings are worn away, or where road construction is underway. Interpretation is similarly difficult where the dynamic environment is more complex, cluttered, and rapidly changing – for example, where vehicles are rapidly changing speed and direction, and vulnerable road users such as cyclists and pedestrians are present. Humans outperform automated systems at interpreting these kinds of complex, ambiguous, poorly defined, "messy" situations (van den Beukel, 2011). These kinds of complex situations are especially common in urban environments, where there may be pedestrians, cyclists, children, animals, officers directing traffic, and doors on parked cars opening into traffic (Shladover, 2013a) (all of which are possible but less likely events in more controlled environments such as freeways). Such conditions are also challenging for automated systems since there is less available time and space to take corrective actions that may be necessary.



Figure 11. Complex, cluttered, highly dynamic urban environments, like this street in Montreal, are challenging for automated vehicles. Image source: Montreal Gazette

Automated systems that depend on highly detailed prior maps of the environment are naturally limited by the range of territory for which such maps are available. Even where they are available, these systems have difficulty interpreting the environment where the reference maps have not been updated to reflect changes in the environment (Seo et al., 2012). This may be the case with construction zones, for example.

Identifying objects is a challenge. Even objects that may be easy for humans to detect and interpret can be difficult for automated systems. For example, a Google engineer has noted that recognizing traffic signals can be challenging (Williams, 2016). Similarly, an automated system may have difficulty distinguishing a speed bump from a fallen pedestrian, or a plastic bag from a rock. Identification may be very difficult in some situations – for example, where a pedestrian is disguised by an elaborate Halloween costume (Kent, 2012).

In addition, after identifying objects, an automated system must be able to make predictions about the behaviour of vehicles, pedestrians, and other objects in the environment. For

example, an automated system may identify an object in the street as a ball, but it should also be capable of inferring that there is a possibility a child might run into the street after it (Levy, 2013).

Automated systems would also be challenged in situations where drivers currently rely on eye contact, gestures, or speech to communicate with other road users. Road users often communicate their intentions through more or less subtle cues – it is not clear how an automated system would function in a situation where a pedestrian waves to let a vehicle pass, for example. A situation that would be particularly challenging is where contradictory signals must be interpreted by the automated system – for example, where a police officer is directing traffic and overriding a traffic light (Blodget, 2013).

Difficulty of ensuring reliability

It will be a challenge to develop automated systems with overall capabilities comparable to those of humans – and the challenge may be increased if, to ensure public acceptance of the technologies, the vehicles need to demonstrate driving capabilities that exceed those of good human drivers.

Steven Shladover of the California Partners for Advanced Transportation Technology notes that Level 5 systems would require failure rates "orders of magnitude longer than the mean times between failures for modern software-intensive consumer products such as laptop computers and mobile phones, and many orders of magnitude longer than any automated vehicle has ever driven continuously, in real traffic, and without human intervention." He points out that currently, fatal collisions involving human drivers "occur about once per 2.5 million hours of vehicle travel and injury crashes occur about once per 55,000 hours of vehicle travel", which is a much better performance rate than existing electronic consumer products or complicated electro-mechanical devices (Shladover, 2013a). He also makes the comparison to aircraft autopilots, arguing that Level 5 "performance requirements are multiple orders of magnitude more difficult than they are for commercial aircraft autopilot systems, but at the same time the system needs to be multiple orders of magnitude cheaper (and cannot be guaranteed to receive the prescribed preventive maintenance). Compared to an autopilot, the automated road vehicle will need to track an order of magnitude more targets, with a tracking accuracy for each target a couple of orders of magnitude higher and the system needs to detect and respond to new threats a couple of orders of magnitude faster as well in order to provide safety."

To prove safety, extensive testing will be necessary. Smith, in a cursory analysis, found that "Google's cars would need to drive themselves (by themselves) more than 725,000 representative miles without incident for us to say with 99 percent confidence that they crash less frequently than conventional cars. If we look only at fatal crashes, this minimum

skyrockets to 300 million miles" (Smith, 2012b). A study by RAND further examined this, and found that automated vehicles would have to be driven hundreds of millions of miles and sometimes hundreds of billions of miles to demonstrate safety (Kalra and Paddock, 2016). As noted above, though Google's fleet has driven approximately 3 million km in automated mode as of late 2015, test drivers intervene whenever risky situations emerge. Interestingly, according to a report from Google, their vehicles drove in automated mode up to 230,000 miles without any "simulated contact events", which they describe as events where human test drivers took over control and where counterfactual simulation of the event afterward indicated that the vehicle would have made contact with another object (Google, 2015a). This may appear to suggest that Google is approaching the threshold of capability postulated by Smith; however, it is important to emphasize that Google's test drivers "err on the side of caution and take manual control if they have any doubt about the safety of continuing in autonomous mode... or in situations where other concerns may warrant manual control, such as improving ride comfort of smoothing traffic flow" (Google, 2015a). Therefore, it is too early to conclude that Google's vehicles have attained very high levels of capability.

Given the potential need to drive huge distances in testing, other testing approaches are being developed; for example, Zhao et al. proposed an approach to accelerate the testing of automated vehicles (Zhao et al., 2016).

Affordability

Another technical challenge is that automated systems must attain the necessary level of safety while being sufficiently affordable to allow for wide adoption. Currently, test vehicles are expensive, especially because of sensors such as LIDAR – currently, the LIDAR used on Google vehicles costs around \$75,000. It is anticipated that these costs will drop. It is uncertain when and to what degree this will happen, though the sensor manufacturer Velodyne reports that its latest prototype will cost \$8000, and prices will drop to under \$200 by 2018 (Young, 2016). On a related note, Shladover points out that the sensor, control, and actuation systems in a Level 5 vehicle would have to be "self-diagnosing, self-healing and functionally redundant to prevent their own failures", which would require extensive development and testing and make the technology more expensive (Shladover, 2013a).

ETHICAL ISSUES

The decision-making process poses ethical challenges for automated systems, as some driving situations may require choosing between alternatives that impose different levels of risk on different road users. Numerous vivid examples of such situations can be imagined, such as a choice between the automated vehicle crashing into a pedestrian vs. a school bus, or a choice between crashing into a pedestrian vs. crashing into a truck and harming passengers in the automated vehicle. Such choices require complex risk comparisons and entail ethical judgements. These ethical challenges are not unique to automated systems – human drivers would also struggle to make effective judgements in these situations. The unique challenge for an automated vehicle is the need to pre-program the vehicle's decisionmaking framework. In such situations, a human driver would be unlikely to be criticized for their ethical judgement, simply because they did not have sufficient time to weigh the alternatives according to their moral value; in contrast, because an ethical framework (whether explicit or implicit) would be programmed into an automated vehicle ahead of time, the programmer has plenty of time to consider what the appropriate action should be. The ethical judgments programmed into automated vehicles could raise legal and liability issues, and could also complicate public acceptance (Goodall, 2013).

However, ethical issues for automated vehicles go beyond dilemma situations on the road. Automated vehicles also must make decisions that determine the level of risk to impose on their passengers and on other road users. The decisions they make will imply tradeoffs between safety and other priorities, such as travel speed. Another example of a decision that implies risk tradeoffs is a decision whether to travel through an intersection without decelerating and re-accelerating. This would reduce energy consumption, but would increase the severity of a potential collision. Similarly, if automated vehicles drive at short headways in platoons, they will consume less road space and could improve traffic flow, but they will also increase the risk of a pile-up collision.

Difficulties in prediction introduce an additional ethical complication. For example, there is some uncertainty regarding the trajectory an automated vehicle may take, where it may steer to evade an object but instead lose traction and strike the object. In addition, the choices made by other actors on the road are difficult to predict. Various complexities may arise. For example, an automated vehicle may be programmed to give the passenger speedy service and to drive aggressively to do so. When the vehicle attempts to merge into freeway traffic, it may encounter another equally aggressive vehicle. Each vehicle may attempt to accelerate and cut in in front; this behaviour increases risk for the passengers in both vehicles.

One possible response to such a scenario would be for manufacturers to program vehicles to be cautious during merges. In this case, when a cautious vehicle encounters another cautious vehicle attempting to merge into traffic, both slow down for each other, which wastes time and again potentially increases the risk of collisions, especially rear-end collisions. Another unintended consequence in this scenario would be where an opportunistic vehicle manufacturer continues to program their vehicles to be aggressive. Merging conflicts would become rare, since the cautious cars always let the aggressive cars ahead, but this would result in unfair delays being imposed on passengers in the cautious cars. To avoid such situations, automated vehicles will need to coordinate their behaviour. While V2V technology would be useful for this, it will still be necessary to develop rules that clarify behaviour in a

range of vehicular interactions, such as when one vehicle should let another ahead. This may be further complicated when automated vehicles must interact with human drivers, who may be less amenable to strict rule-following.

Certain programming approaches may pose additional ethical challenges. For example, programmers may use a "deep learning" approach, used by Google and others (Hsu, 2016b)(nvidia, 2016), where the automated system is exposed to an abundance of data and then guided to learn to recognize patterns. If the programmers use deep learning to allow the system to discover what driving choices to make in various situations, after this learning process is complete, the vehicle will drive itself using rules it has developed for itself. The programmers will not have programmed explicit rules, and will not be precisely aware of the rules the vehicle is following. The system "effectively 'programs itself'" (Surden and Williams, 2016). If the vehicle fails, it may be difficult to explain why the failure occurred (Knight, 2016). However, even if the behavioural rules the vehicle follows were not explicitly chosen by the programmers to align with an ethical framework, the choices the vehicle makes will still imply ethical valuations. A deep learning-based car may make choices that are criticized as unethical. If programmers are unable to predict precisely how the vehicle will behave in given situations, this may reduce public trust in such a vehicle.

Furthermore, ethical questions arise before automated vehicles are allowed onto the roads. For example, key issues that must be addressed include that standard of safety an automated vehicle must meet before it is allowed on the road, and the level of certainty regarding the vehicle's capabilities and limitations that must be achieved (Loro, 2016a).

LEGAL ISSUES

A number of jurisdictions have legalized the testing of automated vehicles with human monitors on public roads. In North America, these include US jurisdictions such as Nevada, California, Florida, the District of Columbia, and Michigan. In addition, the province of Ontario has published regulations for the testing of automated vehicles on public roads (Ministry of Transportation of Ontario, 2015). However, the legality of operation of Level 3, 4, and 5 technologies, without continuous monitoring from a human driver, remains to be clarified. In 2012, Bryant Walker Smith, a leading expert on the legal dimensions of vehicle automation, argued that the legality of such vehicles in the US is not clear, though US law "probably does not prohibit automated vehicles". The U.S. Department of Transportation (USDOT) recently issued a federal policy on the testing and deployment of automated vehicles, including guidance on how to assess automated vehicle safety, guidance to state-level policy-makers, and discussion of existing and proposed regulations regarding deployment. The USDOT has requested the public to comment on the policy (USDOT, 2016). Each state must still develop their own legislation regarding automated vehicles. The legalization of the operation of Level 3,

4, and 5 automation will depend largely on proving safety, which, as mentioned above, would require extensive testing.

LIABILITY ISSUES

The question of who is liable for collisions also needs to be resolved. If the human is not driving, it is reasonable that blame for a crash should be laid elsewhere. Culpability for a crash may be distributed among various parties, such as an auto manufacturer, a designer of system components, or a computer programmer. The apportioning of blame would be a more complex problem with partially automated systems, where the human driver has some monitoring or backup responsibility.² In general, manufacturers will face greater liability for crashes than at present; resolving this could stall the deployment of some rapidly emerging technologies (Marchant and Lindor, 2012).

Some manufacturers have made apparently divergent statements on the issue of liability. For example, Frisoni et a. note that Volvo has stated that it will take responsibility for crashes caused by its automated vehicles, while Tesla has stated that the driver will be responsible for crashes that occur while Autopilot mode is on (Frisoni et al., 2016). However, Volvo has not clarified the details of how liability will be treated, such as in cases where control is being passed between the automated system and the human driver (Volvo, 2015). In the case of Tesla and their current Level 2 technology, while the company states that the human driver is responsible, this may be open to dispute. According to Bryant Walker Smith, a leading expert on automated vehicle legal issues, it is possible to argue that Tesla may in fact be liable in certain crashes, such as a fatal crash that occurred in May of 2016, by arguing that there are deficiencies in how the system is designed and how effectively users are supervised (Martinez, 2016).

Once the question of culpability is resolved, and assuming automation improves safety, insurance costs could decrease. This cost may simply be added to the sale cost of the vehicle, if the manufacturer bears liability for crashes (Peterson, 2012). Other changes may result; for example, no-fault insurance may become more common as manufacturers assume more responsibility (Kalra et al., 2009).

² Volvo recently announced that they would "accept full liability whenever one of its cars is in autonomous mode"; however, they did not clarify various issues, such as how liability would be addressed during or shortly after transitions of control between a human driver and an automated system. (Volvo Car Group, 2015)

SECURITY ISSUES

Security is a concern, especially for automated vehicles equipped with V2X (Petit and Shladover, 2014). In testing, researchers have already demonstrated the potential to gain access to and take control over a vehicle. There is concern that hackers could cause vehicles to crash, for example. The need to solve security problems could slow the emergence of some automated vehicle technologies.

PRIVACY ISSUES

Privacy advocates are also concerned about protecting the data on the movements of people that would be generated. Such concerns could hamper public acceptance of automated vehicles (Fagnant and Kockelman, 2015a).

4.2 Level 3 timeline predictions

There is a general consensus among experts that Level 3 technologies will appear in the range of 2020 to 2025. These systems would be capable of operating in a fully automated mode in controlled environments on freeways. For example, Shladover estimates that such systems could emerge in the 2020 to 2025 period (Shladover, 2013b); this assessment is reasonably close to that given by Steve Underwood of the Center for Automotive Research, who estimates that vehicles that can operate in automated mode on freeways or highways will emerge onto the market around 2020 (Underwood, 2013). These estimates are also close to some other estimates, such as Nissan's statement that their Autonomous Drive technology would be available by 2020.

4.3 Level 5 timeline predictions

Predictions regarding when Level 5 will emerge onto the market are far more divergent.

Some predict it will emerge soon. For example, the market research firm ABI Research has predicted Level 5 vehicles will be on the market by 2020, and panelists at the SAE 2013 World Congress anticipated they would arrive between 2020 and 2025 (Costlow, 2013). The most recent estimate from the Canadian Automated Vehicles Centre of Excellence is that "fully-autonomous" vehicles will be commercially available by 2020 (Canadian Automated Vehicles Centre of Excellence, 2015). Others, such as Richard Wallace, a director with the Center for Automotive Research, and Ralf Herrtwich, who leads automation research at Daimler, have stated that Level 5 could emerge as early as 2025, but not earlier (Blua, 2013; Eisele, 2013).

Statements by Google are often pointed to as indications that Level 5 will emerge very soon even as early as 2017. For example, in 2012, Sergey Brin, one of Google's founders, stated in reference to the Google self-driving car that "you can count on one hand the number of years until ordinary people can experience this" (Fisher, 2013). The implication is that Google would have their technology available by 2017. In early 2015, the director of the project, Chris Urmson, stated that his aim was to have the technology ready in less than five years. Though Google's statements are widely interpreted as referring to Level 5 (e.g., see Globis Consulting, 2013), Google representatives have in fact not specified the level of capability of the technology they are aiming for. Some statements from Google have implied they may be aiming for Level 4 - for example, Anthony Levandowski, a manager in the project, mentioned that the vehicle would need to be able to come to a safe stop by itself if the driver failed to take over when requested. More recently, Chris Urmson of Google stated of their technology: "How quickly can we get this into people's hands? If you read the papers, you see maybe it's three years, maybe it's thirty years. ...[H]onestly, it's a bit of both." He further clarified that early versions of the technology would likely be restricted to favourable geographies and weather conditions (Gomes, 2016).

Statements by other groups working on automation have often been interpreted overoptimistically. For example, it was widely reported in 2013 that Nissan was promising a Level 5 vehicle by 2020 (Bigman, 2013); however, Nissan had simply stated that they intended to introduce a feature called Autonomous Drive by 2020, which would likely be limited to highway driving and would require driver monitoring (Kiley, 2013).

Recently, Mobileye and Delphi, who supply hardware and software to automakers, announced a partnership and an intention to provide Level 4 and 5 systems to carmakers by 2019 (Etherington, 2016). The statement did not make clear when the companies intend to make available Level 5 systems in particular. Ford has stated an intention to make a Level 4 vehicle commercially available in 2021 to provide ride-hailing and ride-sharing services (Ford, 2016)(Mitchell and Wilson, 2016). BMW has also stated that it is aiming to provide highly automated vehicles by 2021(Mitchell and Wilson, 2016).

Some predictions have Level 5 emerging further in the future. For example, Daniel Flores from the advanced technology group in General Motors has stated that Level 5 vehicles are "years, maybe decades away" (Shankland, 2013), and Jürgen Leohold, VW's research chief, has estimated that they may be available in 50 years. Sven Beiker, a director with the Center for Automotive Research, stated in 2012 that "[t]wenty years from now, we might have completely autonomous vehicles", with the qualification: "maybe on limited roads" (Sharma, 2012), thus indicating that he does not necessarily expect that Level 5 will have emerged in that timeframe. Steven Shladover of the California Partners for Advanced Transportation Technology contends that Level 5 may be decades away (Brandom, 2012), and has even stated that it may not be achieved "even within this century" (Shladover, 2013a).

The wide range of predictions indicates a high degree of uncertainty regarding when Level 5 will be available. However, there are several reasons it may be more reasonable to anticipate it will emerge further in the future than the most optimistic estimates suggest.

Technical progress to date often overstated

The level of technological advancement achieved to date is often overstated. For example, as discussed above, the large distance Google's fleet have driven in automated mode, and the fact that they have apparently not caused any collisions while in automated mode, is often alluded to as evidence of very high capability. However, as pointed out above, the fact that testing takes place in favourable weather conditions and less challenging road environments, and under continuous human monitoring, with interventions of undisclosed frequency, means that it is not justified to infer that Google's vehicles must have achieved very high capability. Similarly, while reports that 99 percent of the 3400 mile test drive of a Delphi vehicle from San Francisco to New York in 2015 was completed in automated mode (Prigg, 2015) may appear to suggest a high level of capability, it is not clear what situations the automated system was able to handle, and whether it would be able to reliably do so without vigilant monitoring by a human test driver. In general, where a human driver is available to intervene in the operation of the vehicle, it is not possible to make a meaningful assessment of the capability of an automated vehicle, just as it would not be possible to meaningfully assess the capability of a human driver who always has a driving instructor at their side who is always at the ready to take control with a second steering wheel and set of pedals.

Technical challenges remaining may be underestimated

While there are numerous significant technical problems to be solved, it is possible that they will be resolved soon. Some commentators contend that there is good reason to trust that will be the case. The rapid pace of development of information technologies in recent years and decades is often invoked as a comparison, often using the so-called Moore's Law as a point of reference. While it is sometimes interpreted more broadly, Moore's Law describes how the number of transistors that can be fitted onto a chip tends to increase exponentially over time. It has been suggested that, as was the case for capability and affordability in computing power, the capabilities and affordability of vehicle automation technology will also advance rapidly (Mui, 2013). However, while this may be the case, it is not prudent to ascribe any certainty to assertions that vehicle automation technologies will advance in accordance with the rapid trajectories of development described by Moore's Law, since it is of course only a rule of thumb that happens to fit with recent progress in chip manufacture, rather than a deterministic law. In addition, the analogy to Moore's Law may have limited applicability to vehicle automation since the various components of automated vehicles, such as sensors and software, may be more difficult to advance than transistor density. Nevertheless, it is also

prudent to acknowledge that it is quite possible that vehicle automation technology may advance rapidly in the coming years.

A related note is that some commentators contend that there may be certain technological shortcuts to achieving Level 5. For example, KPMG has argued that the "convergence" of communication and sensors would reduce the need for expensive sensors (KPMG, 2012). That is, because on-board sensors and vehicle communications technologies have their own unique strengths and weaknesses, the contention is that combining the two technologies would allow the strengths of each to offset the weaknesses of the other. In this view, Level 5 could be achieved before the existence of sensor-based technology that can comprehensively and reliably sense the environment, since V2X technologies would be able to "fill in the gaps". However, V2X cannot reduce the need for sensors, as long as the vehicle must account for the presence of some non-communicating entities in the driving environment. For the foreseeable future, many vehicles will be non-communicating, as will most infrastructure, all or most pedestrians, and presumably most children on tricycles, cats. deer, soccer balls, fallen tree branches, and so forth. Unless such non-communicating entities are excluded from the driving environment, an automated vehicle must be capable of operating safely using on-board sensors alone. That is, the vehicle must have sufficient situational awareness with its on-board sensors alone to operate safely; V2X can enhance the vehicle's situational awareness but cannot be relied upon to provide basic safety.

5. Safety

According to various sources, human error causes 75 to 95 percent of crashes (Bayless et al., 2013; Wierwille et al., 2002); so, if automated systems perform with a high level of reliability, it is plausible that augmenting or replacing humans with automated systems could improve safety significantly. Studies of some automated systems lend support to this view – for example, studies by NHTSA have found that crash avoidance systems could reduce various categories of crashes by 24 to 48 percent (Gupta, 2011). It is currently uncertain what degree of safety benefits higher levels of automation would produce, though there is clearly a large theoretical potential. Overall safety improvements would of course require that the rate of machine error is low enough that such errors do not outweigh the human errors that are eliminated.

5.1 Safety benefits from less advanced technologies

Safety improvements can be achieved with less advanced forms of automation. For example, according to some reports, automatic emergency braking systems could reduce crashes by 27 percent, and V2V and V2I systems, without automation, could reduce by approximately 80 percent those crashes that do not involve impaired driver conditions such as being drowsy or drunk (Najm et al., 2010; Rau et al., 2015). In 2016, the Insurance Institute for Highway Safety (IIHS) found that vehicles equipped with forward collision warning technology are 23 percent less likely to rear-end other vehicles. Vehicles that are also equipped with automatic emergency braking were found to be 39 percent less likely to rear-end other vehicles (IIHS, 2016).

5.2 Human factors risks introduced by Level 1, 2, 3

In partially automated systems, driving responsibilities are shared between a human and a machine – either simultaneously or sequentially. While it is possible that this will result in safety improvements, the fact that responsibility for driving is shared between human and machine also introduces novel risks. These are so-called "human factors" issues. Because of these issues, the safety impacts of Level 1, 2 and 3 are highly uncertain – while some crashes might be prevented, new ones might be caused.

ENSURING THE HUMAN DRIVER FULFILLS THEIR RESPONSIBILITIES

With these technologies, there is a risk that the human driver will fail to properly perform their driving, monitoring, or backup driver tasks.

With Level 1, the challenge is to keep the driver engaged and ensure that they are effectively controlling either steering or speed while also effectively monitoring the environment and the performance of the system in controlling steering or speed (depending whether ACC or lane-keeping is in operation).

With Level 2 automation, the challenge is to keep the driver engaged and ensure that they are effectively monitoring the environment and the system's performance and are able to take over immediately when needed. Though the driver is required to continuously monitor the operation of the vehicle, they may become complacent and their attention may wane as the vehicle appears to be dependably controlling the vehicle, but a situation beyond the capabilities of the system could arise suddenly and surprise the driver. There are examples of such failures to properly monitor and be available to take over that have been documented in online videos by drivers who recklessly overestimate the capabilities of the technologies, such as in recent videos posted by Tesla drivers (Zeigler, 2015).

It is questionable how effectively existing Level 2 technologies maintain driver attention. For example, a Mercedes E-Class user reported that the vehicle's Drive Pilot was able to "drive itself" for up to sixty seconds (Roy, 2016), while a Tesla Model S user reported that they only needed to touch the steering wheel approximately every five minutes (Sparks, 2016). Given such long periods of time, it is quite possible that the attention of a driver may drift away from the required task of monitoring the road and the vehicle's performance. Tesla has issued software updates that provide additional warnings to the driver to maintain vigilance (Tesla, 2016); however, it has been reported that Autopilot can still operate for over four minutes without touching the steering wheel to confirm that they are engaged in monitoring the system (Anderson, 2016).

With Level 3 automation, the challenge is to re-engage the driver and ensure that they are able to safely take over control of the vehicle in a given time frame when requested. The driver may be deeply engaged in a movie, for example, or even fallen asleep (despite any prohibitions from the automaker). In such cases, there is a risk that situations may arise that are beyond the capabilities of the system and that require the driver to take over more quickly than they are able to. Depending on what activities the human driver is engaged in, a comfortable transition time could be well over eight seconds (Samuel et al., 2016), or potentially much longer (Merat et al., 2014), if a driver has fallen asleep, for example.

Casner et al. (2016) point out that modern vehicles, even without automation, together with modern roads, already have the effect of making driving "a remarkably mundane task,

sometimes requiring little attention from the driver and luring the driver into distraction." With the introduction of partial automation systems, this problem is significantly exacerbated.

REDUCED SITUATIONAL AWARENESS

In both level 2 and 3, a driver who is asked to take over control may have little awareness of the situation – how their vehicle is operating, what other vehicles are doing, what the road conditions are, and so on. In Level 2 automation, the driver may become distracted with other activities and be surprised by sudden changes in the driving situation. Similarly, in Level 3 automation, situations may arise that require the driver to take over quickly. In such cases, the ability of the driver to respond to safety-critical events may be degraded (Martens et al., 2007; Norman, 1990; Sarter et al.; Young and Stanton, 2002).

DE-SKILLING

As a driver comes to depend on automation to perform various tasks, they get less practice at performing those tasks and, as a consequence, may lose the required skills to perform those tasks adequately when the need arises (Cummings and Ryan, 2013). This is exacerbated by a so-called "irony of automation", where an automated system may be most likely to require driver intervention for the most challenging driving scenarios that a de-skilled driver would find most difficult to handle (Bosker, 2013).

RISK COMPENSATION

Another potential pitfall with partial automation is the possibility of risk compensation and "moral hazard" (Vrolix, 2006) – a driver in control of a vehicle drives more carelessly or recklessly with an unjustified sense of assurance that the automated system will take over if a dangerous situation arises, and as a consequence, puts themselves and other road users at greater risk.

DRIVER OVERLOAD

In a vehicle with multiple automated systems, such as lane-keeping, adaptive cruise control, speed level warning, and route guidance, if these systems are poorly integrated, there is a risk that the driver could experience information overload in attempting to manage these systems.

IMPLICATIONS OF RECENT CRASH INVOLVING PARTIAL AUTOMATION

In July of 2016, Tesla disclosed that an individual driving one of its Model S cars had died in a crash in Florida while using the vehicle's "Autopilot" system in May of 2016. The feature allows the car to control its own steering and speed. This incident, while unfortunate and concerning, does not by itself support a strong conclusion that the Autopilot technology reduces safety. At the same time, there is currently no support for a strong conclusion for the contention that Autopilot actually improves safety. In brief, there is insufficient data at this time to evaluate the safety of the technology.

Tesla noted that the death was "the first known fatality in just over 130 million miles where Autopilot was activated", and further asserted that Autopilot "results in a statistically significant improvement in safety when compared to purely manual driving." However, as RAND has explained (Kalra and Paddock, 2016), very large distances must be driven to provide strong statistical proof that an automated vehicle is safer than a human-driven vehicle. The distances cited by Tesla are not sufficient to provide such proof. Furthermore, Tesla cited the fatality rate "among all vehicles." However, newer, higher-end cars like the Model S tend to be safer; in addition, Autopilot is intended to be used mainly in fair weather, on well-maintained roads, and in less complex traffic. Therefore, it is not useful to compare the crash statistics of Teslas using Autopilot with the broad fleet of vehicles on all roads (Loro, 2016b). In short, the data currently available does not provide a sufficient sample size nor sufficiently representative data to support useful analysis.

5.3 Level 4

In the case of Level 4 vehicles where full automation is achieved by controlling the environment in particular, safety will depend in part on how effectively the environment is controlled. For example, in the case of protected lanes, safety would depend on how effectively potential hazards, such as unauthorized vehicles, or pedestrians and cyclists, are excluded from the lane.

5.4 Level 5

As Level 5 technologies do not exist yet, their safety impacts are inherently highly uncertain.

A recent early analysis of collision rates in Google, Delphi, and Audi test vehicles suggests that these vehicles may have a somewhat higher collision rate than human-driven vehicles, though they were not found to be at fault for any of those collisions. The authors caution that little data is available so far, and the road and weather conditions the test vehicles drive in are not comparable to those that human drivers drive in (Schoettle and Sivak, 2015). In addition,

the test vehicles are continuously monitored by test drivers; therefore, even the tentative conclusions in the study are not well-supported.

A more recent study from the Virginia Tech Transportation Institute, commissioned by Google, compared Google's reported crash rates with crash data from naturalistic driving studies of human drivers in order to address the issue of unreported crashes by human drivers. The authors found that the crash rates for Google's self-driving cars in automated mode are lower than the crash rate for human-driven vehicles (approximately 3.2 crashes per million miles versus 4.2 crashes per million miles) (Blanco et al., 2016). However, the cautionary notes mentioned regarding the study mentioned just above also apply to the Virginia Tech study – because Google's vehicles are not tested in the full range of conditions that human drivers drive in, and they are continuously monitored by human test drivers who actively intervene in difficult driving situations, the crash data for Google's vehicles cannot be meaningfully compared with crash data for human-driven vehicles.

5.5 Safety impacts are dependent on adoption levels

The potential safety improvements resulting from automation of course depend heavily on the level of adoption. This is especially the case with V2V technologies, since vehicles equipped with V2V can only communicate with other equipped vehicles.

5.6 Other effects

The safety impacts of automation technologies will also depend on the travel behaviour impacts. For example, if automation induces people to take more and longer trips, even if the risk of crashes per VKT drops, the overall exposure to risk might decrease by a smaller margin, or even increase. In addition, if traffic speeds increase, the severity of crashes could increase, even if the frequency of crashes decreases; and if traffic densities increase, the number and scale of multiple-vehicle crashes could increase.

Safety may also be affected by unintended behavioural consequences – for example, drivers who see automated vehicles driving with very short following gaps may be tempted to emulate that driving style, despite their lack of ability to do so safely. A driving simulation study found that when drivers were surrounded by platoons with short following gaps, they tended to use shorter following gaps themselves, regardless of the fact that their reaction times would likely require longer following gaps to ensure safety (Gouy et al., 2014).

6. Efficiency of use of infrastructure

6.1 Higher traffic densities

The typical capacity of a freeway lane is about 1800 to 2200 vehicles (not including heavy trucks) per hour at speeds of around 100 km/h (Transportation Research Board, 2000). Under those conditions, around 11 percent of the length of the lane is occupied by vehicles, while the other 89 percent is the space left between vehicles (Chen et al., 2001; Shladover, 2009a). An automated system capable of controlling a vehicle more precisely and with a shorter reaction time than a human makes it possible to safely follow a preceding vehicle at a closer distance, thereby increasing the longitudinal capacity of a lane. The quick, precise vehicle control would also smooth out traffic flows, reducing the shock waves that often disrupt traffic movement and lead to unstable "stop and go" traffic.

To achieve short headways and damp out traffic shockwaves, automated vehicles must not be solely reliant on on-board sensors for information about surrounding vehicles, but must also be in communication with surrounding vehicles through V2V (Shladover, 2009b). V2V can provide information on the movements of other vehicles more accurately, reliably, and with shorter time delays than on-board sensors can (Shladover, 2009b). One reason is that V2V can provide information about the manoeuvres other vehicles plan to execute even before they are executed: for example, rather than waiting until sensors detect a change in the speed of the vehicle ahead, a vehicle equipped with V2V can begin decelerating as soon as it receives a message that the vehicle ahead is about to apply the brakes. Another reason is that sensors are subject to noise, interference, and inaccuracies, so their outputs must be filtered before being used for vehicle control, which leads to delays. Two other advantages of V2V are that it can provide information on vehicles that are beyond the line of sight of onboard sensors, such as a car that is several cars ahead in the same lane, and it can provide information on the characteristics of other vehicles, such as their braking capabilities (Bergenhem et al., 2012; Nowakowski et al., 2010; Shladover, 2009a).

PLATOONING: OPTIMIZING SAFETY AND TRAFFIC DENSITY

To maximize capacity, short headways are needed, but this reduces safety; to maximize safety, large headways are desirable, but this reduces capacity. The 'platooning' approach has been proposed as an acceptable compromise, where both the objectives of achieving capacity and safety are met to a satisfactory degree by driving vehicles together in groups or 'platoons' of several vehicles. Vehicles would drive in groups or "platoons" of several vehicles is commonly proposed (Shladover, 1997a). The vehicles in

each platoon follow each other closely, for example, with gaps of around one to four metres, while the platoons are separated from each other by larger gaps, for example, around 10 to 60 metres, to minimize the risk of collision if a leading platoon were to suddenly stop (Featherstone and Lowson, 2004; Li and Wang, 2007; Michael et al., 1998). Because the gaps between the vehicles in a platoon are small, even extreme decelerations or accelerations would produce small speed differences between the vehicles, thus reducing the severity of potential impacts should the vehicles collide with each other. Meanwhile, the gaps between platoons are large enough that a platoon can stop short of the platoon ahead if that lead platoon stops suddenly, or if less stringent stopping criteria are used, a platoon would impact the preceding platoon at low velocity (Hitchcock, 1995).



Figure 12. Cars traveling in a platoon. Image source: California PATH

The longitudinal and lateral motion of each vehicle is controlled automatically based on data from on-board sensors such as radar, laser, or magnetic sensors, as well as via information communicated between the vehicles on each vehicle's speed, position, and planned manoeuvres, if the vehicles are equipped with V2V (Kavathekar, 2012; Kavathekar and Chen, 2011). As mentioned above, the longitudinal control of the vehicle is usually referred to as adaptive cruise control, with the form that relies on V2V called cooperative adaptive cruise control (CACC), while the sensor-reliant form is sometimes called autonomous adaptive cruise control (AACC).

6.2 Degree of capacity increase

Simulations and tests suggest capacity could increase in the range of 50 to 100 percent with CACC-equipped vehicles in platoons. This means an increase from around 2200 vehicles per hour to around 3000 to 4000, or more.

Shladover estimates that the capacity of a lane occupied only by vehicles equipped with CACC could reach around 4000 to 4300 vehicles per hour. The estimate of around 4000 was based on a simulation where vehicles followed each other at a range of headways from 0.6 to 1.1 seconds, selected from the headways participants in a field test of CACC had been observed to find acceptable. The estimate of around 4300 was based on an extrapolation from a demonstration of platooning that took place in 1997, when the National Automated Highway Systems Consortium demonstrated a single eight-car platoon with vehicles traveling with 6.5 metre inter-vehicle gaps at up to full highway speed (Tan et al., 1998). Such eightvehicle platoons, travelling at 105 km/h and separated by inter-platoon gaps of 60 metres, would provide a capacity of about 5700 vehicles per hour. After this so-called "pipeline capacity" is reduced by 25 percent to account for the extra space needed for entry and exit manoeuvres, the resulting capacity would be about 4300 vehicles per lane per hour (Shladover, 1997a, 1997b). Shladover has also stated that lane capacity could theoretically attain 6000 to 7000 vehicles per hour, but cautioned that not every lane on a freeway could serve that many vehicles, since space would be needed for manoeuvring to enter and exit from platoons and the freeway.

Calvert estimated capacity would increase by around 50 percent to 3200 vehicles per hour when 100 percent of vehicles are equipped with CACC. Calvert's estimate is considerably lower than Shladover's estimate, despite the fact that Calvert's analysis does not consider the capacity-reducing effects of lane changes and other manoeuvres that would reduce his estimate to something less than 3200. This is because Calvert assumes vehicles would follow each other with gaps of 0.9 seconds, since he found that with smaller gaps, traffic flows would become unstable (Calvert et al., 2011). These results were corroborated by similar findings from Ni (Ni et al., 2011).

Harwood and Reed (2014) studied the impacts of platoons consisting of a manually-driven heavy truck in the lead and light-duty vehicles following behind. When 20 percent of light-duty vehicles on the road were contained in such platoons, each with five light-duty vehicles, the researchers found that the capacity of three lanes in the same direction increased to over 7000 vehicles per hour, compared to 6000 per hour in a case with no platooning.

Some studies have reported very large capacity increases; however, these estimates are founded on problematic assumptions. For example, Tientrakool et al. estimated that when all vehicles in a lane use CACC, capacity can exceed 10,700 vehicles per hour (Tientrakool et al.,

2011), a capacity that is a factor of 3.7 times greater than capacity with manual vehicles, and Wang et al. estimated that capacity would exceed 14,000 vehicles per hour at 100 km/h (Wang et al., 2013). According to estimates by Shi and Prevedouros, capacity could triple (Shi and Prevedouros, 2016). Talebpour and Mahmassani (Talebpour and Mahmassani, 2016) found that there was "potential to improve the throughput by more than 100%". However, these studies did not consider interplatoon gaps. As noted above, interplatoon gaps are necessary to ensure safety – without them, it is possible that a collision could result in massive traffic pileups. In addition, the gaps are necessary to allow vehicles to change lanes and to enter or exit the freeway.

Other studies have considered interplatoon gaps and found that CACC could produce large increases, tripling (Olia, 2016) or quadrupling (Olia et al., 2015) lane capacity; however, these studies do not clarify what size of interplatoon or intraplatoon gaps were considered.

Various studies estimate that platooning could reduce traffic delays by between 30 and 60 percent (van Driel, 2007; Wilmink et al., 2007).

The faster response of CACC would also help to reduce the shockwaves that force drivers to suddenly decelerate and create unstable traffic flow (Calvert et al., 2011; Chacon et al., 2012; Swaroop, 1997). CACC increases so-called "string stability", where a disturbance at the head of the platoon will tend to be attenuated as it travels backward through the platoon. Schakel found that CACC can quickly dampen shockwaves when 50 percent of vehicles are equipped; however, he cautioned that it is possible that safety could be reduced when there is a mix of manual and automated traffic (Schakel et al., 2010). Visser found that when 20 percent of vehicles are equipped with CACC, the number of shockwaves is reduced by 25 percent, and when 100 percent of vehicles are equipped, the number of shockwaves is reduced by 90 percent (Visser et al., 2005).

6.3 High adoption of CACC required for large capacity increases

A first cautionary note on platooning is that large capacity gains would come only when a large proportion of vehicles on the road are capable of platooning.

In a simulation study by VanderWerf et al., the authors found that the capacity gains were quadratic, with significant gains coming only after the proportion of CACC-equipped vehicles reached 60 percent, and an especially large gain when the proportion approached 100 percent. This is due to the fact that shorter following gaps can only be achieved between pairs of vehicles equipped with CACC (VanderWerf et al., 2001). When 60 percent of vehicles use CACC, VanderWerf et al. found that capacity would reach 2900 vehicles per hour per lane, not accounting for lane changes, which decreases capacity (loannou, 1998). Similarly, Van Arem found no effect on capacity at penetration rates below 40 percent, with significant

benefits emerging around 60 percent (Arem et al., 2006). Arnaout found that at least 40 percent of vehicles on the road must be equipped with CACC to significantly boost capacity (Arnaout and Bowling, 2011). A simulation conducted by Ma et al. also showed that a small proportion of CACC-equipped cars would have little effect on capacity (Ma et al., 2012). Tientrakool et al. found that for communicating vehicles, capacity improves very little when the proportion of communicating vehicles is less than 30 percent, then improves slowly until the proportion reaches 85 percent (Tientrakool et al., 2011). They found that for vehicles not equipped with V2V, capacity increased nearly linearly with the proportion of equipped vehicles; however, the capacity increase was much lower than in the case of communicating vehicles.

Motamedidehkordi et al. (Motamedidehkordi et al., 2016) also found a small effect when the proportion of V2V-equipped vehicles was not large; they found that when 50 percent of vehicles were connected and automated, throughput increased by 5 percent. Kostikj et al. (Kostikj et al., 2015) found that when CACC-equipped vehicles comprise less than 80 percent of vehicles on the road, flow actually drops slightly; flow increases only when CACC-equipped vehicles make up more than 80 percent of vehicles on the road.

V2V IS NECESSARY FOR LARGE CAPACITY INCREASES

To realize large capacity gains, it is not sufficient that automated vehicles are widely adopted; it is necessary that the vehicles also be equipped with V2V (Shladover et al., 2012). As mentioned above, V2V allows for shorter following gaps. Numerous studies have found that the capacity increases resulting from the use of CACC would be much larger than those resulting from AACC. In one simulation, it was found that without V2V, a 7 percent capacity gain could be realized (Vander Werf et al., 2002); another study found that capacity would increase by up to a 9.5 percent when 40 to 80 percent of vehicles are equipped, but would drop somewhat when more than 80 percent of vehicles are equipped due to some users choosing a following gap longer than they would use when driving manually (Shladover, 1999; Shladover et al., 2001). Minderhoud estimated somewhat larger capacity gains, up to 25 percent when 100 percent of vehicles are equipped (Minderhoud and Bovy, 1999). While Tientrakool et al. found a much greater increase, up to 4100 vehicles per hour when all vehicles in a lane are automated but not connected, the authors also assumed that the capacity of a lane with all manual vehicles is approximately 2870 vehicles per hour, and their model did not include inter-platoon gaps, which, as noted above, is not a realistic assumption.

Le Vine et al. (Le Vine et al., 2016) examined the potential for safety increases with unconnected automated vehicles. They found that, depending on how legal doctrines of driving safety are interpreted, if vehicles drive such that they accept no more than a one-in-a-million risk of a crash in the case of a lead vehicle performing emergency breaking, the

maximum throughput at 70 mph would range from 1,367 to 4,108 vehicles per hour. This seems to suggest a need for clarification regarding desired driving safety levels. Interestingly, the authors also find that while the maximum throughput for human-driven cars occurs at 53 mph, the maximum throughput for automated cars occurs at 26 mph. This suggests a potential tradeoff between speed and capacity with unconnected automated vehicles.

DEDICATED LANES COULD SUPPORT PLATOONING

The benefits of platooning do not depend on the level of adoption in the overall fleet of vehicles in operation, but rather, they depend on the local prevalence of vehicles capable of platooning. That is, it is not necessary for the number of platooning-capable vehicles to be a large fraction of the overall fleet of vehicles on all roads; rather, it is necessary that platooning-capable vehicles be a large fraction of the vehicles using a given lane. Therefore, the capacity benefits of platooning can be realized while adoption levels are still low by enabling platooning-capable vehicles to congregate on dedicated lanes (Bishop, 2001; Shladover et al., 2001; Ward, 1997). Such lanes would also simplify the driving environment and thereby facilitate fully automated operation.

Unfortunately, such dedicated lanes for public roadways suffer from a "chicken and egg" problem. That is, individuals are motivated to purchase platooning-capable technology only if they perceive a private benefit, such as reduced travel time or reduced workload, during their trip, but in order for these individuals to receive these benefits, the dedicated lanes must be present in the first place. If these lanes are not present, the concentration of platooning-capable vehicles will be too low to enable platooning, and owners of the technology will not experience significant private benefits. Meanwhile, infrastructure providers will not be incentivized to provide dedicated lanes until a sufficient demand exists. If they provide dedicated lanes before a demand exists, the lanes will be poorly utilized and freeway capacity will be reduced rather than increased.

However, there may be some traffic flow benefit provided by distributing vehicles with ACC throughout the lanes of a freeway. Vanderwerf argued that since ACC tends to attenuate traffic shockwaves, distributing these vehicles throughout all lanes could lead to more stable traffic flow (VanderWerf et al., 2002).

CAPACITY IMPROVEMENTS LIMITED IF HEADWAYS CHOSEN BY DRIVERS

The capacity improvements resulting from platooning would also be limited if the following gaps are controlled by the travelers. If they are given the opportunity to choose the time gap, some or many travelers may opt to have the longitudinal control system maintain a larger gap

in order to feel safer, more comfortable, or to maintain a degree of privacy from surrounding travelers. As Shladover notes, there would be a 20 percent capacity difference if drivers choose a gap of 1 second rather than 0.8 seconds (Shladover, 2000a).

6.4 Capacity increases focused on freeways with widely spaced interchanges

Because vehicles maneouvring to change lanes, enter into or exit from platoons, or enter or exit the freeway would significantly reduce lane capacity (Ran et al., 1997), capacity increases would occur mainly on freeways where entrance and exit ramps are widely separated. Vehicle entry into and exit from platoons reduces the achievable capacity by around a quarter or a third (Broucke and Varaiya, 1997; Feijter and Netherlands Research School for Transport, 2006). This means that the capacity benefits of platooning would be limited on urban freeways, where entrances and exits are numerous (Minderhoud and Bovy, 1999). Interestingly, in freeway networks, congestion typically occurs at "bottleneck locations such as lane drops, on-ramps, weaving sections or other discontinuities in the road geometry" (Arem et al., 2016), which are also the areas where capacity increases from platooning would be limited.

A related problem is the arrangement of vehicles in a platoon. Safety in a platoon is enhanced if vehicles that are more massive or have lesser braking capabilities are in the lead positions in platoons. Organizing vehicles in such orders could require numerous manoeuvres, or could require the creation of smaller platoons, and could thus limit the capacity benefits of platooning.

LITTLE POTENTIAL FOR BENEFIT ON ARTERIALS AND STREETS

Platooning would give much smaller capacity benefits, if any, on arterials and city streets, especially for those streets with more complex traffic flows. The complex, unpredictable movements of city traffic would diminish the capacity increases that platooning can provide. On streets, manoeuvres like lane changes, stopping at intersections, leaving room for cars turning left or parallel parking, accommodating vulnerable road users such as cyclists and pedestrians, and so forth, would make platooning much more difficult. One example of a study that examined automation on uncontrolled roads simulated the use of ACC on the road network of the greater Athens area, and found that overall flow in the network improved (Golias et al., 2001). The study does not appear to have given consideration to the complexities of urban traffic just mentioned, however.

Considering these points, it is reasonable to conclude that platooning would give much smaller capacity benefits, if any, on city streets. This would hold especially for those streets with more complex traffic flows.

Nevertheless, some researchers suggest flows could increase on city streets. Ambühl et al. 2016 (Ambühl et al., 2016) found that automated vehicles would increase flow through a simple network from 600 vehicles per hour to 1550 vehicles per hour. However, it is open to question whether their assumption that automated vehicles would have very short headways of 0.5 seconds is realistic.

PLATOONING BEST SUITED FOR LONGER FREEWAY-BASED TRIPS

Platooning would provide significant benefits mainly to longer trips that use freeways for a significant portion of the trip. The capacity increases resulting from automation would be focused either primarily or exclusively on freeways. Similarly, the private benefits resulting from platooning, such as faster travel and reduced workload for the traveller, would occur either primarily or exclusively while on freeways. Where trip origins and/or destinations are distant from the freeway network, and where the portion of the trip taken on the freeway is relatively short, platooning would not provide particularly large private benefits (del Castillo et al., 1997).

The process of being automatically manoeuvred into or out of a platoon would of course consume time, and would thus reduce the time spent in a platoon and thereby reduce the benefits of automation for shorter trips. In addition, if many vehicles take short trips on freeways, their frequent manoeuvring into and out of platoons will limit capacity (Featherstone and Lowson, 2004).

For platooning to benefit a large proportion of trips in a city, a large proportion of origins and destinations must be close to freeways (Beimborn, 1996), such as in a city where development is focused along freeway corridors, or with an extensive freeway network. This could be the case in a city where much development is focused along freeway corridors, or where the freeway network covers the city extensively.

Considering these points, platooning would tend to provide greater private benefits for travelers taking longer trips, and would also produce greater capacity benefits where a large proportion of trips taken on the freeway are relatively long.

6.5 Platooning could lead to bottlenecks at entrances and exits

Because platooning would primarily, or possibly exclusively, increase capacity on freeways, the capacity increases from platooning on freeways would attract traffic from other roads. This could reduce congestion on arterials in some areas (Shladover, 1998), but could lead to increased traffic at freeway entrances and exits (Wetmore, 2003) and could create bottlenecks on nearby streets where platooning results in minimal, or no, capacity increases. This would limit capacity increases for the overall network (Menon, 2010). In short, increasing freeway capacity would not increase the ability of the rest of the road network to absorb traffic.

6.6 Flow breakdowns: less frequent, potentially more severe

While breakdown of traffic flow might be less common, if traffic flow does happen to deteriorate on a freeway with dense platoons of traffic, the high traffic density means that queues would grow much more quickly than if the lanes were used by non-automated vehicles. On a related note, Kerner found that the effect of CACC on traffic breakdown at an on-ramp was ambiguous: while there was a potential for CACC to decrease the probability of traffic breakdown, there was also a potential for it to increase the probability of breakdown (Kerner, 2016).

6.7 Truck traffic limits platooning capacity benefits

Capacity increases would be limited where trucks make up a large proportion of vehicles on the road. Heavy trucks can be equipped for platooning; however, their braking capabilities are generally much poorer than those of light-duty vehicles, so they must leave larger following gaps. If heavy truck traffic increases, the anticipated capacity benefits of vehicle platooning may be diminished.

6.8 Other issues for platooning

When a vehicle follows closely in another vehicle's "wake", this can result in road spray problems. The following vehicle can get hit by rain, slush, salt, sand, stones, and other road debris (Templeton, 2012). This can reduce visibility and could disturb or damage sensors or otherwise damage the following vehicle. The simple solution is to increase the following gap; however, this reduces the capacity and energy-efficiency benefits of platooning. A related problem is that a vehicle closely following another may take in exhaust fumes from the preceding vehicle, which could reduce comfort and lead to health problems (Shladover,

1997a). Electric vehicles would of course avoid this problem; however, it does not appear that the problem has been fully solved for vehicles powered by internal combustion following at very close headways.

6.9 Lateral capacity

It is possible that the precise steering control provided by automation could enable the use of narrower lanes, thereby increasing the capacity of existing roads, or reducing the width of road necessary to provide a given number of lanes; however, significant gains are not likely until very advanced automation is very widely adopted. The potential gains from narrower lanes are small compared to the potential gains from shorter headways – while only around 11 percent of the length of the lane is used by manually driven vehicles, around half of the width of the lane is used (Transportation Research Board, 2000). Freeway lanes are typically at least 3.5 metres wide, but even large SUVs are rarely over 1.8 metres in width. The surplus width is provided to accommodate heavy trucks and buses, which can be as wide as 2.7 metres, and to accommodate imprecision in steering by drivers (Shladover, 2009a). Since current lane widths are designed to accommodate heavy trucks and large vehicles, substantial reductions in lane width would require that the narrow lanes be provided exclusively for light-duty vehicles (Shladover et al., 2012).

A more radical idea is roads without lanes, where vehicles follow trajectories that are not delimited by lanes at all. Kala et al. made a preliminary exploration of this idea (Kala and Warwick, 2013). It is not clear how this concept would affect traffic flow, and while it may have potential for application at some point, it is likely that Level 5 automation will have to have attained very high levels of adoption to ensure safety.

6.10 Coordination of vehicles at intersections

Automation combined with V2X raises the potential to coordinate the movements of vehicles to improve traffic flow at intersections.

It has been proposed that intersections would have no need for signals or signs; instead, cars equipped with V2X would "call ahead" to a roadside computer to request a time and space slot in which to move through the intersection. This "intersection manager" grants the request and the vehicle moves through the intersection in that time-space slot. In such a "reservation-based intersection", there would be little stopped traffic (Dresner and Stone, 2004, 2008).



Figure 13. Simulation of vehicle movements through a reservation-based intersection. Image source: Autonomous Intersection Management project

Simulations show that these intersections could significantly reduce delay. Simulations by Dresner and Stone showed that the reservation-based system was able to handle much heavier traffic conditions than can traffic lights, and could very closely approximate the performance of an overpass (Dresner and Stone, 2004). A similar study by Lee and Park found that a hypothetical four-way intersection performed significantly better than a conventional intersection, achieving a 99 percent reduction of stop delay and a 33 percent reduction of total travel time (Lee and Park, 2012). Fajardo et al. studied a reservation system and also found that it performed significantly better than a traditional traffic signal, "reducing average vehicle delay by an order of magnitude in all cases" (Fajardo et al., 2011). They also found, however, that more conservative spacing buffers around the vehicles greatly reduced projected performance improvements. Ma et al. looked at a different application of vehicle automation to intersections. In their simulation, they found that CACC-equipped vehicles at an intersection without traffic lights would result in smaller delays compared to conventional traffic at a signalized intersection, while, in contrast, CACC-equipped vehicles at an intersection with traffic lights with fixed signal times would result in increased delay.

Yan conducted simulations of a similar system and found that queue length was decreased by over 75 percent for some levels of traffic flow, and the average vehicle waiting time was decreased by 77 percent (Yan et al., 2013). Li also simulated a similar system and found that capacities through the intersection were increased between 31 and 37 percent compared to a standard signalized intersection. Park and Lee describe a system that reduces stop delay by 99 percent and reduces total travel time through the intersection by 33 percent. Zohdy analyzed an algorithm to control the movements of automated vehicles through intersections, called iCACC, for intersection management using CACC (Zohdy et al., 2013). The iCACC controller controls vehicle trajectories entering an intersection to avoid collisions while minimizing the intersection delay. Simulations found that iCACC gave similar delays to a roundabout, but significantly shorter delays than a conventional traffic signal.

Levin et al. (Levin et al., 2016) found that reservation-based intersections can be less efficient than signals in certain situations, especially where a higher-traffic road intersects with a lower-traffic road. In such asymmetric intersections, reservation-based intersections (following a so-called "first-come-first-served" policy, where vehicles that arrive at the intersection first are given priority) can increase total delay, and especially increase delay for vehicles on the higher-traffic road. Nevertheless, in a simulation of Austin, Texas, they found that reservation-based intersections reduced travel times by 50 percent. They attributed this mainly to the small number of asymmetric intersections. Patel et al. (Patel et al., 2016) similarly found that, at high demand, reservations performed worse than signals, particularly around local road-arterial intersections.

Automation, especially in combination with V2V, also raises the possibility of increasing the efficiency of vehicle movements at intersections with traffic signals. At traffic signals, there is some delay between when the lights turn green and the first vehicle moves. Friedrich (Friedrich, 2016) found that automated vehicles would increase lane capacity by approximately 40 percent. This finding was based on the assumption that automated vehicles would drive with very short headways of 0.3 seconds. Such a short following gap may not be implementable on the roads until automation and V2X technologies are highly advanced.

An obvious and major limitation of such approaches to coordinating traffic flows through intersections is the degree to which they would be able to accommodate users of nonautomated vehicles, as well as users of other modes of transportation, such as walking or cycling.

Dresner and Stone addressed the question of how reservation-based intersections could accommodate vehicles under the control of human drivers (Dresner and Stone, 2006, 2007). They modified their reservation-based system in order to implement it in a modelled intersection with traffic lights and pedestrian- or cyclist-activated crossing signals. The authors found that when there is a mix of automated and human-driven vehicles, all vehicles benefit from reduced delay, including the human-driven vehicles. Unsurprisingly, they found that the lower the proportion of human-driven vehicles, the lower the delay.

An unresolved issue is the performance impact of pedestrians and cyclists. Dresner and Stone briefly discuss how pedestrians and cyclists can also be accommodated, but they do not discuss how the performance of the intersection would be affected, nor the impact on pedestrians and cyclists. Presumably, higher numbers of pedestrians and/or cyclists would result in smaller reductions in delay for vehicles. It is reasonable to conclude that such intersections would produce limited improvements in capacity in busy urban areas with pedestrians and cyclists, while they could produce somewhat larger improvements in urban areas with fewer pedestrians and cyclists.

Considering these points, until Level 5 automation with V2X is adopted to a high degree, vehicle automation is unlikely to significantly increase capacity at most urban intersections, though some increases would be feasible in areas not frequented by pedestrians or cyclists.

6.11 Transit operations efficiency

While the potential for automation in light-duty vehicles to improve traffic flow is often the focus in discussions of the potential impacts of automation, automation also has the potential to significantly improve bus transit operations (Hardy, 2005; Shladover, 2000b). Automation in transit buses can facilitate operation in narrow rights-of-way, precision docking, bus platooning, and full automation. These applications can increase speeds, reduce dwell times, increase passenger comfort, reduce labour costs, and facilitate increased capacities and frequencies. In short, automated buses can provide a quality of service similar to that of rail.

In cases where travel demands approach the limits of road capacities, automated buses could serve an indispensable role – this is simply because vehicles with high passenger capacities, such as buses, can carry larger numbers of travelers along a given road lane than even densely platooned automated light-duty vehicles could. According to Shladover, if buses were platooned with 15 metre gaps, with sufficient separation between platoons to ensure safety, "a sequence of three-bus trains could provide 70,000 seats per hour in one lane, which is competitive with the highest-volume rail transit services" (Shladover, 2003).

OPERATION IN NARROW RIGHTS-OF-WAY

The steering precision made possible by automated steering systems make it possible for a bus to travel safely in a much narrower lane than a human operator could, and at higher speeds as well (Hardy, 2005). This is a particularly useful application for a bus rapid transit (BRT) service operating in a dedicated busway. An automated bus can maintain its lateral position to within 10 centimetres at cruising speed (Shladover, 2012), allowing the bus to operate in a lane that is only inches wider than the bus itself – considerably narrower than a conventional lane. A conventional bus lane is around 3.7 metres in width, while a guided bus lane can be as narrow as 2.9 metres (Hardy and Proper, 2006).

The precise steering also permits safe full-speed operations where drivers would normally need to slow down, such as through curves, toll booths, and narrow bridges and tunnels, on

busways in former rail rights-of-way, on freeway shoulders (letsgetmoving.org, 2015), or in crowded urban environments, thus reducing passenger delays (Shladover, 2012).

Importantly, the use of narrow rights-of-way reduces land and construction costs for new busways, especially where tunnels or bridges are required, and helps to avoid the need for changes in road alignment (Hardy and Proper, 2006). According to Bu, automated steering could make possible 20 percent lower construction and acquisition costs, or could allow for a bike lane or parking lane on arterial roads (Bu et al., 2007). In addition, precise steering also makes it possible to pave only the wheel tracks, thus reducing the amount of impermeable road surface by over 50 percent (Zhang et al., 2007).

In partially automated applications, automatic steering could also decrease driver workload and stress when driving in narrow lanes or other challenging environments.

PRECISION DOCKING

Precise steering also allows for precision docking, where buses quickly and reliably pull in very close to boarding platforms, thus improving access for passengers, especially those with limited physical mobility, which reduces station dwell time, and enables allows faster and more consistent travel times, increasing schedule reliability. Precise docking can eliminate the need for wheelchair lifts. The lateral precision of around 1 centimetre at low speeds (Shladover, 2012) enables the bus to quickly and reliably pull in very close to the boarding platform without increasing driver workload (Hardy, 2005). It is difficult for bus drivers to achieve this level of accuracy, and in the attempt, tires are often scuffed against the curb, which causes wear, increases maintenance needs, and reduces passenger comfort. An evaluation by Zhang et al. concluded that precision docking offers a high ratio of benefit to cost, even when only small amounts of time are saved at each stop (Shladover et al., 2007; Zhang et al., 2007).

BUS PLATOONING

When automated steering is combined with automated longitudinal control, bus platooning becomes possible. Buses, especially when equipped with V2V, can safely follow each other at closer distances than possible with human drivers – within a half vehicle length.

Platooning with one or more fully automated, driverless buses can be used to increase capacity and lower labour costs. A bus platoon could operate with a driver in the lead bus monitoring operation, and with the following buses operating without drivers, or the entire platoon could operate without drivers.

Following at close distances also significantly reduces aerodynamic drag, which in turn reduces fuel consumption and emissions (VanderWerf et al., 2004). These benefits would be more significant for buses than they would be for light-duty vehicles.

In effect, platooning would allow buses to provide a service similar to trains without the need for rail infrastructure. Unlike trains, the buses could operate on the larger road network, enabling "dual mode" operation, where a bus could operate manually on uncontrolled roads for a portion of its service and join a platoon, on a protected busway, for example, for another portion of its service (Tsao, 1998). This could allow for labour savings if drivers transfer off of buses when the bus joins the protected busway, or if driver wages are lower during automated operation.

FULL AUTOMATION

Fully automated operation would also be possible, especially in protected busways. This would enable reduced labour costs, which would allow for significant increases in service frequency. Full automation in buses would also make it possible to provide higher frequency service with smaller vehicles.

Since buses can operate at shorter headways than trains, there is also the possibility for fully automated BRT to offer higher frequency service and thus allow for shorter station platforms than would be required by rail.

Relevant insights can be drawn from experiences with driverless train operation. Walker explains that in driverless trains, frequency of service is no longer tied to labour cost (Walker, 2010). According to Vuchic, "by far the most significant aspect of transit service that automation can bring is economic feasibility of running high-frequency service with either long or short train consists at all hours of the day and on all days of the week" (Vuchic, 2007). This is particularly useful in off-peak times, where rather than running infrequent and long trains, automation allows the running of more frequent, shorter trains with no increase in operating cost (Erbin and Soulas, 2003; Fischer, 2011; Warren and Kunczynski, 2000). As explained by Stein, "[w]hen paying a driver, a transit system must try to get its money's worth by putting as many passengers in the train as possible. For example, a system might try to use six-car trains. But such trains may fill up only if they do not arrive too often, so the time between trains, or "headway," might be lengthened to 12 minutes. A driverless train system with the same number of vehicles could run three-car trains every six minutes, or two-car trains every four minutes – without increasing its payroll" (Stein, 1992).

The higher operating speeds and shorter dwell times enabled by automation could improve the productivity of BRT, allowing agencies to serve routes and provide given capacities with smaller fleets. The increased productivity and service quality could attract more riders and support increased fare box returns. These improvements in speed, reliability, capacity, frequency, and ride quality could make automated bus rapid transit a strong competitor to light rail.

OTHER BENEFITS OF AUTOMATION IN BRT

It has also been suggested that partial automation could reduce driver stress. For example, because steering is one of the most demanding driving tasks, automated steering allows the driver to pay more attention to safety, speed, and customer service tasks. However, as described above, partial automation introduces human factors challenges.

6.12 Low-speed vehicles

Low-speed shuttles such as the "cybercars" being developed by the CityMobil2 project can take compact, lightly built forms. These compact forms suggest that these low-speed shuttles might use road space more efficiently than conventional light-duty vehicles; however, it is unlikely that they would provide road capacity benefits. This is simply because road capacity depends both on the density and speed of vehicles. If such low-speed vehicles substitute for conventional light-duty vehicles that would have been traveling at higher speeds, then road capacity will probably decrease. Of course, the capacity referred to in this discussion is the number of vehicles that flow past a given point in a given time. Passenger capacity, the number of passengers that pass a given point in a given time, could increase even if speeds drop in the case that low-speed vehicles carry a higher number of passengers than conventional vehicles, on average.

6.13 Reduced vehicle size facilitated by automation

Automation also raises the prospect of increased efficiency of use of road space facilitated by smaller vehicles. If automated vehicles have excellent crash avoidance capabilities, automobile design could shift away from crashworthiness. Vehicles could then be built much smaller and lighter (and thus more cheaply), and various safety features like airbags can be dispensed with. Vehicle design could also be more flexible, as fully automated vehicles would not need steering wheels or other controls, for example, and interior spaces could be designed for other uses. In this narrative of the future, it is often envisioned that the convenience of fully automated taxis would have encouraged a shift away from private vehicle ownership. While some trips would be taken in larger vehicles when space is needed for more passengers or cargo, most trips would be taken in very compact driverless taxis (Gilbert,

2013). Such compact vehicles would be more energy-efficient, material-efficient, and would occupy less road space (Mitchell, 2010). However, these vehicles would be unlikely to be able to share the roads safely with larger non-automated vehicles. Small, light automated vehicles would be vulnerable in collisions with large and heavy vehicles; in such crashes, crashworthiness will still be necessary, especially while some vehicles are still being driven by humans, since there would still be some crashes they would not be able to avoid. Therefore, a broad shift away from crashworthiness toward significantly smaller and lighter vehicle designs is unlikely until very advanced automated vehicles have been very widely adopted, and the technology is advanced enough to guarantee high levels of safety. However, such a shift in design is possible where small, light automated vehicles are segregated from heavier vehicles, especially heavier non-automated vehicles.

6.14 Safety effects on efficiency of road use

Capacity improvements could also be realized through the safety improvements that automation may provide. Improved safety would reduce non-recurrent congestion due to crashes. Level 5 in particular could reduce non-recurrent congestion not only on freeways, but also on streets.

The magnitude of capacity benefits is uncertain due to uncertainty regarding the safety benefits of automation. However, the research literature suggests the improvement would be noticeable, but modest. Non-recurrent congestion is congestion due to incidents such as vehicular crashes, breakdowns, and debris on roads, roadworks, and weather (Medina, 2010). In an analysis by Hall, a complete elimination of incidents would result in a 2 to 9 percent increase in capacity averaged over time (what he calls "effective capacity") for a studied one-to five-mile bottleneck. In a discussion of an estimate by Lindley that about 60 percent of congestion delay is non-recurrent, Hall noted that this estimate can be misinterpreted. While this estimate seems to indicate that 60 percent of the congestion problem is due to non-recurrent delay, Hall writes that "even the complete elimination of incidents would not reduce delays by 60 percent" because improvements would stimulate latent demand and thus increase delays due to recurrent congestion (Hall, 1993). Hajbabaie examined sources of congestion on a freeway in North Carolina and found that traffic incidents were responsible for only 12 percent of delay (Hajbabaie et al., 2012).

6.15 Efficiency of parking infrastructure use

The efficiency of use of parking space could be increased by increasing the density of parking lots. Drivers could exit their vehicles and leave them to park themselves in tight spots. One example of an automated valet system that could facilitate this is being developed by Volvo,

though the main intention of the project is to increase driver convenience rather than improve space efficiency. In this system, a driver drops off their vehicle at the entrance to the parking facility and the car navigates with the aid of transmitters in the road surface (Economist, 2013). Audi is working on a similar garage system for self-parking vehicles that reportedly could reduce space needs by over 60 percent (Bigelow, 2016)(Knight, 2013).

Before parking facilities like these exist, there would have to be sufficient demand, which means that there would have to be a sufficient number of vehicles capable of this kind of automated valet parking. Automated valet parking may also be possible in parking facilities that are not equipped with transmitters or other special infrastructure, provided the vehicles are equipped with Level 4 or 5 automation, or provided that they move at limited speeds and generally operate in a risk-averse manner.

A shift in vehicle design to smaller vehicles could also facilitate such a shift to increased parking density.

Automation could also facilitate changes in parking demand – this will be discussed in Section 9.2.

There are other potential impacts of vehicle automation on infrastructure. For example, KPMG argues that fully automated vehicles, thanks to the use of various sensors, would have no need for traffic signals and bright streetlights, thus allowing reductions in energy use and light pollution (KPMG, 2012); however, these kinds of impacts are likely only in the very long term when very advanced automation has achieved very high or even 100 percent adoption rates. Further research should be conducted on such far-term potential impacts.

7. Environment

Automation, especially when combined with V2V, could enable smoother, more efficient driving, with smoother speed profiles. Mersky and Samaras (Mersky and Samaras, 2016) simulated a range of automated driving styles and found that while some vehicle following strategies could result in slightly worse fuel economy, efficiency-focused control strategies could result in a 10 percent improvement. Platooning could improve aerodynamic efficiency, especially for heavy-duty vehicles such as trucks and buses, which could benefit from significant energy savings.

In addition, if vehicles become lighter and smaller, energy consumption would be reduced. This would also facilitate a shift to electric power. One simulation study found that if small vehicles are used for the 87 percent of trips in the US that are taken with one or two people, the energy consumption of the overall fleet could be almost halved (Greenblatt and Saxena, 2015). However, as noted above, small, light vehicles would be vulnerable as long as heavy vehicles are around – especially heavy vehicles driven by humans. Until crash avoidance is sufficiently advanced, or until heavy non-automated vehicles are rare, a shift away from crashworthiness to very small, light vehicles is unlikely. The exception is where traffic is segregated – in such cases, it would be feasible to operate lightly built vehicles in the near future, even before highly advanced automation has been developed.

Wadud et al. consider (2016) a range of potential impacts on energy consumption. Potentially positive effects include a reduction in energy wasted in congested traffic, more efficient driving styles, reduced aerodynamic drag with platooning, the use of smaller, lighter vehicles, a reduction in travel due to a shift away from private vehicle ownership, and a shift toward new energy sources, such as electricity. Potentially negative effects include an increase in travel speeds, a demand for vehicles with additional interior features and an associated increase in vehicle weight, an increase in travel due to reduced cost of travel time (also discussed by (Rubin, 2016), and an increase in travel by groups such as elderly and young people. They consider a range of scenarios and find that automation, at one extreme, could result in a 45 percent reduction in total energy demand from road transportation, or at another extreme, could result in energy demand more than doubling.

A detailed review of the potential environmental impacts of vehicle automation is beyond the scope of the present report.

8. Adoption

How rapidly and to what extent vehicle automation technologies are adopted will be determined by the expected private benefits and costs of automation technologies for the owner. In particular, the impacts on driving performance and on driver workload discussed above, along with the capital costs of the technologies, will determine how attractive the technologies are and will drive adoption.

8.1 Capital costs of technologies

When highly advanced technologies such as Level 5 vehicles emerge onto the market, it is uncertain how much they will cost. Currently, Level 2 technologies that are available on the market are generally only available in more expensive vehicles. For example, Tesla's Autopilot is available on the Model S, which starts at \$66,000. The feature costs an extra \$2500. The Level 2 technologies on the Mercedes E-Class cost over \$11,000, while the vehicle cost starts at over \$52,000 (Star Tribune, 2016). Regarding test vehicles for more advanced automation, it has been reported that Google's teste vehicles cost around \$150,000. One of the most expensive components used in many automated vehicles is the LIDAR – the version that Google used in its earlier prototypes cost around \$70,000. Less expensive systems are now available, costing as little as \$8000, but may be less effective (Oreskovic, 2015). It is expected that the cost will drop greatly, though the magnitude and timing of the drop is highly uncertain.

High costs may not discourage the earliest adopters, since such early adopters are often willing to pay high prices for highly advanced technologies (Lucey, 2013). However, in order for adoption levels to attain significant levels, costs will need to be reasonable.

Some commentators have ventured estimates for costs of future technologies. For example, the market research firm IHS Automotive has estimated that when they first emerge, advanced automated systems would add about \$7000 to \$10000 to a vehicle's sale price, and this figure would drop to about \$3000 within ten years.

Private vehicle owners would pay the capital costs directly when purchasing a vehicle; in the case of fleet owners, these costs would be passed on to the end users, the taxi, car share, or bus users, who would pay this cost through their fares.

These costs could also be offset by government incentives.
8.2 Private benefits to owners

The potential private benefits of automation that would spur adoption are improvements in driving performance and the reduction or elimination of driving labour.

The prospect of reducing or eliminating driving labour would be a major attraction for both private vehicle owners and fleet owners. Depending on the level of automation, it would reduce driving stresses, free up the traveler's time to perform other activities, and reduce labour costs for fleet owners.

Fully automated vehicles could allow for greater independent mobility for those less able or unable to drive, such as elderly people, children and adolescents, and people with reduced physical mobility.

LEVEL 2 AND 3

Level 2 would have low attractiveness with respect to its ability to reduce or eliminate driver labour. A technology that requires constant monitoring from the driver would ease driving to a limited degree, and only in limited situations. It could actually increase stress if drivers find it difficult to stay engaged in their monitoring duties. Level 3 would be significantly more attractive, as the technology could operate in more situations, and would only requires the driver to be available for backup. However, the fact that such a technology could operate only in certain situations, and could require a driver to take over control quickly, would still limit its attractiveness.

Operators of taxi fleets would probably not be strongly attracted to Level 2 or 3 automation since it would provide very little cost savings or improvement in operations. Taxis equipped with these levels of automation would still require drivers. However, since a taxi driver's workload would become lighter, it is possible that taxi operators may be able to reduce operating costs somewhat by reducing driver wages; on the other hand, the driving performance of drivers of taxis with these levels of automation may suffer due to de-skilling. Operating costs may also be reduced if automation allows taxis to operate more safely and with more energy-efficient driving patterns.

LEVEL 4

The fact that Level 4 can only operate in a fully automated mode in certain situations would limits its attractiveness for private owners and taxi fleet operators. However, Level 4 could be quite useful for transit applications.

Fully automated operation of Level 4 vehicles in protected lanes could be very useful for public transit. Since bus networks tend to occupy a relatively small fraction of the total road network, a fleet of automated buses could derive large benefits by providing protected lanes on a small fraction of the total road network, in contrast with private vehicles or taxis, which would generally derive smaller benefits from a sparse network of protected lanes.

In general, various approaches to reducing risk in order to achieve fully automated operation with automated vehicles of limited capability are easier to implement for bus transit than for private vehicles. Risk can be reduced by controlling the environment, such as providing protected lanes, ensuring road paint is well-maintained, equipping infrastructure for V2I applications, ensuring 3D maps are up to date, and so on. All of these measures would be easier to implement on a limited network of bus routes or lanes than on the overall network of roads in a city.

As it seems likely that much of the potential attraction of driverless taxi service would derive from the potential for door-to-door service between a wide range of origins and destinations, driverless taxis are likely to require Level 5 automation in order to provide very attractive service. However, driverless taxis with Level 4 automation could serve short trips in more restricted settings, for example, in areas with low speed limits and other restrictions on potential driving hazards, and in particular, for trips that cannot be served well by walking or cycling.

LEVEL 5

Private owners

Level 5 would be very attractive for private owners, since it would allow a traveler to completely forget about driving and engage in other activities, such as watching movies, sleeping, etc. The ability to park remotely could also be very attractive for individuals who travel to areas where inexpensive parking is in short supply.

Level 5 vehicles especially could be attractive for those less able or unable to drive, such as elderly people and people with reduced physical mobility. Such technology could allow for increased independent mobility. Parents could also value it for shuttling their kids around.

Drivers who particularly enjoy driving would be less attracted to automation. However, while many people enjoy driving, it seems probable that most would prefer the kind of mythic driving adventure on the open road commonly depicted in automobile commercials – there are probably relatively few who cherish the act of driving itself in a daily commute through heavy traffic, for example. Most drivers who claim to enjoy commuting by motor vehicle might more particularly appreciate the private time their commute affords them, for example, rather

than the act of driving in a commuting context, per se. On this note, some private owners may be especially attracted to cars that can function in a fully automated mode, but can also be operated in a manual mode, allowing them to choose to drive in more enjoyable situations.

Fleet owners

Fleet owners are likely to adopt Level 5 vehicles more rapidly than private owners, for several reasons.

- The elimination of driver labour produces greater benefits for fleet owners than private owners. The elimination of labour results in free time and greater convenience and comfort for private owners, while it results in direct monetary savings for fleet owners, which are arguably a stronger incentive.
- Fleet vehicles are generally used more intensively used than private vehicles, so fleets are refreshed more rapidly than vehicles owned by private individuals.
- Fleet owners could also benefit from economies of scale by purchasing numerous vehicles at reduced costs.
- Cost savings from improved performance due to automation faster travel, improved trip time reliability, increased safety, less vehicle downtime for maintenance, and especially reduced labour costs – are more directly monetized for fleet owners than for individuals. If automation facilitates even relatively small energy savings, fleet owners would have a significant incentive to adopt automation to reduce energy costs, while private individuals would likely need relatively larger savings to incentivize adoption.
- Automated vehicles in fleets may be more likely to undergo regular and quality maintenance than privately owned automated vehicles.

Taxi fleet owners

Level 5 would be very attractive for taxi companies as it would enable them to cut labour costs – driver wages make up the majority of their operating costs. The reduced labour costs would enable them to provide lower-cost service and expand their service offerings.

This discussion of taxis also applies to car-sharing services. If non-automated vehicles are replaced with Level 5 vehicles, taxi and car-share services effectively converge to the same service – driverless taxis and car-share vehicles would both provide trips without human drivers and reposition themselves to the next travelers without human drivers.

The elimination of driver labour costs in taxis would enable major reductions in taxi fares – perhaps down to a third of present levels (Fagnant and Kockelman, 2015c; Gilbert, 2013) – thus increasing demand for travel by driverless taxi and stimulating more rapid adoption. Gilbert estimates that a driverless taxi could provide a 5 km journey at an average speed of 30 km/h for \$3, in 2013 dollars, which would be about the same as transit fare for a single

passenger, and a 10 km journey would cost \$5. His estimates are based on an assumption that Level 5 vehicles will cost no more than non-automated vehicles (Gilbert, 2013).

However, especially when Level 5 technology is newly on the market, the price of the technology may be high; as a result, it may not be possible to significantly reduce taxi fares, and driverless taxi fleets may grow slowly. The supply of driverless taxi trips would be limited and fares would still be relatively high, in which case there would be relatively low levels of driverless taxis ridership at first.

Adoption could be more rapid in taxi fleets than for private individuals, for the reasons discussed above.

A number of commentators, such Richard Gilbert, a transportation consultant in Toronto, argue that driverless taxis will eventually be a dominant form of urban travel (Gilbert, 2012). The door-to-door service of driverless taxis would provide the convenience, comfort and privacy of private vehicle travel, without the hassle of parking. And travelers could choose from a variety of vehicle types (as is true today for some carsharing programs), all of which could offer enhanced vehicle interiors that take advantage of the lack of need for a driver. These myriad attractive features, combined with lower fares thanks to the elimination of labour costs for human drivers, could make driverless taxis attractive for many users.

Gilbert argues that when automated systems become common, a Level 4 automated vehicle would cost no more than a non-automated vehicle because of reduced insurance and operating costs, as well as reduced vehicle manufacture costs thanks to reduced need for safety features and human operator controls. If this argument is correct, then the comfort, convenience, and low cost of driverless taxis could reduce incentives for people to own their own private vehicles.

Since each driverless taxi would provide many trips to many individuals over the day, a relatively small fleet could serve a population. Researchers from MIT concluded that all trips currently taken in Singapore, including those now taken by transit and other modes, could be served by a fleet of taxis that is approximately one-third the number of passenger vehicles currently in use; expressed in other terms, only one taxi for every 4 households would be needed (Spieser et al., 2014)(Zhang, 2016). However, because the estimate did not take into account congestion effects, it is not reliable. In the modeled scenario, the number of vehicles on the road at any given moment would be much higher than now – currently, most Singaporeans use public transit. When road capacity limits are taken into account, it can be seen that driverless taxis would be most useful in areas of lower population density; high passenger-capacity vehicles like buses and trains will still be needed in areas with dense spatio-temporal clustering of trips.

Researchers from MIT also modeled how automated taxis could replace human-driven taxis in Manhattan (Zhang, 2016). They found that all taxi trips could be served with a fleet 70 percent the size of the current taxi fleet. It is notable that this finding is far less dramatic than the finding for Singapore. The researchers also studied the congestion effects of the automated taxi fleet in Manhattan, and found that repositioning of empty taxis would not greatly increase congestion. In another study, MIT researchers found that this "rebalancing" of the fleet could substantially reduce the required fleet size. They found that all trips other than subway and bus trips could be served by approximately 35,000 taxis, but this number would drop to 24,000 if rebalancing was performed (Marczuk et al., 2016).

Modeling by the International Transport Forum (ITF) (International Transport Forum (OECD), 2015) found that in a scenario where 8 percent of trips in Lisbon are taken by walking or biking, 0 percent are taken on transit, and 92 percent are taken by single-passenger driverless taxis, the number of taxis needed would be less than a guarter of the number of cars currently in use. However, the total VKT in the city would more than double. Despite this, the authors reported that travel times would be slowed very little. This resulted from an assumption that currently, less than 40 percent of available capacity on Lisbon's roads is in use during peak periods; this means that there is sufficient road capacity to allow for a huge increase in VKT. It is open to question whether this assumption is accurate, considering the authors' caution that they do not account for bus travel, which makes up 13% of VKT in Lisbon. This could lead to an overestimate of the potential for roads in the network to absorb additional traffic. In addition, according to the TomTom Traffic Index, congestion may already be an issue in Lisbon, as travel times during peak periods are currently 45% to 70% longer than they would be under free-flow conditions. In any case, the authors' explanation that little congestion results in their model supports the following interpretation of the above findings: single-passenger driverless taxis could serve a very large proportion of trips, but only where the roads have the capacity to absorb potentially huge increases in traffic without becoming congested.

The researchers also observed that the largest increases in traffic occurred on local streets. The authors caution that this could make them less attractive places to live. This point deserves emphasis: while the results of the model suggest that currently lightly-traveled roads could absorb additional traffic, many streets serve important purposes beyond being conduits for cars, such as providing facilities for walking and cycling, or serving as public spaces. It is important to consider the impacts of increased motor vehicle traffic on these kinds of uses.

The ITF researchers considered other scenarios. For example, in a scenario where 22% of trips go by subway, 8% go by foot or bike, and the remaining 70% go by driverless share taxis of various sizes carrying up to 8 passengers each, the model estimates peak period VKT would rise by 9 percent. Taxis serving multiple rather than single passengers would also

reduce the required fleet size. Parking demand would also drop: the researchers estimated that almost 95% of all parking spaces in Lisbon could be eliminated.

Fagnant and Kockelman modeled the impact of automated taxis in Austin, Texas, at a low level of adoption. The taxis were assumed to serve 1.3 percent of trips within the study area. According to the model, which considered travel speeds that varied by time of day, one automated taxi could replace about 9 conventional vehicles, when trips that originate from or are destined to locations outside the study area are excluded (Fagnant and Kockelman, 2015b). Chen et al. (Chen et al., 2016) studied a similar network and considered the effects of the limited driving range of battery electric vehicles and the need to recharge. The authors found that each electric automated taxi could replace between 5 and 9 privately owned vehicles, depending on battery range and charging speed.

Other studies have found roughly similar reductions in the number of vehicles needed to serve trips. A simulation of Berlin found that, if trips that started or ended outside the study area were excluded, if all trips currently served by cars were instead served by automated taxis, a fleet of 90,000 to 100,000 would be sufficient. This means that each taxi could replace 10 to 12 private cars. The researchers found that the total time vehicles were in motion increased by 17 percent, but did not expect congestion to result under the assumptions that traffic flows would be smoother and cruising for parking would be eliminated (Bischoff and Maciejewski, 2016). In addition, a study of the Zurich region found that one automated taxi could replace up to ten private cars (Boesch et al., 2016).

As can be seen, studies have generally suggested that widespread use of automated taxis could result in large increases in VKT. One simulation study, examining the city of Sioux Falls, Dakota, examined the mode choice effect of single-passenger automated taxis and the resultant travel impacts. Assuming that fares for automated taxi service would be \$0.85 per mile, and a fleet of 1000 taxis was available, around 37 percent of travelers would opt to travel by taxi, and VKT would increase by up to 60 percent (Hörl, 2016). It is possible that this figure would be reduced if, after taxis repositioned themselves after completing trips to areas where new demands are anticipated.

A study of the Stockholm area found that if single-passenger automated taxis serve all trips within the study area (excluding trips with origins or destinations outside the area), VKT would increase by 24 percent over a scenario where private cars serve all trips. However, the researchers found that in a scenario where up to four passengers at a time travel together in share taxis, VKT would be reduced by 11 percent compared to the private car scenario. The authors treated travel speed simply in their modeling by assuming that all link speeds were 75 percent of their free-flow speeds (Burghout et al., 2015).

Transit fleet owners

There are several factors that favour the adoption of automation in heavy vehicles in general (Shladover, 2009b).

- The absolute cost of automation technologies in light and heavy vehicles would be similar, so it would be a smaller fraction of the total cost of heavy vehicles.
- Heavy vehicles are generally more intensively used, so the cost of the technology would be amortized more quickly.
- Heavy-duty vehicles would experience significant energy savings through platooning since the aerodynamic improvements are more significant for large vehicles.
- Because the absolute capital cost of automation technologies would be similar for lightduty vehicles and heavy-duty vehicles, the technologies would make up a smaller fraction of the total vehicle cost for heavy-duty.

Labour savings and other operational benefits of automation would also be very attractive to bus transit fleet operators. Transit buses have the highest hourly operating costs and the most intensive utilization of any vehicles on the road (Shladover, 2009a), so the prospect of labour cost savings and other operational cost savings would be very attractive for transit operators (especially for transit agencies in the developed world, where labour costs are higher). Public transit is labour-intensive, and costs for drivers, mechanics, and other personnel account for approximately 60 percent to 80 percent of operating costs (Anderson, 1986; Hemily and King, 2008; Hinebaugh, 2009).

8.3 Other factors influencing adoption

If subsidies for automation technologies are provided, this would speed adoption. Subsidies could include subsidies for capital costs, or subsidies for operating costs, such as reduced insurance rates and road pricing.

Adoption of automation will be influenced by the level of provision of infrastructure. If automated vehicles have prioritized access to special infrastructure, such as exclusive lanes, this may enhance their benefits to users, and could speed adoption, especially for lower levels of automation, such as Level 2 and 3. For example, dedicated lanes could enable fully automated operation by Level 2 vehicles. On the other hand, if automated vehicle operation is restricted to special infrastructure, adoption will be limited by the provision of this infrastructure.

If automated vehicles are required to undergo frequent inspection and maintenance, this could be a disincentive for private owners; this may be less of a disincentive for fleet owners who could undertake inspections and maintenance more efficiently. If special driver training is

required for the operation of vehicles with lower levels of automation to ensure drivers understand their new duties when operating vehicles with partial automation, this would also tend to be a disincentive for private owners, but again, this would likely be less of a disincentive for fleet owners with professional drivers, where training could be provided more efficiently.

Finally, competition between different technologies would influence adoption rates and levels – for example, high levels of adoption of Level 3 technology could reduce the levels of adoption of Level 5 automation. In general, it is reasonable to expect that the rate of adoption of lower levels of automation will slow when higher levels of automation emerge onto the market, since the higher levels with their more comprehensive capabilities would be more attractive for many users. When the higher levels first emerge, their capital costs would likely be high, but as their costs drop, they would eventually become more attractive.

8.4 Timelines of adoption

PREDICTIONS

A range of views have been expressed regarding likely rates and levels of adoption of vehicle automation once these technologies become available to the general public. In 2012, the Institute of Electrical and Electronics Engineers (IEEE) released a statement containing the assertion that "autonomous vehicles... will account for up to 75 percent of cars on the road by the year 2040" (IEEE, 2012). According to a report from the market research firm Navigant Research, Level 5 vehicles will emerge onto the market in 2020, and by 2025, will comprise 75 percent of worldwide light-duty vehicle sales (Alexander and Gartner, 2013). Lutin et al. contend that Level 5 automated vehicles could reach market penetration levels of 11 to 34 percent in five years and 22 to 59 percent in ten years (Lutin et al., 2013). The market research firm Strategy Analytics predicts a slower rate of adoption, where Level 4 vehicles that "offer significant support to drivers in multiple different driving situations" and that will at first only operate in fully automated mode "in certain situations – such as highway driving – or in areas with a certain degree of V2X support", will have a market share of around 15 to 20 percent globally by 2025 to 2030, while the number of more advanced automated vehicles, presumably Level 5, will be "in the low single figure percentages" (Riches, 2013). The consulting firm McKinsey & Co. speculates that after technological and regulatory issues are resolved, up to 50 percent of passenger vehicles sold in 2030 will be "highly autonomous" and 15 percent "fully autonomous" (McKinsey & Co., 2016)(Gao et al., 2016). Steve Underwood of the Center for Automotive Research estimates that Level 3 technology will be in 70 percent of vehicles sold within ten years of its emergence on the market, by about 2030 (Underwood, 2013).

Todd Litman of the Victoria Transport Policy Institute predicts that in the 2040s, Level 5 vehicles will likely represent 50 percent of vehicle sales and 30 percent of vehicles on the road, and by the 2050s, would become the majority of vehicles on the road (Litman, 2014). He notes that modern vehicles have increasingly long operating lives, with current models likely operating for 20 years or more. According to the market research firm IDC Manufacturing, new cars are being purchased at a slower rate than previously and the average age of vehicles on the road is increasing, and is currently 11.2 years (Brennan, 2013). If these trends continue, the adoption of new vehicle technologies may be slowed.

A simulation by researchers from the University of Texas at Austin (Bansal and Kockelman, 2016) concluded that if Level 5 vehicles emerge onto the market immediately, and if their price drops by 5 percent every year (from a premium of \$40,000 in 2015 to less than \$9000 in 2045), approximately 25 percent of the overall fleet of light-duty vehicles will be Level 5 vehicles in 2045; while in a more aggressive scenario where their price drops by 10 percent every year (from a premium of \$40,000 in 2015 to around \$1700 in 2045) and consumers' willingness to pay for the technology increases by 10 percent ever year, approximately 87 percent of the fleet of light-duty vehicles would be Level 5 in 2045.

A study by Lavasani et al. (Lavasani et al., 2016) examined the adoption patterns of previous technologies, such as hybrid electric vehicles, cellphones, and internet, and developed a model to estimate adoption of automated vehicles. They found that, if Level 5 automated vehicles become available in 2025, adoption to the point of market saturation, at 75 percent of households, may occur in 35 years.

PROJECTIONS OF ADOPTION RATES

Given the range of estimates of adoption rates discussed above, it is useful to develop some simple projections to provide a frame of reference for comparison. Some simple projections are discussed below.



Figure 14. Projected adoption of automated vehicles in Edmonton

The curves in Figure 14 illustrate a range of trajectories of adoption of automated vehicles in Edmonton, from very rapid to moderate in pace. These hypothetical trajectories can be applied to any type of vehicle automation technology; for the present discussion, the trajectories refer to Level 5 light-duty vehicles.

The most rapid trajectory, illustrated by the red curve, illustrates how the overall fleet of lightduty vehicles would comprise an increasing proportion of Level 5 light-duty vehicles, under the assumptions that, immediately after Level 5 vehicles become available on the market, every single new vehicle purchased is a Level 5 vehicle, and the survival rate of vehicles is the same as it was over the 10-year period from 2006 to 2015 in Edmonton – that is, vehicles of each model year are retired from the fleet at the same rate as they are currently. Under those assumptions, starting from the current distribution of vehicle ages in Edmonton³, the proportion of the overall fleet made up by Level 5 vehicles would increase to 50 percent in around 6 to 7 years; to 90 percent in around 18 years; and to 95 percent in around 30 years.

A somewhat less rapid trajectory is illustrated by the black curve. This trajectory would occur under the assumptions that, after Level 5 vehicles become available on the market, they make up an increasingly large share of new vehicles purchased over an 8-year period, increasing from 20 percent in the first year to 100 percent in the eighth and subsequent years, and the survival rate of vehicles in Edmonton remains at the current rate. In this trajectory, the proportion of the overall fleet made up by Level 5 vehicles would increase to 50 percent in around 11 years; to 90 percent in around 22 years; and to 95 percent in around 30 years.

A moderate trajectory is illustrated by the solid blue curve. In this trajectory, after Level 5 vehicles become available on the market, they make up an increasingly large share of new vehicles purchased over an 18-year period, increasing from 10 percent in the first year to 100 percent in the eighteenth and subsequent years, and the survival rate of vehicles remains at the current rate. In this trajectory, the proportion of the overall fleet made up by Level 5 vehicles would increase to 50 percent in around 17 years; to 90 percent in around 30 years; and to 95 percent in around 36 years.

Finally, a slow trajectory is illustrated by the dotted blue curve. In this trajectory, after Level 5 vehicles become available on the market, they make up an increasingly large share of new vehicles purchased over an 8-year period, increasing from 10 percent in the first year to a plateau of 50 percent in the eighth and subsequent years, and the survival rate of vehicles remains at the current rate. In this trajectory, the proportion of the overall fleet made up by Level 5 vehicles increases to 25 percent in around 16 years, and to 45 percent in around 40 years.

³ Vehicle population statistics were sourced from the Alberta Registries Motor Vehicles Division.

Some factors could result in slower or faster rates of adoption than illustrated in these models. For example, if vehicles have longer lifespans, the turnover rate of the overall fleet would be lower, and thus the rate of adoption would be slower. On the other hand, it is possible that many individuals would find Level 5 vehicles highly attractive and would therefore choose to retire their non-automated vehicles (or vehicles with lower levels of automation) earlier, thus accelerating adoption rates. Adoption of Level 5 vehicles by taxi fleet owners could also accelerate the overall adoption rate, since taxis would be used more intensively than privately owned vehicles and would thus result in higher turnover rates. In addition, labour cost savings would likely make Level 5 strongly attractive for taxi fleet owners, and fleet owners could also benefit from discounted rates on purchases of large numbers of vehicles.

Though it is not certain how rapidly automated vehicles will be adopted, the simple models above broadly indicate that an extremely rapid rate of adoption would mean Level 5 light-duty vehicles would make up a large majority of the overall fleet of light-duty vehicles on the road within 15 to 20 years after their emergence onto the market, whereas more moderate trajectories that assume less extreme but still rapid rates of uptake suggest that it could take 30 years or more for Level 5 vehicles to become a large majority of the overall light-duty fleet on the roads. These points are important to consider, since many of the impacts of automated light-duty vehicles would only become significant at higher levels of diffusion.

Predictions have also been made regarding the rate of adoption of V2X. The automotive consultancy SBD forecasts that 50 percent of new vehicles worldwide will be fitted with V2X by 2020, and 90 percent by 2025 (SBD, 2012). The American Association of State Highway and Transportation Officials has suggested that the portion of the US light vehicle fleet equipped for V2X could reach 30 percent by 2023 and 70 percent by 2029 (Christopher J. Hill and Garrett, 2011). It should be noted that the adoption of V2X could be hampered by a critical mass problem, in the case of V2V, and by a chicken-and-egg problem, in the case of V2I. The value of V2V is determined by the level of adoption – at low adoption levels, V2V will provide very little benefit for the user of the equipped vehicle, since a V2V system can only "see" other equipped for communications. Until a significant amount of infrastructure is equipped, a V2I vehicle will derive little benefit from its communication abilities (Stiller, 2010). Because of these challenges, V2X may require additional incentives, such as subsidies, or mandated implementation, to speed adoption.

9. Qualitative analysis of impacts in Edmonton

9.1 Future scenarios selected for analysis

The future impacts of automated vehicles depend on what kinds of automation technologies are available and how they are adopted. For the purposes of discussion, a qualitative analysis of four scenarios describing hypothetical conditions in Edmonton in 2047 is presented here.

The scenarios are based on combinations of two main variables:

- Level of diffusion of automated vehicles, of particular SAE levels of automation, resulting from different dates at which various levels of automation emerge onto the market and the rates at which they are adopted
- Quality of transit service provided, resulting from different extents to which the City deploys automation in public transit to improve service

Regarding the level of diffusion of automation, two different states are assumed:

1. Widespread diffusion of advanced automation (early emergence and rapid adoption of advanced automation)

- Level 5 becomes available on the market in 2020 and is adopted rapidly (as illustrated in the solid red curve in the graph at the end of the document)
- Resulting composition of the overall fleet of light-duty vehicles in 2045:
 - o Level 5: 90%
 - o Level 0: 10%
 - o Driverless taxis are widely available

2. Moderate diffusion of less advanced automation (later emergence and moderate adoption of less-advanced automation)

- Level 3 becomes available on the market in 2020 and is adopted at a modest pace (as illustrated in the dotted blue curve at the end of the document)
- Resulting composition of the overall fleet of light-duty vehicles in 2045:
 - o Level 3: 40%
 - o Level 0: 60%

Regarding the quality of transit service provided, two different states are assumed. The precise definition of these states should be discussed.

A. Base level of service

This reflects a "business as usual" approach where transit frequency, capacity, network coverage, fares, and other relevant factors are similar to what they are currently.

B. Improved level of service

This state of transit service should reflect increased investment in transit, especially through the proactive deployment of available automation technologies to improve transit service, with respect to frequency, capacity, network coverage, and fares.

The four resulting scenarios are:

- Scenario 1A: widespread diffusion of advanced automation + base level of transit service
- Scenario 1B: widespread diffusion of advanced automation + improved level of transit service
- Scenario 2A: moderate diffusion of less advanced automation + base level of transit service
- Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

In the first two scenarios, Scenarios 1A and 1B, it is assumed that advanced automation technologies emerge very early and are adopted very rapidly. In particular, it is assumed that Level 3 vehicles are available on the market in 2018 and Level 5 vehicles are available in 2020. In addition, it is assumed that driverless taxis have become commonplace. In the first of these two scenarios, public transit investments are given low priority; automation is not deployed proactively in transit and service remains near current levels. In the second of these two scenarios, public transit investments are given high priority; automation is proactively deployed in transit to provide improved service. This includes Level 4 and 5 buses and Level 4 low-speed vehicles.

In the second two scenarios, Scenarios 2A and 2B, it is assumed that advanced automation technologies emerge later (though not as late as some experts predict) and are adopted at a moderate rate. In particular, it is assumed that Level 3 vehicles are available on the market in 2020 and Level 5 vehicles are available in 2040. In the first of these two scenarios, public transit investments are given low priority; service remains near current levels. In the second of these two scenarios, public transit investments are given low priority are given high priority; automation is proactively deployed in transit to provide improved service. This includes Level 4 buses and low-speed vehicles.

The four scenarios are summarized in Table 1 below.

		Base level	Improved level
DIFFUSION OF LEVEL 3 AND LEVEL 5	Widespread	• Level 3 on the market in 2018, Level 5 in 2020	• Level 3 on the market in 2018, Level 5 in 2020
		Driverless taxis are common	Driverless taxis are
		• Level 4 LSVs, Level 4 & 5	common
		bus technology is available but not widely deployed	Level 4 LSVs, Level 4 & 5 buses widely deployed
	Moderate	• Level 3 on the market in 2020	Level 3 on the market in 2020
		 Level 4 LSV and bus technology is available but not widely deployed 	 Level 4 LSV and bus technology widely deployed

DEPLOYMENT OF AUTOMATION IN TRANSIT

Table 1. Summary of scenarios.

The analyses presented below discuss the likely travel and land use impacts of future vehicle automation technologies in the four scenarios.

9.2 Travel behaviour

VEHICLE OWNERSHIP

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

Many individuals would be attracted to own Level 5 vehicles, including individuals who cannot or do not typically drive, such as elderly people and people with limited physical mobility, who would be attracted by the possibility of independent travel by motor vehicle. These increases could be significant: about 13 percent of those of driving age in the US lack a driver's license (FHWA, 2011). In addition, some parents may be attracted to own a Level 5 vehicle to chauffeur their children.

Meanwhile, as driverless taxis emerge, and as fares decrease and taxi fleets increase in size, some individuals would opt out of owning their own vehicles, preferring the overall balance of private costs and benefits of travelling by driverless taxi. Some of these individuals may choose to use a greater diversity of modes for different trips than they would have otherwise, taking some trips by taxi, some by transit, and others by foot, for example.

While the comfort, convenience, and low cost of driverless taxis could reduce incentives for people to own their own private vehicles, for some individuals, the convenience and assurance of having a private vehicle that is always available for spontaneous trips, without delay, and the opportunity to have full control over the private space of their own vehicle would nevertheless be very attractive.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

Level 5 private vehicles and driverless taxis would still be attractive in the scenario where transit service is improved via the proactive deployment of automation; however, improvements in transit service frequency and network coverage and reductions in fares would lead some individuals to opt for transit use, or transit use complemented with driverless taxi use, over private vehicle ownership.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

Level 3 would attract private ownership, but this attraction would be moderate because the technology which would require a substantial level of human driver involvement.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

The attractiveness of Level 3 just mentioned would be further moderated in a scenario where transit service is substantially improved.

MODE SHIFTS

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

The decreased generalized cost of travel (Litman, 2013) by private vehicle will incentivize owners of automated vehicles to travel by private vehicle where they would otherwise have travelled by other modes. This effect would be larger with the higher levels of automation, and would also be larger where infrastructure such as dedicated lanes is provided for automated vehicles.

Most of the potential mode shift to private vehicles would likely come from public transit rather than from walking or cycling, since the decreased generalized cost of vehicle travel would be more significant for longer trips. For the same reason, it would be likely that a greater number of long transit trips rather than short transit trips would shift to private vehicles. It would also be likely that relatively large mode shifts would occur in low-density areas or other areas with relatively poor transit service.

There would be limited incentive to shift to private vehicle travel from walking and cycling, since the generalized cost of travel would remain low for shorter walking and cycling trips, except for older individuals. Many travelers would still find walking or cycling to be convenient and in many cases to be more enjoyable than other modes.

After driverless taxi fares decrease to a sufficiently low level, they could stimulate an increase in taxi trips. Individuals would take some trips by taxi that they would have otherwise taken by private vehicle, transit, walking, and cycling. Much of this shift would be likely to come from transit and private vehicles, since walking and cycling would still be attractive for shorter trips. In addition, some of the shift to travel by taxi would come from private vehicles. The total amount of trips taken by taxi would be limited by the size of the taxi fleet. The attractiveness of taxis would also be limited in more peripheral locations due to the costs of deadheading empty taxis.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

Improvements in transit service through the application of automation would tend to lead to increased ridership. Where buses are able to operate in platoons, with one driver leading a platoon of two or more buses, or where buses are otherwise able to operate in fully automated mode, capacity and/or frequency can be improved with minimal increases, or even with decreases in labour costs. Such improvements in service would tend to attract increased ridership, if they outpace reductions in the generalized cost of travel by other modes, such as private vehicle and driverless taxi. The generalized cost of travel by transit is most likely to be competitive with other modes for trips originating or ending in or near heavily travelled corridors. In these areas, it is more likely that transit service may be sufficiently frequent and rapid to compete with other modes, especially if dedicated busways are provided. If there is a significant shift toward travel by transit in these corridors, at the same time that there is a significant shift toward private vehicle travel or driverless taxi travel in low-density areas, there may be an overall increase in transit ridership, if densities of trip origins and destinations in or near heavily travelled corridors are sufficiently high.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

Level 3 private vehicles would attract increased mode share, though this effect would be moderate because of the limitations of the technology. In addition, because lower levels of automation can operate in automated mode mainly, or exclusively, on freeways or highways, when vehicles equipped with lower levels of automation are used for short trips, they will only be able to operate in automated mode for a relatively small fraction of the trip (since at least the beginning and ending of any trip takes place off the freeway network). Because of this, mode shifts to private vehicles with lower levels of automation would be relatively small for short trips and would instead occur predominantly for longer trips.

Level 2 and 3 automation would have minimal impacts on driver labour costs, and would thus have minimal impacts on taxi fares and the level of supply of taxi service, and therefore would result in minimal mode shifts toward taxi travel. Low-speed Level 4 vehicles could operate on low-speed roads, attracting mode share for short trips.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

The application of Level 1, 2, and 3 automation to transit could improve various aspects of operations, such as reliability of trip times and ride quality. In addition, Level 4 buses, particularly in protected lanes, could reduce labour costs substantially and enable major improvements in service. Level 4 low-speed vehicles could operate on low-speed roads,

attracting mode share for short trips, and could especially be used to improve first mile/last mile access to higher-order transit. These improvements could result in substantial mode shifts to transit.

INDUCED TRAVEL

In all four scenarios, automation would tend to reduce the generalized cost of travel, which would lead some individuals to take trips by automated vehicle where otherwise they would have taken no trip. In addition, some trips that would have formerly been "chained", with trips to multiple destinations bundled into one trip, would now be taken as separate trips.

The decreased generalized cost of travel would lead some individuals to take longer trips than they would have otherwise taken. Marchetti's constant, which posits that people tend to have a constant travel time budget (Marchetti, 1994), may need to be modified when referring to individuals traveling by automated vehicle, since travelers in automated vehicles, especially Level 5 vehicles, would be likely to have a greater tolerance for longer or more congested commutes.

Automation in transit could also result in the generation of longer trips, where service improvements reduce the generalized cost of travel.

Travelers would also be induced to change routes, for example, to take freeways where capacities are higher.

Travelers in automated vehicles would shift some trips to peak periods, even where delays are not reduced, due to the reduced cost of travel time per unit time.

One study examining the traffic impacts of automated vehicles, modified the four-step planning model to account for increased road capacities and intersection capacities (due to the use of reservation-based intersections) resulting from automated vehicle use (Levin, 2015). He found that the total number of trips in private vehicles almost doubled, due to these vehicles remotely parking at home. Nevertheless, the author found that the increases in capacity would "mostly offset or even improve network conditions". Another study, which focused on the traffic impacts of automated vehicles up to Level 3 automation, found that unconnected automated vehicles would lead to a 6 percent increase in highway traffic during peak hours, while connected automated vehicles would lead to a 9 percent increase. In the latter case, it was assumed that connected automated vehicles would be capable of platooning. The authors note that they did not account for various effects that would further increase VKT, including increased trip lengths (Puylaert, 2016).

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

The induced travel effects just mentioned would be particularly strong in this scenario.

Once the capital cost of the technology is sufficiently low, Level 5 would reduce the generalized cost of travel substantially, since the cost of travel time could be reduced greatly, and potentially even eliminated in some cases where travellers engage in particularly enjoyable or productive activities. This would encourage more trips and longer trips. In addition, non-drivers, such as seniors and people with limited physical mobility would be induced to take more trips and longer trips.

With Level 5 automation, there is the additional potential for the generation of trips with no human occupant. Such zero-passenger VKT would include empty driverless taxis travelling from one passenger to the next and empty private vehicles travelling to remote parking spots.

When vehicles capable of platooning have been adopted widely enough that platooning leads to an increase in capacity on freeways, the reduced delays on freeways will attract drivers of both automated and non-automated vehicles to shift their routes to freeways.

The increase in trip lengths would be largest for Level 5 vehicles, but could also be large for Level 3 vehicles, especially where these vehicles make trips that make extensive use of freeways and dedicated lanes.

Where platooning leads to reduced delays, or where automation reduces non-recurrent congestion, delays during peak periods would in general be reduced as well, so travelers in both automated and non-automated vehicles would be induced to shift some trips to take place during peak periods. Similarly, automation in transit could improve service during peak periods, with reduced crowding, for example, and thus induce travelers to shift some trips to peak periods.

Route choices would be affected; in particular, freeways or highways would be used more where dedicated freeway lanes for automated vehicles are provided.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

In this scenario, the higher mode share of transit would result in smaller induced travel impacts than in the foregoing scenario.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

The induced travel impacts described above would be present in this scenario, but would be smaller than in the early emergence scenarios due to the limited capabilities of lower levels of automation.

Drivers of vehicles with Level 2 and 3 automation would tend to use freeways or highways more often than they would in the absence of vehicle automation, in order to have a lower-stress automated drive. In addition, where dedicated freeway lanes for automated vehicles are provided, especially where these lanes offer sufficient protection to facilitate fully automated operation of Level 2 or 3 vehicles, drivers of these vehicles would be incentivized to take routes that use these lanes for a portion of the trip.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

The induced travel impacts described in the foregoing scenario would be further mitigated in a scenario where transit service is substantially improved through the application of available automation technologies.

PARKING

In general, the increased ease of travel due to easier parking, or the eliminated need for parking, would tend to generate new trips, especially to destinations where parking is expensive or in short supply. In the case of Level 5, remote parking and driverless taxis would mean that the supply of parking no longer restricts trips to destinations, such as in downtown areas. This could especially lead to more trips to popular destinations, such as in downtowns. In addition, driverless taxis would tend to generate additional VKT where the taxis move from the last passenger's destination to the next passenger's trip origin. This, along with additional VKT generated by remote parking, would offset reductions in traditional "cruising for parking" (Shoup, 2006). Automated valet parking, by increasing the ease of parking, would also tend to decrease the generalized cost of travel and would thus lead to further increases in parking demand.

One study has considered the impacts of remote parking. A modeling study of Melbourne examined the combined impact of shared taxis and privately owned automated vehicles that would drive themselves to park at the users' homes after use. The researchers found that if 75 percent of trips were taken in share taxis that can carry up to four passengers each, with the other 25 percent of trips taken by single-passenger private automated car, total VKT would be 29 percent higher than in a scenario where all trips are taken by manually driven

private cars (Javanshour et al., 2016). This is despite the sharing of the majority of trips in share taxis. The researchers explained that the increase in VKT was primarily caused by the private automated cars repositioning themselves.

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

With Level 5 vehicles, a shift in parking locations could result as vehicles could drive themselves to park at remote locations. For example, a commuter could travel to work and then send their privately owned car back home to park. This remote parking could reduce the demand for parking in areas of high intensity land uses, such as downtown areas, where parking is expensive or difficult. Parking spaces could then be located more efficiently, further away from areas of high intensity land use.

Remote parking would eliminate "cruising for parking" as it is currently understood, where a driver travels additional distance to find available parking, but it would also generate new trips where vehicles travel to remote parking locations. If these parking locations are distant from popular destinations, significant additional VKT could be generated.

Parking demand could also be reduced as a result of automation. First, automated valet parking could allow cars to be parked more densely and thus increase the efficiency of use of parking space.

Second, demand could be reduced by reducing vehicle idle time and by minimizing the size of the overall fleet of vehicles in cities. Large mode shifts to modes such as transit or driverless taxi, away from low-occupancy vehicle trips taken by private vehicle, could produce these changes.

If there is a significant shift away from private vehicle use toward the use of driverless taxis, there would be less need for parking. Rather than parking their own vehicles, individuals would simply get out of their fully automated taxis, which would then drive off to pick up their next passengers. For example, Mitchell et al. argue that the time an automobile is parked could drop from 80 percent to 20 percent, reducing the need for parking spaces by a factor of four (Mitchell, 2010). They qualify this, saying that "[i]n practice this factor will be somewhat lower, since the demand for vehicles will be distributed unevenly throughout the day, and parking space must be sized to accommodate peak demand." However, while a shift to driverless taxis could result in a significant reduction in peak demand for parking, this effect could be smaller if trip patterns become more temporally peaked, that is, with more trips being taken during peak periods and fewer during off-peak periods.

In addition, while there may be less need for parking to be located very close to destinations, there could be an increased need for areas where travellers could be dropped off or picked up.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

In a scenario where transit mode share increases as a result of improved service, the remote parking phenomenon would be mitigated. Parking demand would also be reduced to a greater degree than in the foregoing scenario, due to the higher number of trips being served by vehicles with high passenger capacities.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

Level 2 and 3 vehicles would tend to simply increase parking demand due to the increase in trips that would result from the lower generalized cost of travel. This effect would be moderate due to the moderate decreases in the generalized cost of travel produced by these levels of automation.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

The increase in parking demand present in the foregoing scenario would be mitigated in a scenario where transit mode share is increased as a result of improved service.

9.3 Land use

LOCATION CHOICE

As automation changes the generalized cost of travel, the resulting changes in accessibility and property values would affect residential and firm location choice.

In general, automation in light-duty vehicles would make suburban and exurban locations more accessible. Users of privately owned automated vehicles and driverless taxis would experience incentives to choose residential locations that are more distant from their jobs or other activities, and that are particularly accessible by freeway, where those residential locations offer lower-cost housing or other perceived benefits.

Where dedicated lanes are provided, users of automated vehicles would experience an incentive to choose residential locations that are more accessible by dedicated lanes.

When automation reaches sufficiently high levels of adoption, it would also influence firm location choice. Automation would provide firms an incentive to choose locations more distant from their customers, employees, or other firms they do business with. These effects would result both from automation in light-duty vehicles and in buses. Where automation is deployed in buses in particular, firms would be incentivized in particular to choose locations that are accessible by transit. These locations would tend to be in or near heavily traveled transit corridors.

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

Level 5 vehicles would produce very strong incentives for individuals to choose residential locations that are more peripherally located. Level 5 could also facilitate seniors in suburban areas "aging in place".

If remote parking becomes a popular practice, a significant shift in the location of parking demand could result, bringing a substantial increase in parking demand in lower-density areas.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

If public transit service is improved through the deployment of automation, transit users would be incentivized to choose residential locations that are accessible by these higher quality transit services. Users of improved transit services would be incentivized to choose residential locations accessible by these services, which would likely be in heavily travelled corridors. Since automation is particularly suited to applications in BRT busways, it is likely that many of the service improvements resulting from automation would take place along more heavily travelled corridors. This means there would be an incentive for transit users to locate near these more heavily traveled corridors.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

Lower levels of automation would also tend to encourage more dispersed location choice, but the effects would be more limited than with Level 5, due to the smaller impacts on the generalized cost of travel.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

The tendency to encourage more dispersed location choice described in the foregoing scenario would be mitigated further in a scenario where transit mode choice is increased due to service improvements.

CHANGES IN LAND CONSUMED BY TRANSPORTATION INFRASTRUCTURE

Due to changes in the efficiency of use of transportation infrastructure and the associated changes in travel patterns, the emergence of automation will present opportunities to change the provision of transportation infrastructure, such as roads and parking. These changes in land consumed directly by transportation infrastructure would in turn present new opportunities and needs for changes in land use.

When automation is sufficiently widely adopted, capacities on some roads could increase significantly. This could allow for the removal of conventional freeway lanes. The land could be used for busways or for other modes, or could be used for greenspace or development. Similar changes could be made on other roads, with automation facilitating lane conversions and road diets on arterials and streets.

Where automation results in reduced parking demand, such as where significant mode shifts toward transit and/or driverless taxis occur, former parking lots and roadside parking spaces could be converted to other uses, such as development, sidewalk, bike facilities, or greenspace. Similarly, remote parking of private vehicles would tend to lead to a shift of parking from intensely developed areas to less intensively used, less central areas. Some former parking lots or roadside parking spaces would become available for other uses, such as development or greenspace (Walker, 2016). These changes would allow for infill development, which could encourage more short trips taken by walking and cycling

(Bamonte, 2013). Park-and-ride parking lots could be eliminated and transit-oriented development around transit stations could be intensified.

However, remote parking would also result in land in other neighbourhoods being consumed by new parking facilities.

Scenario 1A: widespread diffusion of advanced automation + base level of transit service

After Level 5 emerges, if it is widely adopted in private vehicles and driverless taxis, the incentives for dispersed development would increase. However, these tendencies would be mitigated somewhat by new opportunities for infill development and denser, more pedestrianoriented land use patterns that would allow travelers to access a greater number of destinations in relatively short trips that use modes such as walking and cycling. These shifts would tend to mitigate the tendency to dispersed development.

Scenario 1B: widespread diffusion of advanced automation + improved level of transit service

Where automation is deployed in public transit, the tendency toward dispersed development would be mitigated, and there would be an increased incentive toward development along transit corridors and in transit-oriented developments. Automation in transit could also lead to additional opportunities for infill development.

Scenario 2A: moderate diffusion of less advanced automation + base level of transit service

In this scenario, there would be little potential for improvement in road capacities; thus, it is unlikely that there would be significant new opportunities for reductions in the supply of roads.

In addition, Level 2 and 3 automation would tend to increase parking demand, which could lead to the creation of additional parking facilities.

Scenario 2B: moderate diffusion of less advanced automation + improved level of transit service

In this scenario, substantial mode shifts to transit could occur, producing new opportunities for lane conversions and road diets.

10. Review of activities in selected cities

In this section, recent, ongoing, and proposed actions relating to the testing and deployment of automated vehicles in selected cities around the world are reviewed.

HELSINKI, FINLAND

The SOHJOA project, a one-year test of fully automated low-speed electric shuttle buses, is currently underway in Finland, coordinated by the Helsinki Metropolia University of Applied Sciences. Easymile EZ-10 minibuses will be tested in Helsinki until mid-September 2016 along a short section of several hundred meters of seaside public road in the Hernesaari district (EasyMile, 2016a)(Xinhua, 2016)(Yle, 2016)(Daily Mail, 2016). The vehicles will operate at a top speed of 11 km/h, and will accommodate up to six seated and six standing passengers. Additional testing will take place in the cities of Espoo and Tampere. Testing will stop when snowy weather begins, and will resume in spring 2017.

VANTAA, FINLAND

During the summer of 2015, EasyMile EZ10 vehicles were tested in the city of Vantaa (Minna Honkanen et al., 2013). Vantaa, located in the Helsinki metropolitan area, had a population of approximately 215,000 in 2015. The trial took place during the annual Finnish housing fair, which draws close to 200,000 visitors (Minna Honkanen et al., 2013)(EasyMile, 2016b). Four of the minibuses drove along a one kilometre route between the Kivistö railway station and the gates of the Housing Fair. The vehicles drove at a maximum of 13 km/h on a route that was fully segregated from other vehicles, cyclists, and pedestrians (Gilbert Koskela, 2016)(Minna Honkanen et al., 2013)(EasyMile, 2016b). Service was provided free of charge.

LAUSANNE, SWITZERLAND

A fleet of six EasyMile EZ10 shuttles were tested in 2015 on the campus of the Swiss Federal Institute of Technology in Lausanne, Switzerland (EPFL) (EasyMile, 2015). The shuttles drove at a maximum speed of 15 km/h along a 1.5 km route between the north and south ends of the campus. The original intention was to connect the campus to a metro station, but the implementation was changed due to construction in progress. The route avoided roads with

heavy traffic, mostly running through pedestrian areas or roads used primarily by delivery vehicles (Cerottini et al., 2013). Service was provided from 7:45 am to 10 pm Monday through Friday. Riders had the option of making a request for a ride through a smartphone app. Close to 7,000 passengers used the shuttles during the five-month demonstration (Pessaro, 2016).

SION, SWITZERLAND

Testing of two electric automated 11-passenger Navya minibuses is being conducted in Sion, Switzerland, from 2016 through 2017. The vehicles are driving on public roads and in pedestrian areas in the old town tourist area at a maximum speed of 20 km/h. The vehicles do not have steering wheels, accelerators, or brake pedals. However, an attendant on the vehicle monitors operation and can stop the vehicle in an emergency; in addition, a remote operator can also stop the vehicle. The vehicles operate only in good weather and road conditions. The vehicles serve several stops, two of which are at fixed locations. One stop has a screen that displays the locations of the vehicles to users; users can also see the locations of the vehicles on a mobile app. The vehicles are wheelchair accessible. The public bus operator PostBus states that they intend to provide service to previously underserved areas, but do not intend to replace buses on existing routes with automated vehicles (PostBus, 2016a). The vehicles may later be brought into operation on other routes in the city of Sion (PostBus, 2016b).

WAGENINGEN, THE NETHERLANDS

Since 2015, EasyMile EZ10 buses, referred to as WEpods, have been undergoing testing in the cities of Wageningen and the Ede in the Netherlands (WEpods, 2016)(Campbell-Dollaghan, 2015)(Murgia, 2015). The 12-passenger, wheelchair-accessible buses will drive a 7-km route on public streets in mixed traffic between the intercity railway station at Ede-Wageningen and the Wageningen University campus. Initially, the WEpods will not operate during bad weather, during heavy traffic, or at night. Operation will be monitored remotely by a technician at a control center (Gibson, 2015). Users will be able to arrange pick up and destination locations via an app. The routes will be gradually expanded during the test (WEpods, 2016).

BRUSSELS, BELGIUM

The Brussels airport plans to begin providing automated shuttle bus service at the airport in 2018 (Ricardo Rail, 2015)(CityMobil2, 2016b). The buses would connect parking areas with

terminals, office areas, and cargo loading areas at speeds between 15 and 20 km/h. The target is to transport 250 passengers per hour per direction.

TRIKALA, GREECE

Six 10-passenger driverless shuttle buses were tested in the city of Trikala, Greece, over six months in 2015 and 2016 (CityMobil2, 2016c). The buses had a maximum speed of 20 km/h, and were monitored remotely by an operator in a control centre. The 2.4 km route followed a dedicated route, but no barriers were provided to positively exclude other traffic or pedestrians. 70 on-street parking spaces were removed to establish the lane, and a ban on parking was enforced during the hours the shuttles were in service. Seven traffic lights were modified or replaced to provide V2I-controlled signal priority (Raptis, 2016). Over 12,000 passengers were transported during the trial (CityMobil2, 2016c).

MILTON KEYNES, UK

The Lutz Pathfinder, a small, light, low-speed, electric automated vehicle that carries up to two passengers has undergone testing in the UK. The town of Milton Keynes plans to test these vehicles, or a new generation of similar two-, four, and eight-seater vehicles known as Pod Zeros, along pedestrian pathways in the UK town of Milton Keynes (BBC.com, 2015)(OneMK, 2016)(Dimmer, 2016). The vehicles would connect a train station to a shopping centre about a mile away. The vehicles have a top speed of 25 km/h, and will be monitored by attendants.

SINGAPORE

In 2015, the Land Transport Authority (LTA) of Singapore, in partnership with the developer of the technology and business park one-north, identified routes in one-north where testing of automated vehicles would be permitted. A 6 km network of roads with light to heavy traffic was selected. Interested groups were invited to apply to conduct testing in the specified area (Land Transport Authority, 2015). In 2016, the LTA announced that two groups, Delphi Automotive and nuTonomy, would begin testing their concepts for "shared, on-demand, door-to-door, first-and- last-mile and intra-town self-driving transportation concepts" (Land Transport Authority, 2016).

nuTonomy has begun to test six automated taxis. Invited members of the public can hail the test vehicles via smartphone (Associated Press, 2016). Rides must begin and end at designated locations (Illmer, 2016). A test driver rides in the driver's seat to take over when needed, and a researcher in the back seat monitors the computers that control the car. The

company hopes to increase the fleet to a dozen by the end of the year (Associated Press, 2016), and begin "limited commercial deployment where it makes sense and is safe" by 2018 (Volpe, 2016). Service may first be expanded to a neighbourhood adjacent to one-north (Watts, 2016).

Delphi Automotive is testing six automated versions of Audi SQ5s on three fixed routes. The company reportedly intends to phase out the use of test drivers in 2019 and begin providing taxi service throughout the city by 2022 (Ross, 2016b)(Wong, 2016a)(Lye, 2016).

In addition to applications of automation in taxis, the government of Singapore has also expressed an intention to explore other applications of automation, such as driverless buses (Land Transport Authority, 2016)(GovInsider, 2016).

A number of automated vehicle trials have taken place in Singapore in recent years. For example, in December of 2014, the Singapore-MIT Alliance for Research and Technology (SMART) tested two 10-passenger "Auto Rider" vehicles along a ten-station, 1.5 km loop at a public park, Gardens by the Bay. The vehicles provided service to park visitors at a maximum speed of 10 km/h along paths that were also used by pedestrians and cyclists. The vehicles were wheelchair-accessible.

SAN RAMON, CALIFORNIA

A demonstration project involving two EasyMile vehicles is planned to take place in 2016 or 2017 on private roads between office buildings in a private business park and to a nearby train station in San Ramon, California (gomentumstation, 2015)(Burg, 2016)(Torres, 2016). After six months of testing at a test track, GoMentum Station, trials will begin at Bishop Ranch, which is a 585-acre office park in San Ramon. Initially, the shuttles will operate after business hours and during weekends on private roads and parking lots in a limited area of the office park (Torres, 2016)(Pessaro, 2016). The vehicles will be monitored remotely from a control room. A next phase of testing will proceed pending regulatory approval of testing of automated vehicles without steering wheels and pedals on public roads. In this phase, the shuttles would operate during the day on four blocks of public streets in the office park (Pessaro, 2016).

BABCOCK RANCH, FLORIDA

Babcock Ranch is a newly planned greenfield community. The developers plan to make 40 low-speed automated vehicles available to the first residents and businesses in 2017, and increase the fleet to 400 vehicles by 2021 (AUVSI, 2016)(Hanley, 2016)(Babcock Ranch, 2016).

COLUMBUS, OHIO

In December of 2015, the United States Department of Transportation (USDOT) issued the Smart City Challenge, inviting cities to describe how they proposed to use new technologies to address transportation challenges. In March of 2016, seven cities were awarded \$100,000 each to support further conceptual development and planning. In June of 2016, Columbus, Ohio was awarded \$40 million as the winner of the Smart City Challenge (Cronin, 2016). The City is also dedicated \$90 million in matching funds to move forward with their proposals (Feran, 2016).

Among various actions proposed by the City, it proposed to deploy and test automated electric vehicles, linking the Easton Transit station with residential, commercial, and retail facilities in the Easton office/shopping park and Port Columbus areas. According to the City, the Easton area is presently underserved due to low and fluctuating demand (City of Columbus, 2016). It is reported that the shuttles would have room for up to 12 passengers (Gould, 2016).

According to the Federal Highway Administration, Columbus has access to several resources to facilitate testing of automated vehicles, including the Sports Pavilion and Automotive Research Complex (SPARC) facility, which provides a controlled testing environment, the Transportation Research Center (TRC), which has a seven-mile long, high-speed track for testing of truck platooning, and the CAR West site at Ohio State University, which will be equipped with charging infrastructure and signal systems (Cronin, 2016).

AUSTIN, TEXAS

Among various actions proposed in their submission to the USDOT's Smart City Challenge, the City of Austin proposed to deploy low-speed automated and connected shuttles at the City's international airport. According to the City, the shuttles would transport passengers along a "simplified urban street network located wholly on airport property" between the main terminal and a new mobility hub and staging area that would be located adjacent to a cell phone parking lot. The City argued that the shuttles would reduce the number of vehicles entering the terminal road system, and would thereby reduce congestion and improve pedestrian safety (City of Austin, 2016).

BEVERLY HILLS, CALIFORNIA

The City of Beverly Hills is proposing to deploy a fleet of 8- to 12-passenger automated shuttles to provide access to proposed local subway stations. As no parking will be provided

near the stations, the City is proposing the shuttles in order to improve first- and last-mile access (Marcokwitz, 2016).

11. Recommendations

In this section, several preliminary recommendations are offered for consideration by the City. Further work should be performed to refine these recommendations and to develop detailed policies and plans.

11.1 Public transit

In general, these recommendations aim at the proactive deployment of automation in public transit buses to reduce costs, improve service, and to make the most efficient use of limited road capacity.

Proactively deploying automation in transit allows for more efficient use of road infrastructure than is possible with light-duty vehicles. While platoons of automated light-duty vehicles will be able to increase road capacity, automated buses would move much higher numbers of travelers on the same road infrastructure. The improved service made possible by automation would be likely to mitigate mode shifts to travel by automated light duty vehicle, both in the early emergence and late emergence scenarios. It could also mitigate the congestion on streets expected to result from increased light duty vehicle traffic on freeways.

As the various levels of automation emerge onto the market and become affordable, travel by light-duty vehicle would be increasingly attractive to many travelers. This would especially be the case with Level 5 automation. In general, automation in private vehicles and driverless taxis would result in small to large increases in road capacity and small to very large increases in ease of travel. While this would tend to lead to a shift away from travel by transit to travel by light duty vehicle, this shift could be mitigated or reversed by improving transit service. Automation could permit such improvements, by increasing speed, reliability, capacity, frequency, ride quality, and reduced labour costs. Improved cost-efficiency would support the expansion of bus rapid transit networks and other bus routes.

With respect to Edmonton's current transportation planning framework, the following recommendations support several of the strategic goals outlined in *The Way We Move*, especially "Transportation Mode Shift", "Access and Mobility", "Transportation and Land Use Integration", "Sustainability", "Transport and Land Use Integration", and "Economic Vitality". The recommendations especially support the Strategic Objective of developing an efficient, effective, accessible and integrated bus network.

IMPLEMENT BRT WITH LEVEL 1 AND 2 TECHNOLOGIES

Level 1 and 2 technologies such as lane-keeping assistance and precision docking are commercially available and cost-effective. These technologies could be implemented in bus rapid transit lines and support improved performance by enabling increased speeds, reduced dwell time, and improved passenger access. They would also allow for the deployment of narrow dedicated busways, which would reduce infrastructure costs. In addition, these technologies would facilitate buses running on shoulders, which is an application that can be implemented in the very short term, with no need for new infrastructure.

These technologies would produce minimal labour disruption and thus would be unlikely to encounter resistance from bus drivers or unions.

This recommendation should be implemented within 0 to 5 years.

IMPLEMENT PROTECTED BUSWAYS WITH NO AT-GRADE CROSSINGS ON FREEWAYS

Protected busways can facilitate automated operation; with sufficient protection, fully automated operation of bus rapid transit may be feasible in the near term. Platooning would also be facilitated. The reduced labour costs could enable major improvements in service. Early deployments of such protected lanes should be uninterrupted, without uncontrolled at-grade crossings. E.g., such protected lanes could be implemented on median lanes on freeways. Alternatively, controlled at-grade crossings such as used by LRT systems may be appropriate.

Early deployments of automated BRT should be targeted to locations where they would provide the greatest capacity benefits and where other approaches to expanding capacity are expensive or difficult, such as on congested corridors with bottlenecks at bridges and tunnels. In these cases, automated BRT would provide a very clear advantage over alternatives, such as adding freeway lanes for light-duty vehicles.

The deployment of automated BRT could be accompanied by a reduction in the bus driver labour force; alternatively, bus drivers may be employed in operating buses on routes that are less amenable to automation in the near-term to medium-term. Any accompanying reduction of the bus driver labour force may be achievable partly through attrition, given that many bus drivers in Edmonton are older. On this note, a detailed examination of labour issues related to vehicle automation must be conducted, but is beyond the scope of this report.

This recommendation should ideally be implemented within approximately 2 to 5 years.

IMPLEMENT BUS PLATOONING TO SUPPORT INCREASED CAPACITY WITH MINIMAL LABOUR COSTS

Protected busways, mentioned in the previous recommendation, would enable platooning with partially automated buses, with fully automated buses following human-driven lead buses, or with all buses fully automated. Such applications could increase capacity with minimal labour costs.

This recommendation should ideally be implemented within approximately 3 to 10 years.

CONSIDER SMALLER BUSES AND SHORTER BRT PLATFORMS

Where fully automated operation is made possible, either by Level 5 automation or by Level 4 automation in protected busways, the use of smaller buses should be considered. The reduced operating costs made possible by automation would facilitate more frequent service, so high-capacity buses may no longer be necessary on some routes.

This recommendation should ideally be implemented within approximately 3 to 10 years.

CONSIDER AUTOMATED BRT AS AN ALTERNATIVE TO LRT

In some cases, automated BRT could provide similar service to LRT, with lower infrastructure costs. Automated BRT should especially be considered where dual-mode operation could provide superior service – in such an application, buses would operate in a fully-automated mode on a protected busway, and a human driver would then take over and drive the bus off the main line to serve routes on city streets where fully automated operation is not feasible, before the emergence of Level 5.

This recommendation particularly supports the Strategic Action of "evaluating where it is appropriate to provide premium bus service as a precursor to LRT". This recommendation also implies a review of the existing Strategic Objective to expand the LRT to all sectors of the City – while LRT may be the most appropriate transit technology to serve certain areas, automated BRT may be more appropriate in some areas, and therefore should also be considered as an alternative.

This recommendation should ideally be implemented within approximately 3 to 10 years.

DEPLOY LOW-SPEED LEVEL 4 VEHICLES IN LOWER-DENSITY AREAS

In lower-density areas, Level 4 low-speed vehicles can be used to provide automated demand-responsive service. Because of their low speeds, these vehicles cannot provide high capacity, but they can complement higher-order transit, and can serve as a supplement or replacement for walking trips for people with lower levels of physical mobility, such as in areas with large elderly populations.

This recommendation should ideally be implemented within approximately 5 to 15 years.

PROVIDE AUTOMATED DEMAND-RESPONSIVE SERVICE WITH SMALLER BUSES IN LOW-DENSITY AREAS

Especially with the emergence of Level 5 automation, bus service in lower density areas would become significantly less attractive to many travelers in comparison to Level 4 private vehicles and driverless taxis. Level 5 automation in light-duty vehicles would allow travelers to engage in other activities while traveling, as is the case for buses, but with the additional convenience of door-to-door and on-demand service. Bus ridership could be expected to drop.

One response to this would be to change bus service in these areas to a demand-responsive model where smaller automated buses provide more efficient service with flexible routes and schedules.

This recommendation should be implemented once the requisite technologies are available, which could be within a decade, but could be further in the future.

REDUCE BUS SERVICE IN LOW-DENSITY AREAS AND ENCOURAGE USE OF DRIVERLESS TAXIS AS TRANSIT FEEDERS

After the emergence of Level 5, in areas with lower densities of trip origins and destinations, or in off-peak times, where it is difficult to provide effective transit service, and where driverless taxi service attracts a large proportion of travelers would be to cut bus service, bus service could be reduced or eliminated. The use of driverless taxis could be encouraged in such areas and time periods. Driverless taxis could especially serve as feeders to higher-order transit service, complementing BRT and LRT by providing "first mile/last mile" service in areas where it is difficult to provide efficient bus service.
To ensure mobility is provided in a socially equitable manner, it may be necessary to provide subsidies for driverless taxi service to people with lower incomes. It will also be necessary to ensure taxis are accessible to individuals with limited physical mobility.

Private vehicles with Level 4 automation could also serve as feeders to higher-order transit; such uses should be encouraged, for example, through appropriate road pricing or parking pricing.

This recommendation should be implemented once the requisite technologies are available, which could be within a decade, but could be further in the future.

PRICE TRANSIT TO SUPPORT HIGH MODE SHARE

With the increased ease of travel by light-duty vehicle that would result from automation, it may be necessary to reduce transit fares, in general or in selected areas and times, to maintain transit mode share.

This recommendation should ideally be implemented within approximately 3 to 10 years.

PRICE DRIVERLESS TAXI TRIPS APPROPRIATELY TO INCENTIVIZE USE AS TRANSIT FEEDERS

After the emergence of Level 5, it may be necessary to price driverless taxi fares to encourage their use as complements rather than as replacements for transit, where appropriate. For example, shorter taxi trips that begin or end at transit stations or stops could be priced lower to incentivize the use of taxis for first mile/last mile transit access and to reduce the number of long-distance trips that are taken by driverless taxi where efficient transit service exists. Also, as mentioned above, it may be necessary to subsidize driverless taxi service for people with lower incomes, in order to provide equitable service.

This recommendation should be implemented once the requisite technologies are available, which could be within a decade, but could be further in the future.

PROVIDE DROP-OFF/PICK-UP ZONES TO FACILITATE TRANSFERS TO AND FROM FIRST/LAST MILE SERVICES

In order to facilitate efficient transfers of passengers between transit and first mile/last mile services, it will be necessary to provide adequate drop-off and pick-up zones.

This recommendation should ideally be implemented within approximately 3 to 10 years.

11.2 Active transportation modes

The following recommendations support several of the strategic goals outlined in *The Way We Move*, especially "Transportation Mode Shift", "Access and Mobility", "Transportation and Land Use Integration", "Health and Mobility", "Sustainability", "Transport and Land Use Integration", and "Economic Vitality".

SUPPORT WALKING AND CYCLING, ESPECIALLY IN DENSE AREAS AND NEAR TRANSIT STATIONS

Even if Level 5 automated vehicles become ubiquitous, walking and cycling will remain convenient for short trips, and would be continue to produce other benefits, such as supporting liveable urban environments and improving public health. Suitable infrastructure should be provided to encourage walking and cycling trips and to support the use of transit, which of course also requires good pedestrian access.

This recommendation should be implemented immediately.

DEPLOY AND PRICE LOW-SPEED VEHICLES AND TAXIS STRATEGICALLY TO MINIMIZE REDUCTION OF ACTIVE TRANSPORTATION MODE SHARE

Any deployments of Level 4 low-speed vehicles and Level 5 driverless taxis should be strategically managed to minimize cannibalization of active modes. Low-speed Level 4 vehicles would best serve relatively short trips, and driverless taxis may also be attractive for such trips; however, active modes are also best suited to shorter trips. Therefore, Level 4 low-speed vehicles should ideally be deployed where active modes are less attractive or feasible – for example, in areas with larger populations of elderly people. In addition, the use of Level 5 driverless taxis for short trips should be discouraged, by the means of pricing, for example, except for those travelers for whom active modes are less feasible.

This recommendation should ideally be implemented within approximately 3 to 10 years.

11.3 Roads

The following recommendations concern road supply and road pricing.

The following recommendations support several of the strategic goals outlined in *The Way We Move*, especially "Transportation Mode Shift", "Access and Mobility", "Transportation and Land Use Integration", "Well-maintained Infrastructure", "Sustainability", "Transport and Land Use Integration", and "Economic Vitality".

CONSIDER REDUCING SPEED LIMITS ON LOCAL STREETS

Reducing traffic speeds on local streets would facilitate the fully automated operation of Level 4 vehicles, such as the low-speed automated shuttles that have been undergoing testing in various cities around the world. In addition, low speeds improve safety for all road users and help create a more welcoming environment for walking and cycling.

This recommendation should be implemented immediately.

CONSIDER DEDICATED LANES FOR AUTOMATED LIGHT-DUTY VEHICLES WHEN ADOPTION LEVELS ARE SUFFICIENTLY HIGH

When the number of light-duty vehicles capable of platooning is sufficient to make effective use of a dedicated lane without increasing delays for traffic on other lanes – that is, where the number of vehicles using a dedicated lane is at least equal to the number of vehicles using a conventional lane – such dedicated lanes would reduce delays for automated vehicles. In addition, depending on the degree of infrastructural protection provided, such lanes would also facilitate fully automated operation of Level 4 vehicles. In order to ensure the lanes are efficiently used, such lanes could be dedicated to automated vehicles during specific times, such as during peak periods. Similarly, once the requisite technology has been adopted broadly, dedicated lanes for platooning of freight vehicles may reduce delays both in goods movement and in passenger travel.

This recommendation should be implemented once the requisite technologies are commonly available, which could be within a decade, but could be further in the future.

IMPLEMENT LANE CONVERSIONS/ROAD DIETS WHERE OPPORTUNITIES EXIST

When adoption of platooning-capable vehicles reaches higher levels, a smaller number of freeway lanes would suffice to provide a given level of road capacity. Similarly, where high-

capacity transit is provided, in the form of automated BRT, for example, a smaller number of road lanes would suffice to provide a given level of passenger capacity. In such cases, it may be possible to convert the surplus road space to other uses, such as busways, bike or pedestrian facilities, or greenspace.

This recommendation should ideally be implemented within approximately 3 to 10 years.

PRICE ROADS AND PARKING STRATEGICALLY TO MITIGATE INCREASES IN VKT AND CONGESTION ON STREETS

The decreased generalized cost of travel by light duty vehicle will tend to lead to increases in VKT and increased congestion on streets. The resulting external costs should be internalized by applying appropriate road pricing and parking pricing. In particular, one cost that road pricing should account for is the amount of delay imposed on other vehicles.

Roads should also be priced appropriately to discourage empty vehicle VKT from remote parking and from driverless taxi deadheading. As some forms of automation may facilitate the use of electric drive in vehicles and may lead to increased prevalence of electric vehicles, this may also make road pricing both more important and more politically feasible.

This recommendation should ideally be implemented immediately.

INCENTIVIZE ADOPTION OF PLATOONING-CAPABLE TECHNOLOGY WITH LOWER ROAD PRICING

Road pricing should be set carefully. It may be justified to incentivize the adoption of platooning-capable technology (that is, Level 3, 4, or 5 automation combined with suitable V2V technology) through discounted road pricing, since vehicles capable of platooning are capable of occupying less road space and thus increasing road capacity and reducing delays when a sufficient number of such vehicles are present on the road.

However, it should be emphasized that though these vehicles can support more efficient use of road infrastructure, this benefit would mainly occur on freeways. Therefore, to avoid congestion on other roads such as city streets, it would be important to set appropriate prices on the use of different road types. If road pricing is applied only to freeways, then it will be important not to apply an excessive discount to road pricing for platooning-capable vehicles. Such pricing schemes are more likely to produce significant behavioural shifts in regions with extensive freeway networks.

This recommendation should ideally be implemented within approximately 3 to 10 years.

11.4 Parking

The following recommendations support several of the strategic goals outlined in *The Way We Move*, especially "Transportation Mode Shift", "Access and Mobility", "Transportation and Land Use Integration", "Sustainability", "Transport and Land Use Integration", "Well-maintained Infrastructure", and "Economic Vitality".

PRICE PARKING TO MITIGATE DEMAND INCREASES FROM LEVEL 2 AND 3 AUTOMATION

Since Level 2 and 3 automation would decrease the generalized cost of vehicle travel somewhat, travel would tend to increase and parking demand would also increase. Parking pricing may need to be adjusted to manage this demand; for example, parking pricing could be increased, or dynamic parking pricing implemented.

Road pricing would also manage demand, but it might also be necessary to adjust parking pricing to discourage excessive remote parking.

This recommendation should ideally be implemented within approximately 3 to 10 years.

CONSIDER PRICING PARKING TO MANAGE REMOTE PARKING DEMAND

With the emergence of Level 5 automation, consider pricing remote parking locations to limit vehicle traffic destined for remote parking and to encourage transit or driverless taxi use.

Depending on where parking is located, the convenience of remote parking could generate significant additional VKT by vehicles traveling to park in formerly low-demand locations. Road pricing (or other measures, such as fuel surcharges) may be sufficient to manage this additional VKT; however, depending on the road pricing strategies used, it may be necessary to adjust parking pricing to provide a sufficient disincentive against excessive use of remote parking locations.

This recommendation should be implemented once the requisite technologies are commonly available, which could be within a decade, but could be further in the future.

REDUCE MINIMUM PARKING REQUIREMENTS AND CONVERT PARK-AND-RIDES

Automation, especially Level 5, would create opportunities to reduce minimum parking requirements and to convert park-and-rides. Reducing parking minimums in intensely developed areas would encourage a shift of parking to less intensely developed areas and

free up this high-value land for higher-value uses. However, it should be ensured that the new parking locations are sufficiently close to popular destinations so excessive zero-passenger VKT is not generated by vehicles travelling to remote parking locations. A combination of measures may be needed, including road pricing, location-based parking charges or parking taxes, and land use zoning.

Of course, improving transit by the means of various levels of automation would also create opportunities to reduce parking supply, both in central and less central areas.

This recommendation should ideally be implemented immediately.

11.5 Land use

The following recommendations support several of the strategic goals outlined in *The Way We Move*, especially "Transport and Land Use Integration", "Access and Mobility", "Transportation Mode Shift", "Sustainability", "Health and Safety", and "Economic Vitality".

INTERNALIZE COSTS OF INFRASTRUCTURE AND SERVICES TO DISCOURAGE EXCESSIVE DISPERSED DEVELOPMENT

To discourage excessive levels of dispersed development that vehicle automation may facilitate, and to reduce the associated external transportation and other infrastructure costs, such as the costs of providing water and sewer services, land use policies should internalize these costs. For example, development charges can be set to more closely reflect the costs of providing infrastructure and services under different patterns of development.

This recommendation should ideally be implemented immediately.

SUPPORT DEVELOPMENT NEAR BRT AND OTHER HIGHER-ORDER TRANSIT SERVICES

Development patterns that support the use of public transit, such as development near BRT stations and near other strong transit services, should be encouraged. These development patterns will tend to impose lower external costs, including those related to increased VKT, infrastructure, and services.

This recommendation should ideally be implemented immediately.

ENCOURAGE REDEVELOPMENT OF PARKING FACILITIES IN INTENSELY DEVELOPED AREAS AND AT TRANSIT STATIONS

As automated buses and/or Level 5 driverless taxis cut parking demand, or as parking locations shift with the emergence and rise of remote parking, land formerly used for parking, such as in downtown areas, or at park-and-ride facilities at transit stations, can be used for infill development. Various more valuable uses would be possible, though conversion to greenspace may encounter the least resistance from neighbourhood residents. In intensely developed areas, market pressures may be sufficient to trigger redevelopment of parking facilities to better uses, though other measures, such as taxes on parking facilities or rezoning, may be necessary. Reduced dependence on privately owned vehicles could also facilitate other changes, such as the removal/redevelopment of garages in apartments and houses.

This recommendation should ideally be implemented within approximately 3 to 10 years.

CONVERT ROADSIDE PARKING SPACES TO PEDESTRIAN AND CYCLE FACILITIES OR GREENSPACE

With automated buses, Level 5 remote parking, and driverless taxis, the need for roadside parking spaces would be reduced. These spaces could be converted to different uses. Increased vehicle traffic could lead to pressure to use the space to provide more lanes for motor vehicles, but if it is desired to create more livable "complete streets", the space should be preferably used to provide facilities for active transportation, or to provide greenspace or other public spaces.

This recommendation should ideally be implemented within approximately 3 to 10 years.

11.6 Pilot deployments

Before any large-scale deployments of automation in public transit, the City can begin by strategically deploying existing Level 1, 2, and/or 4 automation in small-scale pilot projects.

Such deployments could include Level 4 low-speed vehicles serving short routes, in the range of 1 to 5 kilometres, for example. These vehicles could be deployed in areas other than public roads, such as university campuses, business parks, airports, hospitals, retirement communities, parking facilities, industrial areas, theme parks, golf courses, multi-use paths, and private roads in other areas.

Preferably, any deployment of automated low-speed vehicles should be located where it does not compete inappropriately with active modes of transportation. For example, low-speed

vehicles could be deployed where there is a significant population of individuals with limited physical mobility.

Once a legislative framework exists to permit such activities, Level 4 low-speed vehicles could also be piloted on public roads, especially low-speed roads with light traffic, and if exclusive lanes with sufficient protection are implemented, Level 4 could be piloted in buses; however, these are not likely to be feasible for pilot deployments in the near term. On public roads, Level 1 and 2 automation can be piloted in buses, especially where protected or exclusive lanes are available.

One example of a potential location for a pilot deployment of Level 4 low-speed vehicles would be in the area around the Telus World of Science. In this area, it would be possible to develop a route of approximately 2 kilometres that connects a major public transit node with various destination such as a science centre, an arena, a swimming pool, a lawn bowling club, and a parking lot. An example of a potential route is illustrated in Figure 15.



Figure 15. Example of potential route for pilot deployment of Level 4 low-speed automated vehicles

Antonio Loro Consulting Inc. – 10 October 2016

Other examples of potential locations include the University of Alberta and Hawrleak Park, the University of Alberta South Campus, Fort Edmonton Park, Alberta Research and Development Park, the Edmonton Valley Zoo, Edmonton Northlands, Century Park & Ride, and the West Edmonton Mall; these and other potential locations should be assessed.

This recommendation should ideally be implemented within 1 to 2 years.

11.7 Current shared mobility modes

ENCOURAGE THE USE OF SHARED MOBILITY MODES SUCH AS CARSHARING AND RIDESOURCING AS AN ADJUNCT TO PUBLIC TRANSIT AND AN ALTERNATIVE TO PRIVATE VEHICLE USE

The extent to which current shared mobility modes, such as carsharing and ridesourcing, are used in preference to private vehicles, for trips that cannot be efficiently served by highercapacity vehicles such as buses, may affect the role of future shared mobility modes, such as driverless taxis and share taxis, and the extent to which these future modes are used in preference to private vehicles, for trips that cannot be efficiently served by higher-capacity vehicles. If individuals increasingly opt to use existing modes of shared mobility, such as taxis, ridesourcing, and carsharing, rather than using private vehicles to take trips in the cases specified above, such a trend may lead to reduced incentives for private car ownership in the near term to far term, and may also support stronger future preferences for the use of future modes of shared mobility, such as driverless taxis and share taxis, rather than using private vehicles, for appropriate trips. Considering the potential near-term to far-term benefits associated with such shifts, the City should encourage the use of shared mobility modes such as carsharing and ridesourcing, particularly for trips that cannot be efficiently served by transit modes such as bus and rail.

This recommendation should be implemented immediately.

11.8 Recommendations by timeframe

The recommendations described above are summarized in the table below to highlight the relative timing of each. Note that the timelines given are approximate and may require modification depending on the future speed of technological development.

RECOMMENDATION	2016-2019			202	20-20)24		2025-2030						
PUBLIC TRANSIT														
Implement BRT with Level 1 and 2 technologies														
Implement protected busways with no at-grade crossings on freeways														
Implement bus platooning to support increased capacity with minimal labour costs														
Consider smaller buses and shorter BRT platforms														
Consider automated BRT as an alternative to LRT														
Deploy low-speed level 4 vehicles in lower-density areas														
Provide automated demand- responsive service with smaller buses in low-density areas														
Reduce bus service in low-density areas and encourage use of driverless taxis as transit feeders														
Price transit to support high mode share														
Price driverless taxi trips appropriately to incentivize use as transit feeders														
Provide drop-off/pick-up zones to facilitate transfers to and from first/last mile services														

RECOMMENDATION	201	6-20)19	202	20-20)24		2025-2030					
ACTIVE TRANSPORTATION MODES													
Support walking and cycling, especially in dense areas and near transit stations													
Deploy and price low-speed vehicles and taxis strategically to minimize reduction of active transportation mode share													
ROADS													
Consider reducing speed limits on local streets													
Consider dedicated lanes for automated light-duty vehicles when adoption levels are sufficiently high													
Implement lane conversions/road diets where opportunities exist													
Price roads and parking strategically to mitigate increases in vkt and congestion on streets													
Incentivize adoption of platooning- capable technology with lower road pricing													
PARKING													
Price parking to mitigate demand increases from level 2 and 3 automation													
Consider pricing parking to manage remote parking demand													
Reduce minimum parking requirements and convert park-and- rides													

RECOMMENDATION	2016-2019			202	20-20)24		2025-2030						
LAND USE														
Internalize costs of infrastructure and services to discourage excessive dispersed development														
Support development near BRT and other higher-order transit services														
Encourage redevelopment of parking facilities in intensely developed areas and at transit stations														
Convert roadside parking spaces to pedestrian and cycle facilities or greenspace														
PILOT DEPLOYMENTS														
CURRENT SHARED MOBILITY MODES														
Encourage the use of shared mobility modes such as carsharing and ridesourcing as an adjunct to public transit and an alternative to private vehicle use														

11.9 Next steps

The following are highlighted as proposed next steps for the City of Edmonton to take as soon as possible, beginning in 2016.

CONDUCT FOCUSED RESEARCH ON PRIORITY AREAS

Focused research should be conducted on the following priority topics.

- Conduct modeling of travel and land use impacts of various forms of vehicle automation; leverage the internal capacity of Edmonton's expert transportation modelers in combination with external advice on appropriate assumptions and interpretation for the modeling of the impacts of automation
- Identify opportunities for near-term pilot deployment(s) of Level 4 low-speed vehicles and Level 1, 2, and/or 4 in buses; move forward proactively toward implementation in the near-term to help ready Edmonton for rapid future technological change and to position it as an innovative, forward-thinking city; conduct detailed review of relevant precedents in cities in North America and around the world
- Conduct study on feasibility of future broad deployments of Level 1, 2, and/or 4 in transit buses; study benefits and costs
- Review labour issues related to vehicle automation, especially automation in public transit
- Study issues related to vehicle automation and goods movement in Edmonton

CREATE AUTOMATED VEHICLES ISSUES WORKING GROUP WITH INTERNAL AND EXTERNAL STAKEHOLDERS

In 2015, the City took the proactive step of beginning to explore issues related to the future impacts of automated vehicles. The City should continue this work by creating a working group, comprising both internal and external stakeholders, that focuses on issues related to automated vehicles.

DEVELOP COMPREHENSIVE VEHICLE AUTOMATION STRATEGY

The preliminary recommendations proposed in this report should be used to inform the development of a broad, comprehensive vision and strategy that guides the City's approach to automated vehicles. The recommendations proposed here should be further refined; the benefits, costs, and feasibility of the recommendations should be analyzed, and high priority recommendations should be identified. Implementation steps and timelines should be

developed, and key actors and roles defined. In addition, where necessary, additional recommendations should be developed that address other issues in need of attention.

PUBLIC EDUCATION AND COMMUNICATION

A strategy should be developed to keep Edmontonians informed on the implications of automation and to communicate on the City's related initiatives. The communication strategy should be developed to show how Edmonton is planning and implementing strategic, considered measures to take advantage of automation technologies to in order to improve mobility and quality of life.

UPDATE ANALYSIS OF IMPACTS

Automation technologies are developing rapidly, and research on automation and its impacts is also advancing rapidly. For this reason, the City should expand, refine, and update the analysis provided in this brief report on a frequent and regular basis. Such updated analyses will be necessary to inform optimal policy approaches. On a related note, the impending rapid changes in technology may require an acceleration of the transportation planning cycle in Edmonton, with more frequent revisions of plans.

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Supplement: Discussion on current shared mobility modes

The following discussion supplements the final report on the planning for automated vehicles in Edmonton.

When sufficiently advanced vehicle automation technologies become available, it will become possible to apply them to create new ways to travel, such as driverless taxis and share taxis. Driverless taxis and share taxis will be especially useful to serve trips within a certain range of travel demand. In particular, they will be useful to serve trips where and when travel demand is too low to enable efficient service by fleets of higher-capacity vehicles, i.e., buses and trains; and they will be useful to serve trips where and when travel demand is high enough that satisfactory service by driverless taxi or share taxi can be provided efficiently. Within this range of travel demand, travel by driverless taxi or share taxi will generally produce smaller negative impacts than travel by private vehicle. For example, it is expected that parking demand will be reduced, and in the case of travel by share taxi, it is expected that less VKT per trip will be produced. In addition, driverless taxis and share taxis would be useful for trips where certain benefits, such as shorter travel time, shorter walking distances between the vehicle service and the actual trip origins and destinations, greater privacy, or increased cargo capacity are considered to outweigh the private and/or social costs of travel by those modes.

These future modes of transport have some features in common with currently existing modes of transport. Given that a user of a driverless taxi or share taxi travels in a fleet vehicle that is used to provide service to multiple travelers throughout the day, these modes can be considered to fall under the broad category of "shared mobility" modes. To illustrate some broad features driverless taxis and share taxis have in common with three current share mobility modes: taxis, ridesourcing (often referred to as transportation network companies (TNCs) or ride-hailing), and carsharing similarly involve the use of fleets of motorized vehicles to provide service to multiple travelers throughout the day, and, also similar to the future modes of driverless taxi and share taxi, are useful for providing service especially within certain ranges of travel demand, can produce smaller negative impacts than travel by private vehicle, and are useful for providing service for certain kinds of trips, for example, where speed is considered to justify higher private travel cost.

If individuals increasingly opt to use existing modes of shared mobility, such as taxis, ridesourcing, and carsharing, rather than using private vehicles to take trips in the categories described above (and use public transit and active modes for other trips), such a trend may support stronger future preferences for the use of future modes of shared mobility, such as

driverless taxis and share taxis, rather than using private vehicles, for appropriate trips. In addition, given that applying advanced vehicle automation technology to either taxis, ridesourcing, or carsharing would effectively result in driverless taxis (or share taxis), these current shared mobility modes can be regarded as precursors of the future shared mobility modes of driverless taxi and share taxi.

Given that the actions that the City of Edmonton takes regarding current shared mobility modes may affect the role of future shared mobility modes, and may affect in particular the extent to which these future modes are used in preference to private vehicles, where appropriate, it is useful to also consider the role of current shared mobility modes and their potential to provide travel options that can be preferable to travel by private vehicles. A brief discussion of existing shared mobility modes, with a focus on ridesourcing and carsharing, is provided below. A broader and more detailed discussion of existing shared mobility modes is beyond the scope of this report.

Ridesourcing and carsharing

In ridesourcing, drivers use their personal vehicles to provide transportation services to travelers; travelers connect with drivers through digital platforms such as smartphone applications. These applications facilitate booking, payment, customer feedback on drivers, and driver feedback on passengers (FHWA, 2016)(Murphy, 2016a). Examples of ridesourcing providers include the companies Uber and Lyft. "Ridesplitting" is sometimes used to refer to ridesourcing where customers can choose to travel with other customers for a reduced fare (FHWA, 2016).

In carsharing, members of carsharing organizations have access to automobile fleets for short-term use, usually for short urban trips. Two common forms of carsharing are round-trip carsharing, where a user must return the vehicle to the location at which they borrowed it, and one-way carsharing, where a user can end the trip and drop off the vehicle at a different location (Shared Use Mobility Center, 2015).

Potential benefits

Carsharing is associated with lower rates of car ownership. According to the FHWA (FHWA, 2016), studies and surveys of members of carsharing organizations have shown that up to 32 percent of carsharing members sell their personal vehicles, and between 25 percent and 71 percent of members opt to forego the purchase of a vehicle. The Shared Use Mobility Center (Shared Use Mobility Center, 2015) cites a study from the University of California, Berkeley, which found that, for each car in a carsharing fleet, between 9 and 13 cars are sold or not purchased.

Carsharing may encourage increased use of public transit. In a study from City Carshare, cited by the Shared Use Mobility Center, more than 65 percent of respondents with carsharing memberships took transit a few times a week or more, compared to approximately 41 percent of respondents without carsharing memberships (Shared Use Mobility Center, 2015). The FHWA reports that studies of six North American locations found that 13.5 to 54 percent of carshare users take public transit more frequently after becoming carshare users. Nevertheless, the FHWA also notes that one study has found a slight shift away from public transit ridership (FHWA, 2016). The Shared Use Mobility Center notes that while shared mobility modes may take riders off transit for some trips, because it enables people to get around more easily without owning a car, it may create an entirely new group of transit riders (Shared Use Mobility Center, 2015). More generally, the FHWA points out that reduced car ownership is associated with increased use of public transit, walking, and bicycling (FHWA, 2016).

Ridesourcing may also increase use of public transit. The Shared Use Mobility Center cites a UC Berkeley survey that found that ridesourcing "appears to substitute for longer public transit trips but otherwise complements transit". In addition, according to the Shared Use Mobility Center, Lyft reports that 25 percent of its trips in the San Francisco area are to or from Caltrain stations (Shared Use Mobility Center, 2015).

Carshare users appear to have lower VKT per person. According to the FHWA, the VKT of the average carshare user in the United States "is reduced by 7.6 percent to 79.8 percent" (FHWA, 2016). In addition, use of carsharing may further reduce emissions impacts: because carshare users often shed older vehicles, the carsharing vehicles that they use are much more efficient, averaging "10 more miles per gallon and resulting in lower fuel costs and greenhouse gas emissions" (Shared Use Mobility Center, 2015).

Ridesourcing as an adjunct to existing transit services

According to the Shared Use Mobility Center, shared mobility modes have the potential, in some cases, to provide mobility service with greater flexibility and lower costs than rail and bus. In particular, modes such as ridesourcing can improve first- and last-mile access to transit (Shared Use Mobility Center, 2015). One-way carsharing is described as an effective strategy for first/last-mile access in larger cities with progressive parking policies, and ridesourcing is described as effective in "walkable neighborhoods and in high to moderate-density areas within large and mid-size cities" (Shared Use Mobility Center, 2015). The FHWA asserts that using shared mobility options to improve first/last-mile access to transit can "greatly improve quality of life for low-income households, which are generally disproportionately dependent on public transit" (FHWA, 2016). Another benefit of improving first/last-mile access to transit services like rail through the use of shared mobility modes like
ridesourcing is that stations could be spaced further apart, which would increase train speeds and reduce station construction costs (AJC.com, 2016).

The FHWA recommends integrating mass transit with shared mobility modes such as ridesourcing and carsharing. This requires improving physical connectivity between modes, such as ensuring carsharing services are located near public transit stops. Integrating shared mobility with transit also entails providing integrated, one-stop sources of information on the various services, such as fares, routes, and schedules; and it also entails facilitating payment of fares for all modes with a single payment method (FHWA, 2016).

Ridesourcing also has the potential to be used to provide demand-responsive services such as paratransit (Murphy, 2016a). Transit agencies may be able to provide the public with improved and more efficient service by partnering with ridesourcing companies, for example, by subsidizing ridesourcing trips in certain areas (Kane et al.)(DeGood et al.)(Schmitt, 2016). This could reduce the cost of providing service in low-density areas.

A number of transit agencies have partnered with ridesourcing providers. For example, in Pinellas Park, a suburb of Tampa, Florida, the transportation agency has stopped running two bus lines and instead is paying for a portion of the cost of Uber rides that end at about 20 designated transit stops. User receive a 50 percent discount for rides, up to a maximum of \$3 per ride. It is anticipated that the program will cost approximately a guarter of what it cost to operate the bus lines it replaced (Brustein, 2016)(Bliss, 2016). Altamonte Springs, Florida, a suburb of Orlando, is conducting a year-long trial where 20 percent of the cost of any Uber ride within city limits is covered, while 25 percent of the cost of rides that end at regional rail stations is covered (Brustein, 2016)(Liston, 2016). In addition, in Centennial, a suburb of Denver, Colorado, the local government is temporarily replacing the dial-a-ride program in a specific area with fully subsidized Lyft rides to and from a light rail station (Brustein, 2016)(Bliss, 2016). Summit, New Jersey, is conducting a six-month pilot program where 100 residents will be able to take subsidized trips to and from the local train station in order to avoid building a new parking lot. The trips will cost the same as an all-day parking permit (An, 2016). Metro Transit in Minneapolis subsidizes Uber trips to provide a "guaranteed ride home" for regular commuters who occasionally need to travel outside rush hour, due to unexpected overtime or illness, for example (Metro Transit, 2016).

Other partnership arrangements are possible. For example, Parkmerced, a development in San Francisco containing 8900 apartments, is offering new tenants \$100 a month toward various transportation options if they agree to forego parking spots. A tenant can use the money for transit, taxis, and car-sharing, provided they spend at least \$30 on Uber rides. In addition, trips by Uber Pool (a service where multiple customers can share rides) to or from Parkmerced to selected transit stations will have flat fares of \$5. This arrangement should

enable the developer to reduce the need to create more parking spaces as the development expands (Hawkins, 2016).