Road vehicle automation:
Elephant in the infrastructure room

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Table of contents [delete for final version]

Abstract 2
Explanations, definitions, and scope of this chapter 2
Prospects for autonomous road vehicles 4
Driving the move towards autonomous road vehicles 6
Liability concerns posed by autonomous road vehicles 8
Autonomous taxicabs 9
Implications of autonomous road vehicles for the automobile industry 11
Autonomous taxicabs (ATs) and public transport 11
Energy implications of widespread deployment of autonomous taxicabs (ATs) 13
Personal Rapid Transit (PRT): Autonomous taxicabs on guideways 15
Freight movement by autonomous road vehicles 16
Infrastructure implications of deployment of autonomous road vehicles 17
References 19
Table 1: Results of a survey of attitudes of 1,000 UK drivers to driverless cars 29

Abstract

The technology relevant to the development of driverless or autonomous road vehicles (ARVs) is advancing rapidly, but has been mostly ignored by transport infrastructure planners. This chapter discusses the possibility that ARVs will become a major feature of road traffic during the next few decades, noting implications for transport infrastructure, including megaprojects. Chiefly because of concerns about liability, ARVs are likely to be deployed by fleet operators rather than being individually owned. Autonomous taxicabs may well be so appealing, on cost and other grounds, that they replace most individually owned vehicles and also much public transport. Autonomous light- and heavy-duty road vehicles used primarily for freight movement may also become a prominent feature of road traffic. The shift from individual to fleet ownership of vehicles could well facilitate transitions to electric traction. The widespread deployment of ARVs could reduce substantially the transport infrastructure challenges faced by richer and poorer countries, although relatively minor infrastructure requirements will be added. Such is the promise of ARVs, infrastructure projects that could be obviated by their widespread deployment could well be delayed or stalled until ARVs' viability, feasibility, and utility are more firmly established. This could be achieved by about 2017, paving the way for possible widespread use of ARVs in the early 2020s.

Keywords: autonomous road vehicles; infrastructure planning; passenger transport; freight transport; liability concerns; car ownership; public transport; urban transport; intercity transport energy implications; personal rapid transit.

Explanations, definitions, and scope of this chapter

The idiom 'elephant in the room' refers to an obvious truth, problem, challenge or risk that is being ignored. In this chapter's title, the elephant is the progressive automation of the control of road vehicles. The 'infrastructure room' is the metaphorical space that contains academic and other discourse about transport infrastructure, discourse that has mostly not addressed the potential impacts of road vehicle automation. There is no discussion of such impacts, for example, in these reports on the future of transport:

- The European Commission's White Paper *Roadmap to a Single European Transport Area* (EC, 2011)
- The World Energy Council's *Global Transport Scenarios* (WEC, 2011)
- The Organization for Economic Cooperation and Development's *Strategic Transport Infrastructure Needs to 2030* (OECD, 2012)
- The International Transport Forum's *Transport Outlook 2012* (ITF, 2012)
- The World Bank and the Asian Development Bank's *Urban Mass Transport Infrastructure in Medium and Large Cities in Developing Countries* (Vandycke and Wright, 2012).

This chapter concerns what may be the likely widespread deployment over the next few decades of autonomous road vehicles (ARVs) and the implications of this deployment, particularly for infrastructure planning. ARVs have or are expected to have sufficient on-board sensing and computing resources to travel safely and reliably on regular streets and expressways (motorways) without human intervention. The information ARVs receive from their sensors can be augmented by information conveyed by wireless communication, including vehicle to vehicle (V2V) and vehicle to infrastructure (V2I). ARVs can also receive directions in this way as to destination and other matters. Dual-mode ARVs allow control by a human operator as well as or instead of computer systems.

ARVs may be propelled by internal combustion engines or electric motors. If ARVs' traction is electric, energy may be provided by on-board batteries that can be recharged or replaced automatically. If appropriate infrastructure is available, electrically propelled ARVs can be energized from the electric grid while in motion.

ARVs that could replace today's personal vehicles are also called driverless cars (Benenson et al., 2008), autonomous cars (Marks, 2012), robocars (Templeton, 2012a), and cybercars (Nashashibi et al., 2012). ('Automobile' is rarely used for road vehicles that do not require a human operator.)

Autonomous taxicabs (ATs) are ARVs managed in fleets to provide taxicab services without drivers. The term 'shared autonomous taxi' has also been used (Ford, 2012).

Personal Rapid Transit (PRT) comprises on-demand, origin-to-destination passenger (and sometimes freight) service in small, automated vehicles mostly moving on a network of guideways with off-line stations (Carnegie and Hoffman, 2007, p. 18–19). PRT essentially consists of small ARVs moving on guideways rather than roads.

Autonomous local delivery vehicles (ALDVs) are ARVs managed in fleets to provide local delivery of goods between automated collection and delivery points. The terms 'robotruck' and 'deliverbot' are also used (Templeton, 2012a). Autonomous heavy-duty vehicles (AHDVs) are large ARVs used primarily for long-distance travel on expressways. They can be propelled by diesel engines, as heavy-duty trucks (lorries) are now. They are unlikely to be electrically powered unless energy can be provided from the electrical grid while in motion, likely via overhead wires (catenaries).

This chapter discusses all of the above, proceeding on the assumption that ARVs could well become widely deployed during the next two decades. This is a debatable assumption, as is almost any prediction. It is an assumption worth making because of the evidence and opinions set out below. It is worth making too because it stimulates exploration of the revolutionary implications of such deployment, and raises important questions to be addressed by transport infrastructure planners.

More general matters addressed in this chapter include the potential impacts of deployment of ARVs, mostly as ATs, on car ownership and use, on the evolution of public transport, on energy consumption for transport, and on the electrification of transport. Implications for infrastructure planning are noted at several points in the chapter and brought together in the final section, which also touches on how the deployment of ARVs as ATs might unfold.

Prospects for autonomous road vehicles (ARVs)

This and the next section build on several reviews and overviews of the development of and prospects for ARVs including these: Dickmanns (2002); Sun et al (2006); Benenson et al. (2008), Campbell et al (2010); Berger and Rumpe (2012); Silberg and Wallace (2012).

These two sections also build on several more popular but nevertheless substantial discussions including those by Anon. (2012a), Folsom (2012), and Vanderbilt (2012a, 2012b), and two web sites: Templeton (2012a) and DCMW (2012).

Appendix A lists some key academic and governmental research centres in the development of ARVs.

Parts of the road vehicle manufacturing industry appear to be embracing ARVs, as supporters of academic research teams (see Appendix A) and separately. The German company BMW AG sees automation as a way of making car ownership more attractive. "You may have the option to drive or not. Sit back, relax, do other things," said a company official (Proudfoot, 2012). An official of General Motors Company of Detroit, Michigan, said that "self-driving cars could be in showrooms by the end of the decade" and that vehicles that "partially drive themselves" may debut by the middle of the decade (Lienert, 2011).

The Swedish Volvo Car Corporation (a wholly owned subsidiary of a Chinese company) is said to be "staking its future on … [producing] an accident-free vehicle within seven years" (Duxbury and Stoll, 2012). This means, in effect, producing a marketable ARV, although Volvo has said it would like humans to remain in control most of the time. A Volvo official has said, "The car of the future will be like the farmer's horse. The farmer can steer the horse and carriage but if he falls asleep the horse will refuse to walk into a tree or off a cliff." (Joseph, 2012).

Other automakers engaged in ARV development include the German companies Audi and Volkswagen (Squatriglia, 2012), and Mercedes-Benz (Vijayenthiran, 2011). Work of companies outside the regular auto industry is relevant including, for example, that of Autonomous Solutions, Inc., Utah, US, which produces autonomous off-road vehicles for military purposes.

The pacesetter in driverless technology appears to be Google Inc. of Mountain View, California, working through Stanford University's Artificial Intelligence Laboratory. Google has a fleet of more than a dozen ARVs that by August 2012 had completed some 500,000 kilometres of testing. "They've covered a wide range of traffic conditions, and there hasn't been a single accident under computer control," explained Google's official blog (Google, 2012).

Google's interest in transportation in a sense antedates its primary interest in search engines. During his May 2009 Commencement Address at the University of Michigan, Google co-founder Larry Page said,

> "When I was here … I wanted to build a personal rapid transit system on campus to replace the buses. It was a futuristic way of solving our transportation problem. I still think a lot about transportation – you never lose a dream, it just incubates as a hobby. Many things that people labor hard to do now, like cooking, cleaning, and driving, will require much less human time in the future." (Page, 2009)

In 1993, Page was an undergraduate member of the University of Michigan's Solar Car team. He met Sergey Brin, Google's other co-founder, while they were graduate students at Stanford University. At the September 2012 signing of the State of California's bill concerning autonomous vehicles at Google's headquarters, Brin said the company "will have autonomous cars available for the general public within five years" (Tam, 2012).

The Japanese government has set the goal of having ARVs on the road during the early 2020s (Hornyak, 2012). Members of the authoritative Institute of Electrical and Electronics Engineers (IEEE) anticipate that ARVs will account for up to 75 per cent of cars on the road by 2040 (IEEE, 2012).

Sebastian Thrun, the leader of Google's ARV project, has noted that current ARVs have not quite reached the performance level of an attentive human driver (DCMW, 2012). He would want millions of kilometres completed without a crash before Google could be considered to have a marketable product (Mosher, 2012).

Across such a testing period, there would be the challenge of bringing down the cost of ARVs. The hardware required for full automation now costs several tens of thousands of dollars per vehicle (Fountain, 2012). With refinement and mass production, this cost is expected to fall to about $3,000 (Anon, 2012a; Yvkoff, 2012). The extra purchase cost could be more than offset by reduced insurance costs (because vehicles and roads will be safer), reduced operating costs (because autonomous vehicles will drive more uniformly, using less fuel and wearing out the vehicle less), and reduced vehicle manufacture costs (because autonomous vehicles will need fewer human-operated controls and fewer safety features).

Led by Nevada, there has been authorization of deployment of ARVs or moves towards deployment in several US states (Florida, California, Hawaii, Oklahoma, and Arizona), with more jurisdictions in the US being approached by Google and other interested parties. Road testing is also occurring in several European countries, and much relevant work is under way in Japan and China.

There has been opposition to these moves. During a race for the Republican nomination as a candidate for a seat in Florida's senate in the November 2012 election, one contestant attacked a rival's support for ARVs, resulting in the headline, "Florida political ad suggests that self-driving cars will be the death of grandma" (Wolford, 2012). The supporter of ARVs won the nomination and then the senate seat.

Surveys on attitudes towards ARVs in North America and Europe suggest an age divide: young people welcome them; older people do not. Table 1 presents results from a survey of 1,000 UK motorists conducted during 2012 for Robert Bosch GmbH, a maker of automotive parts headquartered in Germany (Anon, 2012b).

Table 1 goes about here

In spite of their relatively strong opposition to ARVs, older people reported welcoming automatic safety features in driven automobiles almost as much as younger people (63 vs. 71 per cent).

JD Power and Associates, a California-based information services company, surveyed 17,400 US vehicle owners early in 2012 and found a similar divide: a third of those under 38 years would buy an ARV even if it cost $3,000 more, but less than nine per cent of respondents over 56 years would buy one (Yvkoff, 2012).

Accenture plc, a global management consulting, technology services and outsourcing company headquartered in Ireland, surveyed just over 1,000 adults in each of the US and the UK early in 2011 and found a similar amount of discomfort with riding in an ARV to that found by Bosch (Accenture, 2011). In both countries, 51 per cent said they would not feel comfortable in an ARV; Bosch found that overall 53 per cent would feel unsafe.

Accenture went further and asked what might reduce the discomfort. In both countries the main considerations would be: 1. Ability to take control over the vehicle if needed; 2. A record of 100-per-cent reliability; 3. Evidence that deployment of ARVs actually reduces accidents.

Puls, a German market research firm, interviewed 1,002 German drivers and confirmed another result of the Bosch survey. There were higher levels of positive regard for specific safety features and driving aids than for the prospects of widespread deployment of ARVs (Wagner and Mendle, 2012).

The reported level of acceptance of ARVs, especially among younger people, complements the general optimism of developers that ARVs will be a feature of road traffic within a decade and a predominant feature not long afterwards. The optimism is reinforced by understanding that what needs to be improved in function and cost-effectiveness are no more than electronics and software, and that results in similar areas – such as autopilots and drones in aviation – provide encouragement.

Driving the move towards autonomous road vehicles (ARVs)

Vanderbilt (2012b) noted, “The idea of autonomous vehicles gained widespread public exposure at General Motors’ Futurama exhibit at the 1939 World’s Fair, where the automaker envisioned ‘abundant sunshine, fresh air [and] fine green parkways’ upon which cars would drive themselves.” The cars were not seen as ARVs but rather as freeing drivers through “a collaborative partnership between the car and the highway” (Gelertner, 1995, p.35).

Research along these lines continued in the US and Japan until the 1970s, when more ‘intelligence’ began to be located in the vehicle. Progress became substantial during the 1990s with the massive expansion of computing power per unit volume, which is continuing (Tsugawa, 2008). Progress in sensor technology was also important.

A major boost to the development of ARVs came in 2001 when the US Congress mandated that one third of military aircraft were to be unmanned by 2010 and one third of ground combat vehicles by 2015. Aviation regulators have been asked by the US Congress to integrate unmanned aircraft into the air-traffic control system by 2015 (Anon, 2012c).

For ground vehicles, implementation of the 2001 mandate was spearheaded by the Defense Advanced Research Projects Agency (Luettel et al., 2012). DARPA is the successor to ARPA (Advanced Research Projects Agency) whose Arpanet, operational in 1969, was the progenitor of the Internet, developed to provide a communications system that could survive a nuclear attack.

Military interest remains prominent in vehicle automation, not only in the US. Appendix A indicates that military universities in China and Germany serve as centres of research on this topic. However, car manufacturers are automating road vehicle operations today chiefly to provide safer driving.

In richer countries, injuries requiring hospitalization and deaths resulting from road-traffic collisions have fallen steeply. In Canada, they fell by much more than half per capita between 1990 and 2009 (Transport Canada, 2011). Nevertheless, road crashes remained the leading cause of death for persons aged 15-24 (PHAC, 2012).

The fall in serious injuries and deaths from crashes on Canadian roads is typical of richer countries, as is the prominence of road crashes as a major cause of death among young people. Poorer countries, which are rapidly motorizing often with inferior vehicles and infrastructure, mostly show an increasing rate of road-traffic-related serious injuries and fatalities, described as a “major global public health crisis” (Sharma, 2008). On a per-capita basis their average rate passed that of richer countries around the year 2000 and is expected to be more than double that of richer countries by 2020 (Peden et al., 2004).

A key result of detailed analyses of crashes is that the overwhelming cause is driver error. In its June 2008 report to the US Congress, the National Highway Traffic Safety Administration described analysis of 5,471 road crashes (NHTSA, 2008). Of the 5,361 for which a critical reason for the crash could be determined, 95 per cent were attributable to drivers, and five per cent to vehicles or road conditions. Of the driver-related critical reasons, 41 per cent were recognition errors (inattention, internal and external distractions, and inadequate surveillance); 34 per cent were decision errors (travelling too fast for conditions, making false assumptions about others’ actions, and illegal manoeuvers); ten per cent were performance errors (overcompensation and poor directional control).

Automobiles sold in richer countries have some or all of these automated safety features: antilock brake system, emergency brake assist, forward-collision warning, traction-control system, blind-spot detector, lane-departure warning, lane-departure prevention, electronic stability control, adaptive cruise control, and drunk-driving prevention. Also available in high-cost vehicles are automatic braking, backover detection, traffic sign recognition, and automatic pedestrian recognition (Ashley, 2008). Other automatic features are less related to safety, including self-parking systems (Kane, 2011). Most of these features are elements of control systems for ARVs.

Particularly with Google's eminence in relevant research and development, interest has returned to the early considerations of convenient and productive travel. In a late-2012 interview, Google chief executive Larry Page justified the company's work on development of ARVs as helping to improve quality of transport and access to employment, reduce wasted labour, and reduce the need for parking facilities (Helft, 2012).

Noted earlier was the motivation of German car manufacturer BMW, which sees automation as a way of adding to the appeal of their products. BMW recognizes that car sales may fall, perhaps more because "young people have learned that life without a car is still a life." Thus the appeal is to younger people for whom BMW sees interactivity as the key: "The car may say to its driver on the way into Munich, 'Stop, take the train,' because of information it has received regarding conditions within the city" (Proudfoot, 2012).

Liability concerns posed by autonomous road vehicles (ARVs)

Technology relevant to ARVs seems presently ahead of the law (Brandom, 2012), which mostly requires one or more operators to be in a car even though it is driven by a computer, and which does not yet address who would be responsible if an ARV entirely under computer control were indeed to cause the death of a grandmother.

Consideration of liability issues seems no more intense than in California, where the law school of Santa Clara University, in the Silicon Valley region, is a focus of discussions. In January 2012, Santa Clara Law held a symposium entitled 'Driving the Future: The Legal Implications of Autonomous Vehicles'. Papers from the event are available, notably those by Beiker (2012), Douma and Palodichuk (2012), Marchant and Lindor (2012), and Peterson (2012).

The considerations are complex. Some are specific to California law and practice, including those to do with vehicle insurance, about which Peterson (2012, p. 1395) noted, "... the drafters of Proposition 103, and the voters convinced to follow their lead, embedded in California a regulatory system ill-suited to insuring self-driving automobiles that are controlled by new and fast developing technology".

The more general issue was summarized by Marchant and Lindor (2012, p. 1339): "Autonomous vehicles will increase the safety of vehicle travel by reducing vehicle collisions. Ironically, autonomous vehicles are likely to *increase* the liability exposure of vehicle manufacturers. Autonomous vehicles will shift the responsibility for avoiding accidents from the driver to the vehicle manufacturer."

Manufacturers could reduce their liability by selling ARVs only to fleet operators, who may be more willing than individual owners to assume some of the liability. Fleet operators could in turn rent to individual users or, perhaps more likely, use the ARVs to provide an autonomous taxicab (AT) service.

Google has hinted that it may see car-sharing as the primary business model for its ARV technology (DCMW, 2012). The above-noted statement by IEEE members observes that "autonomous vehicles will make car sharing programs more prevalent". A car-sharing service using ARVs and a taxicab service using ARVs amount to essentially the same thing.

Autonomous taxicabs (ATs)

This section builds on previous characterizations of possible AT services, notably those by Mitchell et al., (2010), Ford (2012), Kornhauser (2012), and Templeton (2012a).

A client would order an AT by smartphone or computer, specifying destination, number of passengers, and amount of baggage, negotiating exact pick-up and set-down locations with the dispatch computer and the time of pick-up. An ARV of an appropriate size would arrive at the agreed time and take the client and companions to the destination. When passengers and baggage have been unloaded, the vehicle will be available for a new assignment. For large loads, whether passengers or baggage, two ATs might arrive, linked electronically to travel together to the destination.

An AT could be shared by strangers if they agreed. Sharers would benefit from lower hire rates. One proponent has made sharing a central feature of an AT service (Ford, 2012), but the extent of willingness to share small vehicles with strangers may be in doubt, even if there is monitoring of vehicle interiors and other security features.

ATs could be better than today's taxicabs in three ways and worse in one:

- ATs could be better because the vehicles could be more comfortable. Interior space arrangements would match passenger rather than driver needs. ATs could more readily provide passengers with entertainment, communications, and other services.
- ATs could be better because the rides would be smoother and speedier. As roads become populated with autonomous vehicles, traffic would become better managed with fewer starts, stops and changes in speed, resulting in briefer trips.
- ATs could be better because the rides would cost less. A comparison of taxicab fares and car-sharing rates suggests that today roughly two-thirds of a taxicab fare covers the cost of the driver. As suggested above, ARVs, when widespread, need not cost fleet operators more than regular automobiles. Fares for ATs could be about a third of present taxicab fares – even lower if users opted to share with strangers.

- ATs would be worse for the user who needs other services a taxicab driver provides. But an AT fleet operator could provide human assistance for a premium, and could be subsidized for doing so for particular classes of passenger.

The startling advantage of ATs would be their low cost. A typical fare structure within an urban area (in today's US dollars) could be a $1.00 hiring charge and then 15 cents a minute and 10 cents a kilometre. A five-kilometre journey at an average speed of 30 kilometres/hour (i.e., taking 10 minutes) would cost $3.00 or 60¢/km. This could be about the same as the adult public transport fare for one traveller (about $3.00 in Toronto) and less than the fare if there were more. A 10-km trip at the same average speed would cost $5.00 or 50¢/km – less than the public transport fare for two people travelling together. Rates could be higher or lower according to the time of day and the size of the vehicle requested.

The per-kilometre rates are instructive when compared with the costs of owning and operating a car, which in Canada average about 55¢ per kilometre driven for cars less than four years old (CAA, 2012). For many – younger people in particular (Davis and Dutzik, 2012) – relying on a well-managed and comprehensive AT service could be more appealing than owning a car, or a second or third car. This would be not only for the lower overall cost of using ATs but also because of their convenience and flexibility. ATs will carry people door-to-door, will not have to be parked, will be usable by people who cannot or should not drive, and will allow the use of a wide variety of vehicles according to demand.

ATs need not be only for urban and suburban areas, although that may be where they are first deployed. A Google consultant has suggested that ATs (or individually owned ARVs) could compete on journey time and convenience with high-speed rail for trips other than station to station, at much lower public cost (Templeton, 2012b).

On expressways, ARVs will be able to be platooned at high speed, perhaps bringing energy costs down by about a third (Tsugawa, 2011). If, because of such energy savings, a volume discount, and possible exploitation of grid connection (discussed below), the per-kilometre cost of a five-hour, 500-km, door-to-door AT trip from Toronto to Montreal were 7.5 cents (rather than the 10 cents for local trips), and the per-minute cost remained at 15 cents, the total cost for one or more people could be less than $85 (assuming the AT could remain for hire in Montreal until used for a return trip). This cost can be compared with typical station-to-station costs per person of $50 by bus, $100 by train, and $200 by air. For longer trips, ATs with beds and washrooms could be available at a premium.

Operators of fleets of ATs may be the only adopters of ARVs. Early deployment by fleet operators will help iron out the legal and technical bugs, making ARVs potentially more available to individual owners. However, fleet owners could meanwhile be establishing AT services that would be convenient and inexpensive enough to reduce car purchase substantially.

Potential purchasers of ARVs may question whether the purchase is advisable when ATs can be summoned on demand, in a range of sizes, at a lower cost than ownership, and used more conveniently because they do not have to be parked, refuelled, and cared for in other ways. The arrival of ATs could mark the beginning of the end of individual automobile ownership.

Some people may think they will always want to be able to drive their own car, or that cars must always have human operators. Many decades ago, elevators usually had operators and aircraft were flown only by pilots. A few decades from now, only driverless cars may be allowed on most roads, for safety reasons. Human operators could be a hazard when most vehicles are under automatic control.

Implications of autonomous road vehicles (ARVs) for the automobile industry

Individually owned cars are used on average for about an hour a day in the US (Santos et al., 2011) and probably about the same elsewhere. If ATs were to carry passengers for an average of eight hours a day, other things being equal, only one eighth of the present number of automobiles per person would be needed.

Other things would not be equal. Because ATs could substitute for much public transport – discussed below – there would be more ATs on the road than the number required to replace today's personal automobiles. Also, because ATs would be used more intensively they could have a shorter life. Nevertheless, the deployment of ARVs could well cause car production to shrink to less than half its present level over the next few decades.

This potential impact of ARVs provides a further reason for automobile manufacturers to counter their development, in addition to the liability issues noted above. Google has already complained that some parts of the auto industry have impeded deployment of driverless cars (DCMW, 2012).

Nevertheless, as also noted above, many parts of the industry appear to be contributing strongly to the development of ARVs. To repeat, General Motors has said that "self-driving cars could be in showrooms by the end of the decade" and that vehicles that "partially drive themselves" may debut by the middle of the decade (Lienert, 2011).

Autonomous taxicabs (ATs) and public transport

In richer countries, there is usually more travel in large urban regions by motorized personal vehicles than by public transport. For example, data on mode shares in 16 such urban regions showed a preference for travel by personal automobile over public transport in 10 of them: Barcelona, Berlin, Chicago, London, Melbourne, New York, Osaka, Rome, Sydney, and Toronto. Public transport was used more than personal automobiles in six of them: Hong Kong, Madrid, Paris, Singapore, Tokyo, and Vienna (Anon, 2011). Travelling by AT will be more like travelling by car than travelling by public transport. As a consequence, AT services could replace much of the present kinds of public transport.

An AT service could be considered a form of public transport in that it moves people in a manner available to almost all of a population. However, taxicab services are often not considered to be public transport, e.g., Walker (2012, pp. 13-14). Nevertheless, some communities provide public transport through taxicab companies, e.g., the taxibus services in 11 districts of Montreal (STM, 2012) and the taxibus service that covers much of Rimouski, Quebec (Rimouski, 2012). AT services could thus be considered a type of public transport, but superior to the services usually on offer today.

ATs will be superior because they will travel door-to door and provide a more comfortable journey than today's services. They will be speedier – chiefly because of uninterrupted travel between origins and destinations – except along highly travelled routes, for which something like present heavy-rail services will still be required.

Consider, for example, the Toronto Dominium Centre in downtown Toronto, a tight cluster of six office towers where 21,000 people work. If a fifth of the people working there were to arrive by AT within 15 minutes in the morning, or leave within 15 minutes in the afternoon, there would be gridlock.

ATs can be narrower (the smallest might have only two facing seats), drive more closely together (because of the more precise automatic control), and follow each other at shorter distances (at one-second-or-less rather than two-second intervals), and they will be more likely to be shared. As a consequence, ATs will carry up to four times as many passengers per lane as human-driven cars (8,000 rather than 2,000 per hour). Even with this advantage, roads could not cope with the flow from the Toronto Dominium Centre. Moreover, there are several other highly occupied office towers at or close to the intersection of Toronto's Bay and King Streets. There could be even worse congestion at this area's set-down and pick-up points for ATs.

Locations such as Toronto's Bay and King Streets will continue to require heavy-rail transit – subways or regional trains – capable of moving tens of thousands of people per hour per direction. Peripheral stations on the lines serving the dense districts could be served by ATs, as would the dense districts themselves outside of busy periods. Heavy rail lines need extend only from high-density areas to the nearest place where passenger activity would be at a level low enough to allow for ready access by AT during peak periods.

With superior signalling and multi-unit trains, light-rail transport (streetcars or trams on their own rights-of way) can have near the capacity of heavy-rail transport, However, the peak load of light-rail systems is usually within the potential capacity of AT systems. This could make many light-rail systems unnecessary because of the greater convenience of AT systems and their lower cost to operators, users, and governments.

Bus systems are almost always well within the capacity of AT systems and would also likely not survive. This includes school bus systems, which in Canada are responsible today for much more movement of people than urban transit systems (NRCan, 2011).

Thus, driverless cars could bring a major shrinkage in public transport systems as well as in the automotive industry. However, to the extent that AT services would be considered to be a form of public transport, public transport could be due for major expansion, but in a very different form from what we have now.

Energy implications of widespread deployment of autonomous taxicabs (ATs)

With widespread deployment of ARVs – mostly as ATs – there could be more vehicles on the road because ATs will substitute for most, and perhaps eventually all, personal automobile use as well as much use of buses and other conventional public transport. Moreover, ATs will serve users who cannot drive or use public transport, including young people and the elderly. As well, ATs will spend less time parked than today's automobiles, and more of the day on or moving between assignments, contributing to the increase in the number of vehicles on the road. An offsetting factor will be some growth in car sharing by strangers – in the form of sharing of part or all of trips by AT – but likely not enough to compensate completely for the factors contributing to an increase in traffic.

More movement of vehicles will not necessarily result in more fuel use. ATs will be smaller and lighter on average than today's personal vehicles because they will need fewer safety features and driver controls and because the capacity of particular ATs will be matched to the trip requirements. As well as using less energy for these reasons, they will be operated so as to use less energy. This will happen through attainment of more even speeds as a result of better traffic management as well as more even vehicle operation.

The resulting energy savings could be more than enough to offset any growth in traffic. Folsom (2012) has estimated that fuel consumption of ATs propelled by internal combustion engines could be as much as an order less than that of today's automobiles, i.e., in the range of 0.25-0.50 litres per 100 kilometres at 50 km/hour vs. an average of about 6.2 L/100km for today's vehicles at that speed. More modest reductions could be sufficient to meet even quite ambitious targets for reductions in consumption of petroleum fuels.

Some of the extraordinary potential reduction in fuel consumption posited by Folsom could be achieved with any motorized vehicle but most would depend on two particular features of ATs. One is what should be ATs' remarkably low mass compared with regular taxicabs, as much as an order less, achievable mainly because of reduced need for safety features and better matching of vehicle size to occupancy. The other would be ATs' more even movement, achievable through the better traffic management and vehicle operation that ATs would allow, resulting in less energy-consuming acceleration and a need for lower maximum speeds during the attainment of particular average speeds.

Reducing oil consumption for transportation remains an imperative, whether for supply or environmental reasons, or both. If petroleum products continue to provide the main fuel for transportation, a major gap between potential demand for and world supply of oil seems likely to emerge within a decade or two (Murray and King, 2012), notwithstanding recent bursts of optimism about supply (Gilbert, 2012) and ongoing heroic efforts to improve the efficiency of transport fuel use (e.g., NHTSA, 2012). A shift from internal combustion engines to electric motors as the source of traction seems the best direction to take, because of the relative ease of producing electrical energy sustainably and then distributing it (Gilbert and Perl, 2010).

Operators of fleets of ATs could be in a better position to switch to electric traction than individual owners of driven or driverless cars, for several reasons:

- Taxicabs travel much more per day than individually owned cars. In New York City, which may be atypical but for which there are good data for 2005, the average taxicab travelled 276 kilometres a day in that year, carrying fare-paying passengers for 61 per cent of the distance (Schaller, 2006). In the US in 2009, personal automobiles travelled an average of 50 kilometres per day (Davis et al., 2012). For a car less than four years old, operating costs are less than a third of total costs (CAA, 2012). For a taxicab – using the above New York data and excluding driver's remuneration, medallion cost, and other taxicab-specific items – operating costs are about two thirds of vehicle ownership costs. As a consequence, fleet operators have good reason to be more concerned with vehicles' operating characteristics and costs. Electric vehicles can have substantially lower operating costs because they use less fuel, and cheaper fuel, and because the relative simplicity of electric vehicles results in lower maintenance costs (van den Bulk, 2012). Thus, electric vehicles could be relatively more appealing.
- The main challenge in using a battery electric vehicle is accommodating its short range (Deloitte, 2011; Element Energy, 2012; Gerssen-Gondelach and Faaij, 2012). A fleet operator could deploy enough electrically propelled vehicles to ensure that a sufficient number is available to meet demand even though many may be unavailable because their batteries are being charged. An AT with a battery approaching depletion would automatically seek a charging station between hires. Connection, charging, and disconnection would be automatic. Fleet operators may choose to invest in fast-charging stations and fewer vehicles, or vice versa, according to circumstances. Individual owners could not make that trade-off.
- Fleet operators could achieve what would in effect be very fast charging through automatic battery exchange (Anon, 2012d). Batteries for battery exchange could be charged during off-peak periods. This would reduce fuel costs overall, but raise outlays on batteries, presenting another trade-off effectively available only to fleet operators.

ATs would have much less mass than today's automobiles and would use much less energy for a given task. Battery-electric ATs could have smaller batteries, thereby reducing costs and further reducing energy use.

The energy costs of vehicle manufacturing and infrastructure maintenance could be lower for ARVs. Energy costs of vehicle manufacturing could be lower because many fewer vehicles could be produced – if ATs are widely used – and because what is produced will be much lighter. The energy cost of infrastructure maintenance could be lower because lighter vehicles and more even movement will mean less wear and tear on road surfaces.

Personal Rapid Transit (PRT): Autonomous taxicabs (ATs) on guideways

If feasible, electric traction should be powered by connection to the grid while in motion – as are electric trolley buses and streetcars – rather than by on-board batteries. This avoids the high financial cost of batteries, the energy cost of moving energy into and out of batteries, which is about 25 per cent (Gerssen-Gondelach and Faaij, 2012), and the energy cost of carrying the weight of batteries (a cost that varies considerably with amount of storage carried, topography, and driving characteristics).

Electrically propelled automobiles could in principle be powered from the grid while on regular roads as trolleybuses are so powered: by stringing pairs of wires (catenaries) above one or more lanes. The wires would have to be several metres above the road, to allow space for trucks (lorries) and other large vehicles, and thus the poles or pantographs required to reach such wires from small vehicles could be unwieldy. Connection could be made to roadway-level rails or even inductively to buried wires (Chopra and Bauer, 2013), but these would present additional problems of highway safety and, in the latter case, energy loss. Satisfactory grid-connection of small vehicles could require guideways designed for the purpose.

Use of such guideways by ARVs would constitute what is known as personal rapid transit (PRT), defined in the opening section. PRT is usually envisioned as being powered directly from the grid, although in at least one early implementation – at London's Heathrow Airport – the pods are battery powered (ULTra, 2012).

The initial all-in cost of a PRT system including guideways and vehicles appears to be about $15 million per two-way kilometre (Meyer and Morache, 2010). This is low compared, for example, with a light-rail system, which seems to average about $35 per kilometre in the US (Guerra and Cervero, 2011) and can cost much more (a mostly tunnelled light-rail line in Toronto is costing more than $250 million per kilometre). The PRT cost is nevertheless high enough to require what may be considered to be substantial investment in infrastructure, e.g., $300 million for a relatively small 20-kilometre system. Resistance to spending even this amount – low for a transit investment – would be reinforced by the novelty of PRT, which could make for a risky venture.

An AT service could deliver much of the service provided by PRT, at perhaps about the same cost to users, chiefly because passengers would stay in the same low-capacity vehicle during speedy, mostly non-stop trips from origin to destination. An AT service would have the added advantages that travel could be literally door to door, and there would be no new public infrastructure cost because existing roads would likely be sufficient.

AT services, requiring less infrastructure, would thus be less disruptive than PRT and, accordingly, could be more successful. Araujo et al. (2012, p. 3) concluded, "We can glean from our knowledge of innovation that the less disruptive innovations are, the more they can make use of or insert themselves seamlessly into the existing socio-technical infrastructures, the greater their chances of success."

If the need for a new road is apparent when AT services are established, this could be a guideway allowing powering of electrically propelled ATs from the grid while in motion. To the extent such guideways will be available, ATs' batteries can be smaller. The cost of ATs would be lower as would their energy requirements. Guideways might be constructed to achieve these benefits, as well as to separate vehicles from pedestrians and free present road space for other purposes. Over time, guideways might thus replace many roads as we known them. PRT would evolve from AT services.

Guideways that provided power to ATs and other small ARVs could be of special value for longer journeys by reducing the need to stop for battery charging or replacement. Such guideways might also be constructed where roads are needed but none exist, as in industrializing countries. However, guideway construction, which could cost more than $10 million per kilometre (Meyer and Morache, 2010), may not be a good investment compared with the cost of constructing two-lane paved roads, which in poorer countries is less than $1 million per kilometre (Queiroz, 2012).

Freight movement by autonomous road vehicles (ARVs)

Freight-carrying ARVs could provide for revolutions in the way goods are moved. There are three main considerations: (i) movement of goods now moved in personal automobiles; (ii) other movement of goods in urban areas; and (iii) other movement of goods between urban areas.

Much movement of goods occurs in personal automobiles, consuming a surprising share of energy used for freight movement. An analysis of the transport energy involved in moving breakfast cereal from field to table found that 80 per cent was expended in the shopping trip (WBCSD, 2001). In both the US (NHTS, 2011) and the UK (DfT, 2012), shopping is a major purpose of travel by car, exceeding travelling to and from work in number of trips although not in distance travelled. People who use their cars for business purposes often have additional reasons to value the goods-carrying capacity of personal automobiles. If ATs were to substitute for personal automobiles, goods carrying arrangements would be essential.

One option has been suggested above: an AT user with a lot of baggage could hire two linked ATs that would travel together to the user's destination. Another possibility would be to have a standardized 'stuff locker' (Templeton, 2012a) that fits in any AT and can moved by hand or moved automatically to and from stationary lockers. ATs could also move items in this way without carrying passengers, as taxicabs are used today to carry small packages.

Autonomous local delivery vehicles (ALDVs) could do the same thing, carrying many containers. Such vehicles could substitute for mail and courier services if destinations were equipped to receive the standard containers. Larger items and amounts could be so delivered in appropriately-sized containers, refrigerated when necessary. However, much business delivery – e.g., for construction materials – may require human supervision for many more years.

For reasons of energy supply and local and global pollution, ALDVs may well move to electric traction. As with ATs, fleet management of ALDVs could facilitate electrification.

Large vehicles, e.g., trucks (lorries) with trailers, can be automated as readily as smaller vehicles, but the path to electrification of autonomous heavy-duty vehicles (AHDVs) could be different. The primary advantage of automation for heavy-duty vehicles could be facilitation of platooning on expressways. Trucks could be marshalled automatically into platoons providing energy savings of about a third (Tsugawa, 2011).

Battery powering of heavy duty vehicles may not be expedient. To match the range provided by the diesel fuel tank of a typical long-distance heavy-duty truck, which when full weighs about a tonne, a heavy-duty battery-powered electric-drive truck would have to carry almost 30 tonnes of battery. This is much more than the average payload of heavy-duty trucks in the US (FHA, 2009) and Europe (De Ceuster et al., 2009). Put another way, a heavy-duty electric-drive truck would require 1-2 tonnes of battery per hour of operation.

A more feasible way of providing electric propulsion of heavy-duty trucks would be to provide power while in motion, as streetcars and trolleybuses receive power. This is not a new concept. Electric trolley trucks were on German roads more than a hundred years ago (Anon, 2009). Today, they are used in mines and for other off-road uses (Adey et al. 2011). Trials of on-road trolley truck operation are under way in Germany and the US (Siemens, 2012), and in Sweden (Ranch, 2010).

A possible scenario for much freight movement across the 500 kilometres between Toronto and Montreal could involve electrically propelled AHDVs. Such a vehicle could leave a loading bay in Toronto under battery power, travel ten kilometres to the expressway connecting Toronto and Montreal, and then raise its pantograph to allow direct powering of its electric motors from the pair of wires strung over one lane. As soon as possible during expressway journey, the AHDV is marshalled automatically into a platoon of, say, four vehicles travelling a few metres apart. At Montreal, the AHDV would disengage from the platoon, exit the expressway, and travel the ten kilometres to its final destination under battery power.

This AHDV's energy consumption for the 500-kilometre trip would be about a quarter of that used by one of today's trucks, chiefly on account of its electric propulsion (Gilbert and Perl, 2010). Moreover, electricity could be generated without use of fossil fuels. Energy consumption would still be higher than if the freight were sent by rail, even counting that used to move the freight the few kilometres before and after the rail trip, and very much higher than if the rail line between Toronto and Montreal were electrified (Gilbert and Perl, 2010). However, with AHDVs, road transports' advantages of reliability, security, and overall speed could be achieved at lower financial cost, because of reduced energy and labour costs, and lower environmental and resource costs.

Infrastructure implications of deployment of autonomous road vehicles (ARVs)

The above discussion has touched on several implications for infrastructure planning of the likely widespread deployment of ARVs, including ATs, ALDVs, and AHDVs:

1. Existing road space could be used much more intensively, obviating the need for additional roads and road expansions, whether minor in nature or major such as the proposed one-billion-dollar bridge between Detroit, Michigan, and Windsor, Ontario, which is to supplement an existing road bridge and road tunnel.

2. Nevertheless, guideways – often elevated – could be constructed to allow for reduced energy consumption and emissions, to separate road traffic from pedestrians and street activity, and free urban space.

3. Continuing roads would require less maintenance because on average ARVs would be lighter and move more evenly.

4. There would be many fewer vehicles, although more vehicles on the road at any one time; the result would be much reduced need for parking infrastructure.

5. Vehicle manufacturing would decline substantially, thereby reducing the demands of this sector for transport infrastructure.

6. Excepting heavy rail whose functions would be limited to servicing very high density areas, ATs could replace the need for much public transport, thus obviating, for example, most or all of the recently commenced construction of the $5.0-billion, 19-kilometre Eglinton-Scarborough Crosstown light-rail line in Toronto, which is to be completed in 2020, and which for a decade or more after that appears unlikely to exceed ridership achievable through an AT system on the existing roadway, which is mostly several lanes wide (Munro, 2011; Matlow and Stintz, 2012). A comprehensive AT service providing intercity service could even obviate construction of most or all of the proposed California High Speed Rail project, planned to be over 1,300 in length and to cost more than $50 billion (CHSRA, 2012; Templeton, 2012b).

7. Energy consumption in respect of vehicles, including their manufacture and use, and for the construction and maintenance of their infrastructure would be much lower, thereby reducing the demands of the energy sector for transport infrastructure.

8. Extending the advantages of automation and electrification to heavy-duty long-distance road vehicles would require installation of catenaries above single lanes of expressways.

9. Although ARVs will generally have sufficient ‘intelligence’ to move autonomously, their function would be greatly enhanced by wireless communication –V2V and V2I – which will require appropriate, secure infrastructure and common standards.

In brief, the likely widespread deployment of ARVs could reduce substantially the transport infrastructure challenges faced by richer and poorer parts of the world, although relatively minor infrastructure requirements will be added.

The primary task of transport infrastructure planners in richer countries could become that of accommodating and even facilitating this coming transformation in transport activity: from the present arrangement whereby most travel is performed as a vehicle operator to a future in which most travel is performed as a vehicle passenger.

Such is the promise of ARVs, infrastructure projects, including megaprojects, whose use could be obviated by widespread ARVs could well be delayed or stalled until ARVs' viability, feasibility, and utility are better established.

A particular challenge if AT services become widespread could be that of sustaining the use of some rail-based public transport in order to take sufficient advantage of the investment in it. As noted above, this could apply to most light-rail installations and some of the less-used parts of heavy-rail facilities. In many cases this kind of challenge could be addressed by greatly intensifying residential and commercial development at and near stations, thereby creating circumstances where existing rail systems would not be obviated.

The chief uncertainties for transport infrastructure planners are whether and – perhaps more important – when ARVs will be deployed. Here are some requirements of a possible path towards widespread use of ARVs in richer countries in the early 2020s:

1. Reliability is assured by attainment during 2013 of two million ARV kilometres without a crash for which the primary reason was the ARV equivalent of a driver error – beyond the present 500,000-plus such kilometres – with much of the testing distance being travelled in the demanding circumstances of a Canadian winter.

2. Liability issues are resolved during 2013-2014, which seems possible given that already one insurance policy covering ARVs has been issued (AutoNOMOS, 2012); and necessary legislative changes are also made during the same period.

3. A company such as Google completes successful trials of AT services during 2014-2017.

The situations in poorer countries are more complex, with much variety among them. In general terms, the planners' tasks there could be to help bypass the current practices of richer countries and exploit as soon as possible the opportunities offered by ARVs, subject to the results of the testing regime for richer countries or similar tests. The process could be analogous to poorer countries' bypassing the telephone practices of the 20th century and embracing mobile phones with vigour and enterprise (Anon, 2012e; Khan, 2012).

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Table 1: Results of a survey of attitudes of 1,000 UK drivers to driverless cars

	Per cent agreeing	
	Under 35	**Over 55**
Would feel unsafe being a passenger in a driverless car	32%	65%
Would *not* consider buying a driverless car	48%	85%
Would enjoy a driverless car as much as driving themselves	51%	12%