Automated Vehicles - Virtue or Vice?

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How Might Vehicle Automation Influence Infrastructure?

ABSTRACT

Two distinct markets are developing for vehicle automation: semi-automated vehicles for personal/household ownership and fully automated vehicles for shared and public service use as robo-shuttles and robo-taxis. These two markets will compete for consumers (car-buyers vs. ride-buyers), as household vehicles and public transit do now. As these markets develop, the competition between them will complicate infrastructure, require complex regulations, delay our path to the promised 90% reduction in crashes and fatalities, and push out the time at which we can achieve a hoped-for new level of optimal land-use and optimal urban mobility given by lowered pressure from massive storage of parked vehicles and the flaws of human drivers. This paper outlines why this is competition unavoidable and will mean a significant period of difficulty on the way to a new era of mobility.

MOBILITY DIGITIZATION

The launch of Uber in 2009 marks our entry into the era of *Mobility Digitization* (**Figure 1**). Over the next 30 to 40 years digital technologies will do for automobiles, trucks and transit what digital technologies have done for music, print, broadcast, hotels, entertainment and hundreds of other facets of human consumption since the 1990s.

The first stage of mobility digitization, ride-sourcing from *Transportation Network Companies* (TNCs), provides digital aggregation of hundreds of thousands of full and part-time drivers and their underutilized cars. The second stage, *Mobility as a Service* (MaaS), ups that capability by aggregating access to all forms of transportation—cars, buses, taxis, subway, streetcars, bicycles, shared cars, motorbikes—into a single app. MaaS, provides trip coherence with minimal hassle and without car ownership. MaaS has already débuted: Maas Global launched their app, *WHIM,* in four cities in Scandinavia in 2016 and expects to launch in more cities by year-end. Toronto is under consideration as one of these cities. MaaS is an instance of the *Mobility Internet*.

These first two app-based mobility digitization technologies tend to reduce the need for car ownership. Two other digital technologies, related to place and presence, are virtual reality and telepresence. Ongoing advances in each of these greatly extend current video-conferencing capabilities and tend to further reduce the need to travel.

The most far-reaching of all digital mobility technologies—more than all others combined—is *vehicle automation* (including connectivity). Robotics, far more than an issue of safety and convenience, is a powerful optimizer of time, space, human attention, and energy. Vehicle automation is an enabler that will affect human mobility at least as much as did the shift from horse to combustion engine. Vehicle robotics will alter fundamentally how, why, and how much we travel. Altering how easily we can sprawl, vehicle automation and connectivity will tend to flatten our cities.[1]

Figure 1: Mobility Digitization comprises three major waves

FOR BETTER OR WORSE?

To ask whether vehicle automation will make us better off or worse off is to imply a simple binary categorization and understanding of the effects of this technology. There isn't one.

For example, will vehicle automation result in a future of more or fewer vehicles in our cities? Some fully-automated formats of vehicle automation are expected to reduce vehicle ownership while increasing trip counts and trips lengths,[2] while semi-automated formats and circumstances will increase the demand for vehicle ownership. This contradiction alone—driven as much by social and demographic trends, behavioural economics, and choice availability as by technology maturity—will cause more uncertainty in urban transportation and land use planning over the next two decades than any other single aspect of mobility digitization.

Vehicle automation—sooner or later—is almost certain to radically transform how people and goods move within and between cities. The list of expected changes is substantial—traffic volume, average speed, travel time reliability, safety, modal preferences, congestion, parking, land use, travel cost, emissions, energy consumption, and other environmental and social effects. There will be others, as yet unimagined.

This certainty of change is matched by a complete lack of certainty about when and how changes will occur, in what order and—of paramount concern—in which direction. For example, there are as many warnings of *increases* in road congestion as there are promises of *reduction* in congestion. The prediction of vehicles that almost never crash is inconveniently clouded by safety concerns for the decades-long period of time (and in excess of one quadrillion[3] vehicle kilometres, worldwide) in which

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[1] If interurban rail and automated vehicles make commuting less unpleasant and less costly, patterns of out-migration will intensify. Over three million people have chosen the suburban ground-related home in the Greater Toronto and Hamilton Area (GTHA)—because they had a choice. Denying affordable choice through land-use policy can only constrain this impulse until there are economic and electoral consequences. Hence, we will likely see a flattening of our cities, as well as a resurgence of cities well beyond the current shadow of the metropolitan commuter-sheds, whose single-family home and business costs increasingly exclude a large portion of urban populations. (M. Fenn, personal communication)
[2] CityMobil2 (2015) D27.2 Results on the on-line DELPHI survey
[3] Given an expectation of 27 trillion VKT worldwide in 2021 and a 2% annual growth rate in VKT, the planet will experience a cumulative 1.6 quadrillion VKT by 2060. Given automation, we should expect an even higher number of VKT.

non-automated, semi-automated and fully automated vehicles will co-exist in formats and systems that are, as yet, undetermined. This uncertainty means the next few transportation planning cycles will be unlike any long-term planning cycle we have experienced to date.

During these next decades, we can expect that individual travelers will continue to make decisions about trip modality and vehicle ownership as needs arise and circumstances warrant. Such decisions are relatively short term—made for the day or for the few years immediately in front of that individual. These decisions carry small personal risks. Regrets can be undone tomorrow or next year.

Transportation planners, on the other hand, make decisions dealing with majority behaviours based on a significant number of assumptions about large populations of diverse travelers over large geographic areas decades in advance of those assumptions playing out and often within a governance structure constrained by political interventions unrelated to any of those factors. Regrets cost many billions of dollars and cannot be readily undone.

Mistaken assumptions and subsequent miscalculations about the uptake of vehicle automation imply huge risks that can create over- or under-supply, exacerbate congestion, distort land values, and shift tax-bases. Inability to predict the timing and effects of vehicle automation and mobility digitization is now the single most troublesome aspect of regional infrastructure planning—even worse than the staggeringly common complaint of an inadequate funding model. This is not because vehicle automation is a bad idea; it is because the technology tends to develop much faster than it can be governed and faster than society's ability to sensibly adopt it or reliably adapt to it.

Systems of moving people and goods involve three major components: vehicles, infrastructure, and users. Each component comprises innumerable elements and aspects, and automation means components and elements can interact to influence each other in new ways some of which are increasingly difficult to model and predict. Significantly, observers of vehicle automation have over-focussed on the vehicle technology at the expense of infrastructural and social issues.

AUTOMOBILE vs. AUTOMOBILITY

Current descriptions of the future of surface transportation indicate that automated vehicle technology will evolve through a fixed number of agreed stages along an organized trajectory to an eventual milestone—possibly quite soon—wherein the driver will no longer be needed (**Figure 2**). Vehicles will keep ferrying people and goods as they do now, but with the driver increasingly redundant—perhaps eventually banned. For persons and families there would be little need or motivation to own a private vehicle. Robo-taxis, robo-shuttles, and robo-trucks would do most of the work, and several problems related to safety, congestion, parking, energy, pollution and numerous other current vehicle-related costs would be mitigated. Most appealing for some urbanists and urban planners is the possibility we may need less infrastructure—certainly less new infrastructure—dedicated to automobiles.

This simplistic construction misleads consumers, misguides planners, and is distracting for governance. Politicians will be tempted by its easy promise. Any assumption by civic leaders that vehicle automation is the long-sought solution to many or most of the problems we blame on the automobile will mean abdication of responsibility.

The *automobile as technological artefact* is the wrong focus for understanding the larger picture of complex governance of urbanization: planning, infrastructure, city building, and movement of people and goods. *Demand* for *automobility* is the more critical focus. We are accustomed to thinking about automobiles. We can see, own, desire or revile them. But it is automobility—how and whether we need mobility, how we consume it, how independent, personal, comfortable, private, styled, and powered we expect it to be, how much we demand, and how it is supplied—that matters more. Changing the artefact by automating it does not guarantee that this will show us the way to address root causes of urban-mobility governance problems given by our various planning focuses on the automobile (or anti-automobile!) as practiced until now.

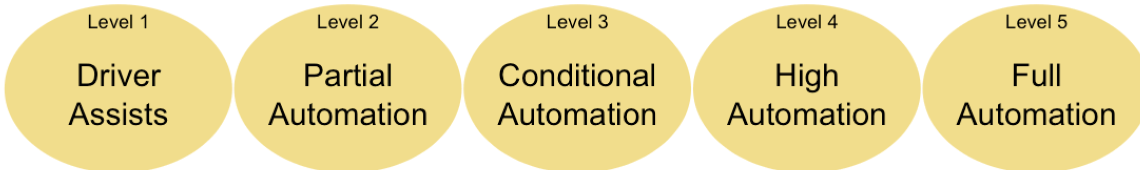

Figure 2: Stages of Vehicle Automation as set out by the Society of Automotive Engineers[4]

Even while vehicle technology is changing, urbanization continues to generate more congestion. Overall, rising demand for motorized person kilometres traveled (PKT) outstrips the relatively modest and unevenly distributed growth in alternatives such as transit, ride-sourcing and active transportation. At best it is risky to assume that the coming technologies for automation will finally overcome the harms from the unrelenting demand for personal motorized travel. Depending on how we handle the impending fork in the road to automation, we can easily make some matters worse.

TWO MARKETS

There are two different automotive worlds emerging (**Figure 3**), one comprises semi-automated vehicles with a driver required even though often operating in an automatic mode; the other comprises fully automated vehicles—never with a driver and always in an automated mode.[5] It is natural to assume that fully automated vehicles follow *technically* from semi-automated vehicles, but full automation does not follow from semi-automation in a social, planning, regulatory, taxation, or infrastructural perspective.

To be clear, the hardware and software components—sensors, maps, intelligence, connectivity, learning and actuators—mean semi- and fully automated vehicles share technology components. However, rather than being a continuum of innovation, these two technologies will spawn two competing markets—semi-automated, a continuation of 20th century automotive congestion and distorted urban form, and fully automated, a disruptive force that shifts jobs, alters energy consumption, and modifies urban form—but in ways and at a time that are still uncertain.

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[4] SAE International, Levels of Automation for On-Road Vehicles http://www.sae.org/misc/pdfs/automated_driving.pdf

[5] This distinction between semi-automated and fully automated vehicles is a simplification of the several levels of the SAE standard levels of vehicle automation. For our purposes, any form of automation that requires an operator within the vehicle in attendance is semi-automated, not permitted to be operated on a roadway without a responsible driver aboard the vehicle. When the presence of a driver is not required, the vehicle is by definition fully automated—even if the vehicle is range-limited (geo-fenced). This can also include some oversight or even operational control by remote operators, which is the case with flying drones and the automated minibuses trialed in Europe and elsewhere. When a semi-automated vehicle is switched to an "auto-drive" mode, but the presence of a driver is still required—even if that driver might attend to other activities while in the driver's seat—that vehicle is still a semi-automated vehicle. Sometimes a fully automated vehicle may be severely restricted in its permissible operating range (such as the minibuses already being deployed in very limited environments and at low speeds). Such range-limited vehicles would be considered "Level 4" in the SAE spectrum, but in this paper, I simplify the market taxonomy to semi-automated and fully automated—i.e., driver-in or driver-out.

The semi-automated market will enjoy dominance for a few decades, but eventually the fully automated market will become preponderant. How long will these markets co-exist? When and how will the competition be decided? What will be the final mix? How will they co-exist (safety, rights-of-way, access, subsidies, entitlements) before and after market maturity?

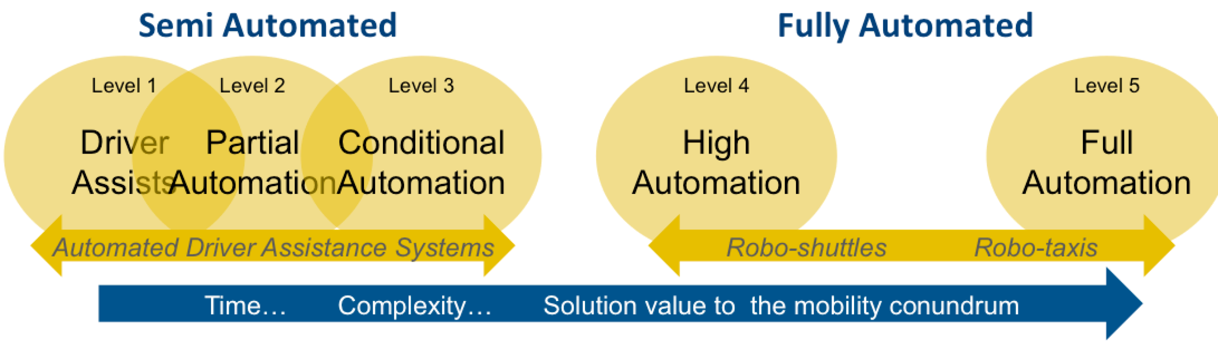

Figure 3: Semi- and fully automated vehicles initially form two competing markets: private use and public use, comparable to the household vehicle and transit, today. While both markets are commencing now, the semi-automated market will mature first (mid 2030s), while the fully automated vehicle will mature as late as 2075[6] before it is sufficiently competent to be a personal household vehicle.

We are uncertain how these two trends—semi- and fully automated—will coexist within any infrastructural regime; how they will affect or be affected by land-use planning. What we plan and how we regulate will become both more difficult and more critical than ever.

Consider the ways in which private cars and public transit share the roadway now—or perhaps how cars and bikes share the roadway. Even these comparisons are weak because newer vehicles will increasingly have an operator who is severely distracted—perhaps legally so—or no operator at all.

Because regulators, planners, and technologists are each motivated differently and each work at a different pace—glacial and cautious at one extreme vs. out-of-the-box and unpredictable at the other—collaboration amongst these parties is likely to grow in complexity and be plagued by hype[7] and delays. Collaboration will suffer as regulation lags the technology, planning awaits regulations, and technology is forced to work around[8] or wait for delays.

TENSION BETWEEN TWO VEHICLE AUTOMATION MARKETS

Starting now and for the next forty years, the competition between these two kinds of vehicle automation will shape our cities, continuing the century-long trend of motorized transport vehicles shaping urban form. Initially, semi-automated personal and household vehicles will tend to increase congestion and sprawl, overwhelm traditional transit, suppress ride-sharing, compete with cycling, and

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[6] Shladover, S. (2016) *What "Self-Driving" Cars Will Really Look Like*, Scientific American, June 2016

[7] Grush, B., Niles, J., (2016) Getting Past the Hype. Thinking Highways http://endofdriving.org/wp-content/uploads/2016/02/What-Gartner%E2%80%99s-Technology-Hype-Cycle-teaches-us-about-the-autonomous-vehicle.pdf

[8] Ditta, S., Urban. M.C., and Johal, S. (2016) *Sharing the Road: The Promise and Perils of Shared Mobility in the GTHA*. The Mowatt Centre. p38, provides a superb, *projected*, example of this: "after a protracted legal battle, UberHop and Lyft Line were found to be infringing on the TTC's transit monopoly. This ruling lost most of its force the day it was handed down, however, as both companies immediately shifted their services from fixed routes to dynamic routing – thereby escaping legal categorization as transit services."

delay the release of trillions of dollars in urban real-estate currently occupied by consumer-owned vehicles when parked.

Lagging this by one or two decades, full automation in the hands of transportation network companies, transit agencies, and P3s could drive down congestion and parking demand by replacing taxis, carshares, rideshares, shuttles, and traditional transit with a continuous service spectrum of automated mobility, as mediated by Mobility-as-a-Service (MaaS) operators. This path will tend—depending on regulatory intelligence and foresight—to drive up vehicle-sharing, ride-sharing, cycling and walking and release massive amounts of urban real-estate for human use: buildings, parks, and active transportation.

Semi-automated vehicle market

SAE Level 3, semi-automated vehicles will make driving easier, more convenient, more pleasant, and more productive during significant portions of trips. By definition, they will require the presence of a licensed driver and they will make these drivers more amenable to longer and/or more frequent journeys.[9] PKT will increase VKT (vehicle kilometres traveled), congestion, demand for parking, distracted driving, sprawl and demand for infrastructure and its maintenance. Drivers of non-automated vehicles will develop an enmity of entitlement toward automated vehicles (and vice-versa) as some motorists and cyclists currently harbour for each other. Depending on how they mix with non-automated vehicles, and depending on whether automotive engineers can address distracted driving, it is hoped that they will reduce accident rates and fatalities. Tellingly, however, insurers remain cautious on this matter, preferring to wait for the accumulation of reliable actuarial data.[10]

Semi-automated vehicle availability for household buyers is imminent (circa 2020).[11] Sales are expected to trend toward a peak in the mid 2030s.[12] However, during the next 20 years *worldwide* consumption of motorized VKT is expected to double. Given trends in vehicle sharing and vehicle lifecycle (vehicle longevity is increasing[13]), this doubling may portend slightly less than a match in vehicle manufacturing rates—but without massive sharing rates, the current matter of road and parking congestion will, on the whole, worsen worldwide. In regions of stabilized wealth[14] or population, or hard-won shifts in preferred modalities, road and parking congestion may plateau.[15] But even with such mitigation, congestion will remain an issue for the foreseeable future.

Fully automated vehicle market

Fully automated vehicles (SAE Level 4 and Level 5) do not require the presence of a driver, but in many circumstances they will require stewards, cargo-assistants, or fleet overseers (e.g., by remote video) at least at trip end-points or in particular areas of operation. At first, many vehicles will still command a high human-to-machine ratio, even as a driver per se is not required. The fully automated vehicle,

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[9] CityMobil2, ibid

[10] Kovacs, P. (2016) Automated Vehicles: Implications for the Insurance Industry in Canada. Insurance Institute of Canada

[11] http://www.caranddriver.com/features/semi-autonomous-cars-compared-tesla-vs-bmw-mercedes-and-infiniti-feature (In 2015, Tesla released an early (beta) version of a semi-automated product it calls Autopilot. By early 2016, Tesla's system, the best of the tested set, disengaged frequently and is not yet reliable (or recommended) for hands-off driving.)

[12] Bernhart,W., Winterhoff,M., Hasenberg,J., and Fazel,L. (2016) (R)evolution of the automotive ecosystem. Roland Berger. Munich.

[13] Davis, S., Diegel, S., Boundy, R., (2015) Transportation Energy Data Book, Edition-34, US Dept. of Energy, p 3-15

[14] Dargay, J., Gately, D., and Sommer, M., (2007) *Vehicle Ownership and Income Growth, Worldwide*: 1960-2030

[15] Davis et al, ibid indicates that such a plateau may have been reached in the US, but not in Canada; p 3-4 & 3-10

available at the same time as the semi-automated vehicle, will be suitable, at first, to constrained, well-prepared routes and areas, making it wholly unacceptable for household ownership due to "access anxiety".[16] Its initial use as a people mover will be in the form of robotic shuttles and then as robotic taxis. Robotic shuttles would likely be subject to more oversight, hence for some time would generate the same level of employment that a normal shuttle vehicle does today.

Fully automated vehicles are fundamentally harder to engineer than semi-automated vehicles. Semi automated vehicles have to be almost perfect in much or most of their range—the driver can be expected to get the vehicle through any tough spots (as long as the technology can get a distracted or sleeping driver to respond appropriately). The fully automated vehicle has to be perfect in all of its range, a feat that can work well enough in constrained areas or on restricted, pre-planned, and pre-groomed routes. Not only does this explain why semi-automated vehicles are for household consumption, it relegates fully-automated vehicles to geofenced or route constrained public-service functions—at least until they are perfect almost everywhere, sometime in the second half of the century.[17] This also explains why both vehicle classes will see applications at the same time—albeit very different ones—and why the semi-automated vehicle market will peak first and why we may wish to wait for several decades until purchasing a fully-automated vehicle as a household vehicle.

The doubling time for automotive demand (whether measured in vehicle registrations or PKT) implies a race between consumer demand and the efficacy of full-automation in driving down congestion—it may seem obvious to predict the mitigation of *relative* congestion in twenty or thirty years but foolhardy to predict a reduction in *absolute* congestion. Recent consultant projections of automotive utopia for the 2040s are skating to where the vehicle consumption puck was in 2015. The demand problems to be addressed by massive robo fleets will likely be far worse by the 2040s than they are now (on a global basis). As technology capabilities ramp-up, so too do social demands and human consumption. Will the benefits of robotic vehicles in 2040 outweigh the increased demand for PKT in 2040?

TRANSITIONING THROUGH MULTIPLE AUTOMATED FORMS

What is not known is the relative progress of these two automation streams. Will the semi-automated, personal-vehicle stream swamp the fully automated, public service stream, as cars now frustrate buses in many congested cities and regions? This would seem likely for the first few decades if human consumption behaviour that currently prefers buying vehicles to buying rides does not change significantly. Will full automation eventually dominate? This would seem certain—at least at some point. Will full automation provide a real solution to the problems of motorized automobility and urban form, or just move us to new formats for congestion, as automotive congestion replaced horse congestion? This will depend more on ownership patterns than any other factor.

I expect full vehicle automation in the long run to increase shared vehicle use, reducing demand for parking, and easing congestion. I see it changing the nature of optimal infrastructure but in ways that are not yet clear. Semi-automated and fully automated VKT will peak at different times: semi-automated will likely peak two decades earlier.[18] This has powerful implications as we go through a period of time where our household cars continue to be an urban livability barrier until automation fully matures. The

[16] Access anxiety, akin to range anxiety electric vehicles, is the sociobiological panic experienced by a car buyer that realizes that the automated car he wishes to purchase cannot go everywhere.
[17] Shladover, ibid
[18] Nieuwenhuijsen, J., (2015) Diffusion of Automated Vehicles: A quantitative method to model the diffusion of automated vehicles with system dynamics. (Masters Thesis, Delft University of Technology)

change from all horse-drawn vehicles to no horse-drawn vehicles took 40 years. We can expect a similar trajectory for the transition from no automation to full automation—2015-2055—if not longer.[19]

Semi-automated vehicles are imminent. They will begin trending in the next couple years and sales will be in full swing during the 2020s. Fully automated vehicles will have no measureable sales to private household consumers for at least two and as many as four decades due to access anxiety and regulation. During these decades, fully automated technology will be used for special purpose and public-service vehicles: robo-taxi and robo-transit. The nature of semi-automated vehicles—making driving more attractive, relieving some of the occupants' pain from congestion, increasing safety for its passengers, and restoring the convenience of driving a family-owned vehicle—coupled with its immediate availability within three or four years vs. the nature of fully automated vehicles—constrained locations and uses, slower travel, shared rides, public transit focus and a much longer wait until availability—means that PKT in semi-automated, privately-owned vehicles will immediately, and for a considerable time period, far out-number PKT in fully automated shared vehicles. What is predictable is that the public-sector effort and P3 collaboration necessary to make fully automated PKT a dominant component in intra- and inter-urban mobility will take far longer to regulate, plan and mobilize than it will take auto makers to stock showrooms with desirable, understandable, and affordable semi-automated vehicles that can be driven and parked, starting today, on the infrastructure that is already in place.

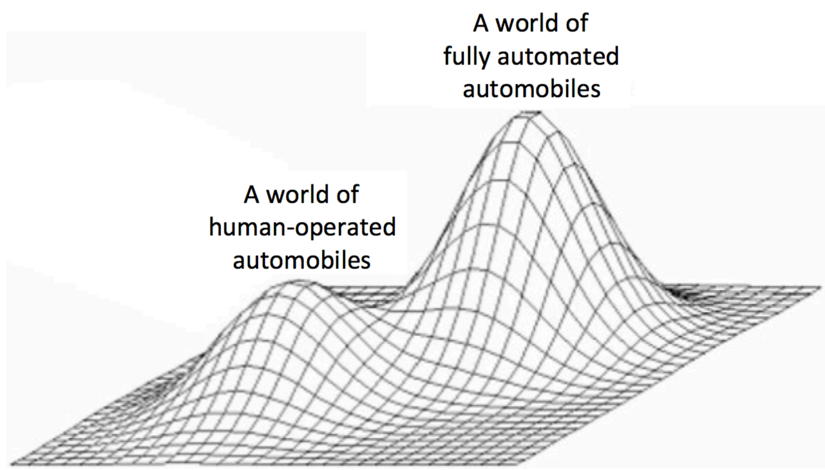

Figure 4: Many assume that a world of fully automated automobiles is a better place, but how we traverse from predominantly human-operated to predominantly fully automated will not likely be so easy.

The current 20th-century system of automobility, with its drivers and its faults is arguably a system that serves many valuable purposes. Many portray the imagined system for mid-21st-century automobility—safe, clean, instantly available robo-taxis—as an improvement over the current system.

Any effort to move from one system to another, from one situation to another or from one method to another implies a cost. That cost or pain is represented in **Figure 4** as the dip between two local optima. The relative dip between any two such solutions is often deeper than expected. Such will be the case as we shift to automated vehicles. [20]

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[19] Shladover, ibid

[20] This descriptive system-change model was suggested by Edgar Baum, the Chief Brand Economist at Strata Insights and Lecturer on the Finance of Brand Management at the University of Toronto.

One of the common features of moving from one system, circumstance or method to another is that we are often moving by trial and error. We might not already have a road map, as it were. The optimal route in the illustration (**Figure 4**) would be along the ridge or saddle between the two peaks. But there is no way for us to know with certainty where that saddle is. So the likelihood is that we will take a highly sub-optimal route to the desired new state. This will be the case as we move from non-automated to fully automated vehicles. It is impossible to guarantee that we can reach the optimal state much less that we will find a tolerable path to it. The even bigger question is how can we avoid getting stuck in the saddle, as we have arguably gotten stuck during the migration from horses to cars, trading one set of problems for another.

Critically, a dip is unavoidable when moving between two optimal states, and the improvement is not 100% efficient. Rather, it is an evolution that requires the mutual acceptance and enablement of going through the saddle with as little pain as possible. That requires going in with eyes open and acknowledging that the dip will be experienced and taking responsibility for that as makers, planners and labour leaders.

THE TRIUMPH OF HABIT

There is also a multi-generational attachment to past comforts and habits. It's what people grew up with, making this as much about psychology and behavioral economics as it is about technology. Will our history with family owned vehicles influence or exacerbate the tension between semi- and fully automated mobility—i.e., between ownership and ridership? It is hard to overestimate how much humans are unwilling to change without hedonic motivation.

Worse than what is illustrated in **Figure 4**, is the dawning realization, that we need to either pass through two saddles (non-automated to semi-automated, then semi-automated to fully-automated) or pass through an even deeper saddle to move from non-automated to fully-automated. Compare this to the glacial progress we have made over the past decade in starting the traversal of the saddle between the internal combustion engine and the all electric vehicle.

It's one thing to imagine life while watching a science fiction movie with robotic vehicles embedded in the storyline. It's another matter now without us yet having futuristic dystopias on the bridge between semi-automated and fully automated. It's not in the public imagination. We must also acknowledge the risk of NIMBYism and the power of nostalgia for how things used to be. People are patterned to this behavior.

The immediate and *relative* familiarity of the semi-automated experience for the great majority who currently own and use household vehicles means a low personal/cognitive transition cost relative to switching to fully automated public vehicle use. In transition cost, I include financial, social, schedule habits, dress and packing habits for travel, where we live, how our kids are chauffeured and monitored, and numerous other elements of using an owned vehicle that may hover below conscious awareness. For many, the sideways move to owning a semi-automated vehicle will be a "no-brainer" until the fully automated vehicle is sufficiently mature.

The transition to automated public vehicles will be easy for people who do not own or have easy access to a family-owned vehicle, but far more difficult for person or family that is habituated to owning one or more vehicles. In this way, the customers for the two markets are largely pre-determined, and this is a key difficulty. The lowest-friction path for most of us to take is the one that we already know: car-owners will become owners of semi-automated vehicles and transit users will become users of automated transit. This is not to say that there will be no change in the ratio of ownership to ridership, but it is to say that the switch could be very little indeed, unless the benefits of ridership consistently outweigh the benefits of ownership for a significant portion of our urban populations.

WHAT DIFFERENCE COULD REDUCING HOUSEHOLD VEHICLE OWNERSHIP MAKE?

The doubling time for our current world vehicle fleet population is approximately 20 years.[21] Assuming this implies an equivalent doubling time for worldwide PKT, what difference could be made if we satisfied the implied quadrupling of PKT demand (2010-2050) with a lower world vehicle population than extant in 2010?

The emerging technology of automated vehicles offers an enabler that could help reduce car ownership to 20% of its projected 2050 level of four billion vehicles (i.e., 80% of the 2010 vehicle population). This would be a critical and likely indispensable advantage in addressing the problem of environmental sustainability and urban livability.

The robotization of motorized vehicles has value independently of whether these vehicles are shared. Sharing is neither a given nor a necessity for market success. Furthermore, vehicle robotics are part of a broader mobility digitization spectrum and will not unfold in isolation. What would happen if by 2050 vehicles were emission free, fully-automated and if household ownership is near-universally replaced with shared fleets? As a thought-exercise, let's examine these three features layered progressively against a base of business-as-usual: our current world fleet, internal combustion engine (ICE), semi-automated (only), personally-owned after two projected doublings to four billion vehicles 2010-2050.

When concerned about the footprint of fossil-fuel vehicles, we primarily focus on the tailpipe: CO2, chemical pollutants and particulates. In general, only 50% of the total *direct* footprint of a motorized vehicle is its tailpipe contribution. So a second portion, the other 50%, is in its manufacture and maintenance—mostly manufacture.[22] Hence, if we were to make all vehicles 100% emission-free (100% renewables, emitting only water), we'd cut the problem in half—but only if our vehicle population stayed constant, which is not what is projected.

Imagine in twenty years when the world vehicle population doubles (highly likely) and all vehicles are squeaky-clean (unlikely), we might hope to have at least broken even. We would have traded one billion dirty cars for two billion clean ones. Then the entire footprint would be in manufacturing and maintenance and none in operation.

Not quite: there is a third component. It turns out that the value of all parking infrastructure (in the US, at least) is equivalent to the total value of all the motorized vehicles (in the US[23]). Actually, its worse, but I rounded down to be conservative. I further simplify by equating the total environmental harm caused by parking and parking infrastructure to be equivalent to that of today's tailpipe emissions. The harm from parking is likely greater; it simply does not all exhibit as GHGs or air-pollution, although most does so indirectly.

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[21] These are global numbers. U.S. numbers appear to have slowed, even saturated on a per capita basis. Canadian numbers are still growing

[22] Mike Berners-Lee, M. (2011) *How bad are bananas: The carbon footprint of everything*

[23] Shoup, D., (2004) The High Cost of Free Parking, American Planning Association

There is a fourth component: the environmental cost of the world's road, bridge and tunnel infrastructure. It effects are numerous and complex and they do harm in yet different ways, but I give them the same conservative weight—even while we continue to build—just to be sure not to overestimate the harm.

Lastly, there is a fifth element: the cost to the environment of 1.3 million (and growing) road deaths and a far greater number of grievous injuries each year, could again be considered, for simplicity, an equal environmental burden matching each of the previous four harms.

Hence, if we were to quadruple the 2010 world vehicle population by 2050 AND we commit only to zero out tailpipe emissions,[24] we will have diminished the 2050 problem (slated to become 400% worse if nothing changes) by 20%—in other words the environmental problems contributed by motorized surface transportation would be 320% (rather than 400%) worse than now.

Such back-of-the envelope reckoning is crude, but I have been conservative. To complete this thought exercise, how might some assumptions play out?

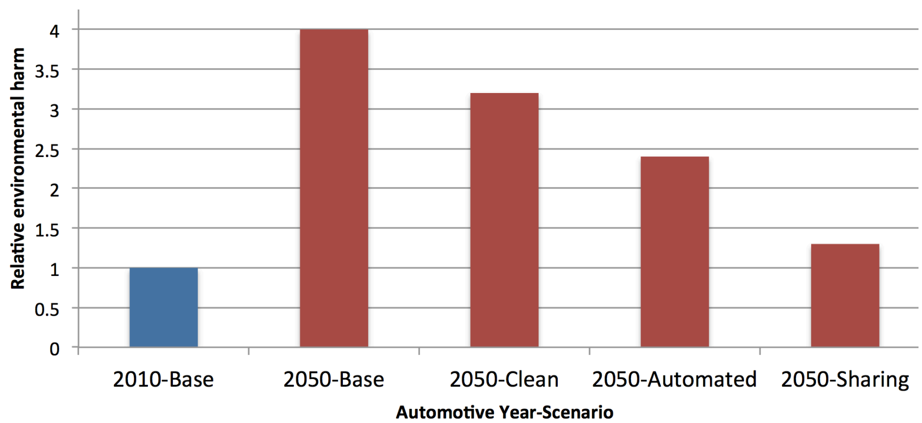

Figure 5: The Base (business-as-usual) scenario assumes a 20-year doubling time with linear growth in harm to the environment and urban livability. A Clean scenario means all things remain the same, except all energy comes from renewable resources and produces zero-emissions. The Automated scenario adds automation (and connectivity) to the Clean scenario and the Sharing scenario adds 100% non-ownership to the Automated scenario. (The y-axis is the relative environmental and livability cost. The 2010 Base is set to 1.)

Base scenario. This is a business-as-usual scenario, using only semi automated vehicles—except that vehicle population quadruples. In this case, the total problem increases 400%, a simple linear assumption. As a consideration, consumption usually seems to make things worse exponentially, but innovation sometimes makes them better disruptively or, conversely, compounds consumption,[25] so a linear assumption is both neutral and naïve. But it is a safe starting point.

Clean scenario. Add to the base scenario a worldwide conversion to zero-emission vehicles. Include zero-emission power-generation. This is not likely by 2050. But let's include it, here, as a first approximation. In the Clean scenario, vehicle manufacturing, parking, roads and road-building, and road carnage continue linearly with vehicle population (another simplifying first approximation).

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[24] Sperling, D., Gordon, D., (2009) *Two Billion Cars*

[25] Jevons Paradox. If you make it better, cheaper, easier, faster, more will be consumed.

Automated scenario. Add to the clean scenario that by 2050 the only sorts of vehicles available are fully automated, that there is not a single driver left anywhere except on movie sets and that road-carnage drops to zero (a minor exaggeration as a first approximation) while manufacturing, parking, and roads and road-building continue linearly (also a simplification).

Sharing scenario. Add to the automated scenario that by 2050 the universal way to access a motorized vehicle is via TNCs that provide only automated vehicles, and that the total worldwide quadrupled PKT demand can be satisfied with the 2010 vehicle count. Manufacturing would tick upward a bit faster from the extra wear due to the *tragedy of the commons*) and tick down a bit (fleet optimizations related to scale and automated distribution) so I simplistically assume manufacturing continues linear growth matching the PKT demands, i.e., 400% of 2010 output. I assumed a parking drop to 50% from now since the same number of cars need less parking, but we still want to reduce deadheading so we'll keep a lot of parking around for off-peak parking. I assume we can also reduce the road footprint by half of base (i.e., 200% instead of 400%) since sharing makes many road-use, scheduling and navigation optimizations possible.

The grossly simplified assumptions I have made to generate **Figure 5**, while possible, are unlikely in the time frame, but this is the direction we want to be headed: zero-emissions, automated, and shared. Furthermore, there are many other elements of optimization—especially materials, additive manufacturing and tailoring (right-sizing)—that would enable further footprint reduction. Without a full, systems approach to addressing the demands of automobility the introduction of vehicle automation is unlikely to reduce our current environmental and livability burden of automobility. Rather, at best it will merely slow down the rate at which these burdens will get worse.

Hence, even while my assumptions are simplifications, there are many other pending potential changes and technologies that when realized could make it possible that the global footprint of surface transportation in 2050 need not be worse than it is today. Programs to ensure massive fleets of robotic taxis and shuttles, such as Transit Leap,[26] are designed and managed in a way to shift from 80 percent to 20 percent household vehicle ownership over 40 years are important ingredients.

ATTRIBUTES OF AUTOMOBILITY

We humans consume the type and quantity of automobility that pleases us in the short run; we have so far proven ourselves to be unlikely, if not unable, to consume intelligently in order to reduce carbon, congestion, or carnage unless the choices offered also provide the personal mobility we desire.[27] Providers of regional transportation systems and infrastructure face fundamental constraints:

- There is no satisfactory substitute for independent, responsive automobility;
- There is no quenching of human preference for powered mobility;
- There is no avoiding human distraction;
- There is no turning back from vehicle automation;

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[26] Grush, B., Niles, J., (2016) How cities can use autonomous vehicles to increase transit ridership and reduce household ownership. (2016) Joint Conference of the Canadian Transportation Research Forum and the Transportation Research Forum. (http://endofdriving.org/wp-content/uploads/2016/02/How-cities-can-use-AVs.pdf)

[27] Thaler, R., Sunstein, C., (2008) Nudge: Improving Decisions About Health, Wealth, and Happiness

- Vehicles that are privately owned—because they are so little used and so often parked—generate two or three times the environmental and livability harm (direct and indirect) compared to vehicles that can be use-shared or ride-shared;
- Vehicle automation—however important—is only an enabler and multiplier of other automobility attributes that need to be managed as a package toward a desirable systems solution: convenience, speed, cost, availability, and scalability;
- For the last 120 years, the nature of the pre-digital technology that provides automobility means that human preference for individualized and personally optimized mobility service has been inextricably bound to vehicle ownership.

It is not fully understood to what degree mobility digitalization (including full vehicle automation) can break this bond between our fundamental need for automobility and its expression in vehicle ownership. What evidence we do have has been gathered in a world without automated vehicles. This provides us only with evidence from transit, carshares and ride sourcing, all of which correlate with personal wealth and pale in volume to household ownership. If there is a way to break that bond it would only come about by offering something better, attainable, and scalable. The coming robotic fleets, if they do come, cannot look and behave as do taxis and transit today.

Stacked against this challenge is a century-old industry with skilled designers and cunning marketers who have a deep and experienced understanding of human foibles and preferences for automobility. The world automobile industry can design something this year, make it next year, and sell it into targeted household consumer segments the year after. How will government compete with that?

CONCLUSION

The gathering speed of mobility digitization—ride sourcing, mobility-as-a-service, vehicle automation and connectivity—is catching us off guard. Innovation moves more swiftly than government; bits move faster that concrete and steel. Digitization carries hopeful potential to assist cities and regions to better cope with the demands of travelers while addressing the outsized footprint and inefficiencies of transportation, but it also carries the seeds of disruption that our transit authorities (and our transportation planners) both need and fear. It is likely that the recent history of disruption in the taxi industry is a tiny microcosm of the coming disruption of transit, and that few transit authorities will be sufficiently nimble to collaborate.

The current fever of hype and expectation for the technology of vehicle automation makes matters worse as we too-seldom distinguish between the impending household market of exciting consumer-oriented semi-automated vehicles and the slightly more distant market for currently-plodding, fully automated, public-service vehicles. The attention-getting semi-automated vehicle, falsely described as a driverless vehicle,[28] makes a sober understanding of these two markets harder to achieve. We are at risk of concurrently being fooled by hype and missing the real opportunity for cities.

I respectfully submit that the answer to the titular question: "*Automated Vehicles - Virtue or Vice?*" is: "yes".

[28] For example, by Volvo in Stockholm and Uber in Pittsburgh.