TRANSITION ACCELERATOR REPORTS
Volume 3 • Issue 2 • April 2021

Thinking about the future of autonomous vehicles

Climate impacts and the case for directed disruption

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The Transition Accelerator
L'Accélérateur de transition

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TO CITE THIS DOCUMENT:
Roberts, C. and Meadowcroft, J, 2021. Thinking about the future of autonomous vehicles: Climate impacts and the case for directed disruption. Transition Accelerator Reports Vol. 3, Issue 2, Pg. 1-50. ISSN 2562-6264

English version of this document available at www.transitionaccelerator.ca

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ABOUT THE TRANSITION ACCELERATOR

The Transition Accelerator (The Accelerator) is a pan-Canadian charity that creates positive, transformational system changes that solve societal challenges while moving Canada down viable pathways to reach net-zero greenhouse gas emissions by 2050. To achieve this, The Accelerator harnesses existing economic, social and technological disruptions already affecting multiple sectors and regions. Using momentum already underway, it acts as a catalyst and convenes innovators, progressive industry, researchers and other key groups into **collaborative teams that advance Canada down credible, compelling and capable pathways to a stronger, net-zero future.** Our current priorities are Canada's hydrogen economy, electric vehicle market penetration, building decarbonization and electrification and grid integration.

DISTRIBUTION: Transition Accelerator Reports are available online at www.transitionaccelerator.ca

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ISSN: Transition Accelerator Reports (Online format): ISSN 2562-6264/ISSN 2562-6272

MEDIA INQUIRIES AND INFORMATION: For media inquiries, please contact info@transitionaccelerator.ca.

PLACE OF PUBLICATION: The Transition Accelerator, Calgary, AB

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EXECUTIVE SUMMARY

There has been a lot of hype about the role that autonomous vehicles could play in achieving radical reductions in the carbon intensity of the personal mobility system. Some proponents of autonomous vehicles predict a radical disruption of car ownership, as shared autonomous vehicles replace gasoline-powered private cars, resulting in massive carbon savings. Other analysts, however, warn that the mass use of private autonomous vehicles could undermine efforts to decarbonize personal mobility. Which prediction will come true is difficult to determine on a purely technical level, because the answer to the question depends more on how people, companies, and institutions will integrate autonomous vehicles into everyday life than it does on the shape of the technology itself. This poses a dilemma for people interested in a more sustainable transportation system: Should we support the rapid introduction of autonomous vehicles in the hope that they will unlock changes in the mobility system that facilitate more low-carbon travel? Or should we be more cautious on the grounds that autonomous vehicles might make things worse?

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This paper explores this question, using a detailed review of the academic literature on autonomous vehicles. The literature reviewed includes quantitative modelling exercises showing the impacts of various autonomous mobility scenarios on energy consumption, vehicle-kilometers travelled, and greenhouse gas emissions. It also includes social science research on how ordinary people respond to the prospect of self-driving cars; which model of use they might be more likely to embrace; and how they might integrate them into their lives. By combining these literatures, this paper develops a branching pathways analysis of autonomous vehicles, identifying key uncertainties about what an autonomous road transportation system might look like in three technical scenarios. For each scenario, it discusses the likelihood of different possible outcomes based on the available social science research, and uses quantitative models to describe environmental impacts.

The analysis is based on three broad technical scenarios for autonomous vehicles, each of which has a different set of uncertainties and possible outcomes:

LIMITED AUTOMATION in which autonomous technology exists only to assist drivers, who must remain actively engaged in the driving task. Automation at this level promises substantial gains in the energy efficiency of cars, and in the efficiency of the traffic system as a whole, but some of these gains face social obstacles. Motorists, for example might not be comfortable driving cars whose motions are coordinated closely with the cars around them. These efficiency gains may also bring about rebound effects, which will increase the total distance that people travel. This scenario therefore offers modest potential improvements in the efficiency of the road transportation system, which would likely be offset by the risk of increased travel distance.

FULL AUTOMATION in which cars can fully drive themselves, leaving their occupants free to do other things. This builds on the efficiency gains of the previous scenario by creating the potential for fully autonomous roads. These roads, however, would be politically contentious, and would further exacerbate the potential for rebound effects. An additional hazard with full automation comes from the potential for multitasking. If people can work, play, sleep, or relax while their car does the driving, this is likely to result in an increase to the total distance they travel, because it will make travel more convenient. It could also result in bigger and thus less efficient cars to accommodate more spacious interiors. The safety benefits of these cars might also lead to their being driven faster, and thus less efficiently. This could result in an increase in greenhouse gas emissions from private cars.

FULL AUTONOMY in which cars can not only drive themselves, but can operate without a human present at all. This enables radical new forms of mobility. Supporters of autonomous cars as an environmental boon typically argue that full autonomy will result in the growth of cheap, convenient autonomous electric taxi services which would disrupt private car ownership, resulting in a far more sustainable system of personal mobility. It would be a mistake to treat this outcome as a foregone conclusion, however. Due to additional costs (such as cleaning and administrative overhead), and mismatches with the established habits and preferences of motorists, these autonomous taxis might take passengers away from public transit and active transportation rather than reducing private car use. This would result in an increase in total vehicle-kilometers travelled. Private vehicles in this scenario, meanwhile, might see a massive increase to the total vehicle-kilometers they travel, as their owners send them back home rather than paying for downtown parking, or dispatch them to conduct errands independently.

The takeaway from all three scenarios is that it is at least as likely that autonomous vehicles will have a net-negative impact on efforts to mitigate climate change as that they will have a net-positive impact. While predicting the outcome of this transition, or even assigning probabilities, is an inherently speculative endeavour, the weight of social science evidence suggests that models

> Autonomous vehicles are a very new technology. This creates an ideal opportunity for intervention to guide the development of an autonomous personal mobility system.

of autonomous vehicle use that promise the greatest benefits are not necessarily those that will appear in practice. Use-cases with large environmental downsides are also highly plausible. Thus, while autonomous vehicles will almost certainly disrupt the transportation system, it should not be taken for-granted that this will occur in a way that is beneficial for efforts to reduce carbon emissions.

This should not be taken to suggest that people trying to make the transportation system more sustainable should oppose autonomous vehicles. Rather, it makes a compelling case for directed disruption. Autonomous vehicles are a very new technology. Most of their applications are still in an experimental stage. This creates an ideal opportunity for intervention to guide the development of an autonomous personal mobility system. Ideally, this guidance should be in pursuit of a model of autonomous mobility that complements existing sustainable mobility systems, such as public transit, cycling, and walking.

1 INTRODUCTION

Over the past decade, several forecasts have made bold claims about the potential of autonomous vehicles to not only make travel cheaper and more convenient than ever before, but also to disrupt the institution of car ownership, replacing it with a system of shared efficient electric vehicles [1-3]. If these predictions come true, then autonomous vehicles could be very good news for the climate, resulting in massive cuts to greenhouse gas emissions from transportation in the immanent future. Even better news is that this would effectively achieve climate policy 'on autopilot'. According to the most enthusiastic boosters of autonomous vehicles' climate benefits, these radical cuts to greenhouse gas emissions will emerge without politically-contentious policy interventions or unappealing changes to travel habits. Given the profound challenge of radically reducing greenhouse gas emissions from our transportation system, [4] these reports read as very good news.

There are, however, other analyses of the environmental impacts of autonomous vehicles which might temper this enthusiasm. Autonomous vehicles, some scholars tell us, threaten a dystopia in which city streets are clogged with empty vehicles, and in which people vastly increase the distance they travel by car every day, thanks to the ability to work, sleep, or relax on the go [5]-[7]. Safety benefits could result in faster, and thus less efficient driving, and the ability to turn a car almost literally into a mobile office or living room could cause cars to grow much larger than they currently are.

These two positions have important practical implications. If autonomous vehicles and the private-sector actors developing them can transform the transportation system to something radically more sustainable almost automatically, as their boosters claim, then the best policy is to simply get out of their way. If, however, this technology carries the hazard of much higher carbon emissions, then its implementation will have to be carefully monitored, guided, and regulated—if it is permitted at all.

This debate has very high stakes. In 2010, transportation was responsible for 23 percent of global energy-related carbon dioxide emissions. [8] Electric vehicles show promise in cutting carbon emissions from transportation, but many scenarios find that they will not bring about the necessary changes quickly enough unless supplemented with behaviour change that reduces the total distance travelled by car. [9]-[10] According to a 2018 report from the Intergovernmental Panel on Climate Change, the world has about 10 years to cut emissions by more than 45 percent to keep warming within levels that don't risk severe impacts and potentially catastrophic global feedback loops. [11]

The ultimate impacts of autonomous vehicles on greenhouse gas emissions will depend on the extent to which the autonomous vehicles, and the transportation system more broadly, are electrified. In a fully-electric road transportation system powered by renewable energy, the impact of autonomous vehicles on vehicle-kilometers travelled will be irrelevant for greenhouse gas emissions. There are still good reasons to consider the impacts of vehicle automation in isolation from electrification, however. Firstly: the process of vehicle electrification will take a long time. Many analysts have therefore argued that electrification must be supplemented with efforts to reduce vehicle ownership and use. [4], [12] If any automation that happens before full electrification increases vehicle use, then this will also increase carbon emissions from personal mobility. The electricity system will also assume many additional loads during decarbonization, and the resulting expansion of electricity provision system will require significant investments in physical resources and capital. Holding steady and reducing electric vehicle kilometers can therefore ease the overall electricity supply challenge during accelerated decarbonization. Limiting road vehicle kilometers traveled can produce other environmental benefits such as reduced congestion and better quality of life in cites. It is therefore critical that if self-driving cars become a major part of our personal mobility system, they are implemented in a way that reduces, rather than increases, greenhouse gas emissions. Given constraints on the pace at which road transportation can be electrified, [12] this will likely have to involve a reduction in the total vehicle-kilometers travelled.

To settle the question of what autonomous vehicles imply for the climate, it is tempting to look at the evidence provided by quantitative models of their impacts on vehicle-kilometers travelled, or the total energy requirements or greenhouse gas emissions of the transportation system. Unfortunately, these modelling exercises are largely inconclusive. Many analyses predict that autonomous vehicles could increase the total vehicle-kilometers travelled due to rebound effects, but have a hard time being specific about their magnitude. [13] It is also unclear whether a shared or private model of autonomous vehicle use would predominate, [6], [14] and there are uncertainties about self-driving cars' relationships with infrastructure, public transit, pedestrians and cyclists, and electric vehicles. When these uncertainties are added up, as shown in **FIGURE 1**, it results in a huge range of potential environmental outcomes for autonomous vehicle technology, ranging from a near-total decarbonisation of the transportation system, to a doubling or even tripling of carbon emissions from personal mobility.

FIGURE 1. Estimates of the impacts of autonomous vehicles on vehicle-kilometers travelled and energy consumption of the personal mobility system.

Breaking down this analysis by scenario, rather than by paper, tells a similar story. While shared vehicle scenarios tend to reduce vehicle-kilometers travelled, energy use, and greenhouse gas emissions, the range of potential estimates is still huge, as illustrated in **FIGURE 2**.

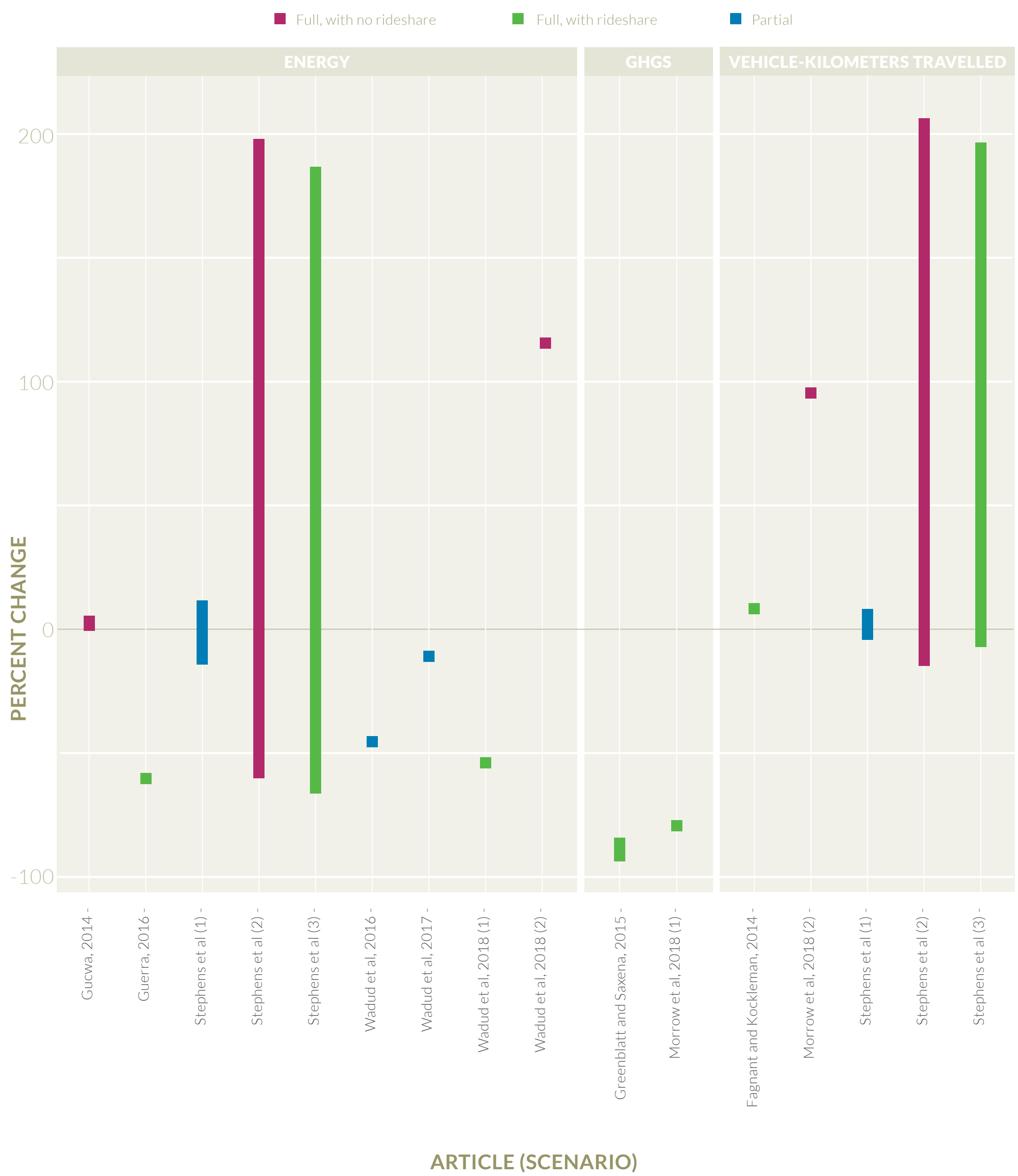

FIGURE 2. Different scenarios of shared autonomous mobility.

The things that make the difference between these two predictions of autonomous vehicles' impact are largely assumptions about the technical details of the vehicles, or the preferences of the people using them. So-called "third order impacts", in which people adapt their lifestyles to autonomous mobility, for example, tend to increase the environmental impacts of autonomous vehicles' (**FIGURE 1**). Scenarios involving shared autonomous mobility, meanwhile, tend to yield environmental benefits (**FIGURE 2**). The question of which scenario will predominate cannot be predicted by modelling alone, because it depends on the emergent outcome of millions of complex decisions made by travellers, which are often as much the outcome of cultural or psychological biases as they are on a rational assessment of transportation options. Social scientists have been therefore been writing their own literature on autonomous vehicles, which uses methods such as surveys, revealed choice experiments, and historical case studies to determine which forms of autonomous mobility people are most likely to embrace. This research, however, often focuses on the societal barriers facing autonomous mobility, or the broader societal impacts it might have, rather than on its environmental consequences.

This report provides insight into the debate over whether autonomous vehicles, when left to their own devices, will be environmentally beneficial or harmful. It does this through a detailed literature review, which considers both quantitative modelling exercises on the sustainability impacts of different autonomous mobility scenarios, and social science research on which scenarios are more likely to occur in practice. In doing so, it engages with a critical question about sustainable transportation: Are self-driving cars a climate ally, which should be allowed to exert its positive influence free from interference? Are they an enemy, which should be actively opposed? Or are they something more ambiguous, which will require careful guidance to succeed in a way that benefits the global climate?

Assessing the potential societal, economic, and environmental impacts of autonomous vehicles is a challenging task. This report is a 'think piece', which uses secondary academic literature to explore the implications of different autonomous vehicle scenarios. It is not based on original empirical research or quantitative modelling. This means there are gaps in its findings, and often it does not address the Canadian context specifically. In addition, this report primarily focuses on the impacts of autonomous vehicles on greenhouse gas emissions. It does not consider other environmental issues such as air pollution, and it only considers other social issues (such as traffic accidents and economic inequality) when these have implications for carbon emissions. Finally, this report only considers urban and intercity passenger travel. Other forms of mobility, such as rural, intercontinental, or freight transportation will also be impacted by autonomous vehicles, but because these transportation systems are so different from the ones that operate within and between cities discussing the impact of autonomous vehicles on them is a separate question.

1.1 Methodology

There are many ways to approach the environmental performance of autonomous vehicles, or of any other radical innovation in transportation technology. Vehicles can be evaluated in terms of greenhouse gas emissions per unit energy (GHG/E) or energy consumption per vehicle-kilometer travelled (E/VKT). Transportation systems as a whole, meanwhile, can be evaluated in terms of vehicle-kilometers travelled (VKT), which is influenced as much by the social and economic circumstances of mobility (i.e., where, when, and how people travel) as it is by any specific mobility technology. Different developments in sustainable mobility can impact different measurements of sustainability. Vehicles powered by electricity or by biofuels will reduce the greenhouse gas emissions per-unit energy. More efficient vehicles (for example those with more aerodynamic bodies) will reduce the energy consumed per vehicle-kilometer travelled. Changes to the mobility system as a whole, such as better incentives for public transit use, can reduce the total number of vehicle-kilometers travelled. And the greenhouse gas emissions from the system result from a combination of all three of these variables:

$$GHG = \left(\frac{GHG}{E}\right) \times \left(\frac{E}{VKT}\right) \times VKT$$

In practice, this picture can be quite complicated, because some innovations can affect all three of these variables, and can sometimes do so in opposite directions. A reduction in traffic congestion, for example, might reduce the energy requirements per vehicle-kilometer travelled (because driving in a traffic jam is inefficient) but increase the total vehicle-kilometers travelled, as people adapt to better traffic conditions by driving more. [14]

This paper uses the available academic literature to examine the impacts of autonomous vehicle technology on all three of these variables. It does so by summarising the diverse research on the uncertainties, potential scenarios, and likely impacts of autonomous vehicles, to describe several forks in the road of autonomous vehicle implementation. For each fork, it summarises research on which outcome is the most likely, and the impacts of the various possible outcomes. It then moves on to discuss the additional uncertainties that follow on from those outcomes. This allows us to anticipate climate impacts that are most likely to occur from autonomous vehicles, and consider critical strategic points at which intervention might secure more positive consequences.

1.2 Three Types of Autonomous Mobility

Automation in vehicles can take several forms. It can provide minor forms of driver assistance; it can be full-blown self-driving cars that do not need a person to be present to travel to their destination; or it can be anything in between. The Society of Automotive Engineers has developed a five-level scale of vehicle automation to describe this spectrum (**BOX 1**).

BOX 1

THE SOCIETY OF AUTOMOTIVE ENGINEERS'

Five Levels of Vehicle Automation

LEVEL 0: NO AUTOMATION
This includes most cars on the market today.

LEVEL 1: DRIVER ASSISTANCE
This includes features that assist the driver in the driving task, but which at no point allow the driver to take their attention off the road. These features include things like adaptive cruise control, lane-keeping assist, and parallel parking assist.

LEVEL 2: PARTIAL AUTOMATION
Level 2 cars contain autonomous features which can remove some, but not all aspects of the driving task from the driver's direct responsibility. Adaptive cruise control, for example, is able to completely take over the longitudinal control task from the driver, although it is unlikely to be able to do so in all circumstances, it will require the driver to resume control if the software runs into difficulty, and it still requires a human driver at all times to steer.

LEVEL 3: CONDITIONAL AUTOMATION
The automated features in these cars are able to take full responsibility for the driving task, but only in specific circumstances. Level 3 autonomous vehicles could, for example, drive long distances on a highway without any human intervention. Level 3 vehicles still require human supervision at all times, however, as the car's software may require them to take over at short notice if new circumstances arise, such as changing weather or road conditions.

LEVEL 4: FULL AUTOMATION
A fully autonomous car can handle all aspects of the driving task without ever needing a human driver to take over. These kinds of systems, however, could still be restricted to a particular location, type of use, or condition. They might, for example, only be able to function at low speed in a local neighbourhood during daytime in the summer.

LEVEL 5: FULL AND UNRESTRCICTED AUTOMATION
A fully autonomous car that can handle all aspects of the driving task, including driving without a human present at all, in all locations, conditions, and situations. These cars would be one hundred percent independent of any human intervention or guidance.

It would be too cumbersome for this report to discuss each of these levels in detail, particularly as some of them are roughly the same from the perspective of environmental harms and benefits. The level of automation, however, is a useful top-level classification for autonomous vehicle scenarios. This paper will therefore sort the discussion of the impacts of autonomous vehicles into three categories.

1. **LIMITED AUTOMATION.** This includes Levels 1, 2, and 3, as described in **BOX 1.** The climate benefits from these vehicles mainly stem from incremental efficiency improvements enabled by autonomous technology. The potential harms are mainly related to the rebound effect.

2. **FULL AUTOMATION.** This includes Level 4, and some Level 5, vehicles, which function fully autonomously but which require at least one human occupant. These vehicles could radically change how people think about and approach car travel, which could lead to cascading changes in the mobility system with profound environmental consequences.

3. **FULL AUTONOMY.** This includes Level 4 and 5 cars which, due not just to their technical design but also to legal developments, can drive themselves without any human presence or guidance whatsoever. This scenario involves the biggest potential changes, ranging from efficient electric micro-taxis to mass use of private, (and in the absence of internal combustion engine phase out, even gasoline-powered) autonomous vehicles which could travel long distances unoccupied.

These categories are designed primarily for methodological expediency, allowing a grouping of different potential outcomes. The logic behind them is therefore somewhat ad-hoc. Unlike the five-point scale mentioned in **BOX 1**, which reflects only autonomous car technology, these scenarios are sorted more in terms of what they imply for the usage of autonomous vehicles. This is shaped in large part by the technology, and indeed the difference between Scenarios 1 and 2 is mainly one of technical capabilities. The difference between Scenarios 2 and 3, however, includes not just technical differences, but also legal and commercial developments. It is important to make a distinction between full automation and full autonomy because, the potential for cars to drive around empty entails some of the most radical potential outcomes of autonomous car technology, and therefore deserves its own separate treatment.

These three descriptions capture not only the possible outcomes of autonomous technology, but also the steps that the technology is likely to go through as car and tech companies pursue fully independent autonomous vehicles. They therefore have an important relationship: use patterns established for Level 3 autonomous vehicles, for example, might remain locked-in after technology enabling Levels 4 and 5 autonomy is developed. The benefits and harms of these forms of autonomy also compound. The efficiency gains from Level 1 autonomous vehicles, for example, will likely still be present once the technology reaches Level 5, unless some development resulting from higher-level automation wipes them out.

2 SCENARIO 1: LIMITED AUTOMATION

These are the cars in which the driver must remain present and keep at least some attention on the task of driving. They include vehicles equipped with adaptive cruise control and lane-keeping assist features that are already available, as well as future vehicles that still require the driver to intervene if the software gets confused, makes a mistake, or reaches the limit of its capabilities. Cars such as these are likely to remain the dominant form of autonomous technology for some time to come, including the critical few decades in which the bulk of carbon abatement must occur. [5], [16] There is massive uncertainty on this point, however, with some optimistic predictions saying that fully autonomous vehicles could be on the market by the early 2020s, [1], and others saying that they might not appear until the latter decades of the twenty-first century. [17]

2.1 Efficiency Improvements

Vehicles with driver assistance features can bring about incremental gains both to the efficiency of vehicles (i.e. the energy required to drive a given distance), and to the efficiency of the road system (i.e. the number of vehicles that can pass through a given stretch of road in a set time [18]). These all have their own various uncertainties and potential environmental impacts:

- **TRAFFIC SMOOTHING:** Computer models have found that driver assistance technology, and in particular adaptive cruise control (or the more advanced cooperative adaptive cruise control, in which cars communicate with each other in order to facilitate more efficient flow), can radically reduce traffic congestion and the emissions it causes. [19]–[21]

- **ECO-DRIVING:** More efficient driving patterns, with smooth acceleration and deceleration, would reduce the per-kilometer energy consumption of automobiles. Estimates for exactly how much this would impact fuel economy vary widely, [18], [22]–[25] ranging from marginal reductions in fuel consumption as low as 2.9 percent [26] to a 45 percent across-the-board reduction in the energy requirements of transportation. [27]

- **PLATOONING:** Computer models and physical experiments, both of which have focused the most attention on transport trucks, have found that vehicles following closely behind each other can achieve significant fuel savings by reducing air resistance. The reduction in fuel consumption this would bring about is commonly predicted to be less than 15 percent, [28]–[30] and potentially as low as 4.3 percent, although at least one outlier report predicts fuel consumption reductions of as much as 50 percent. [31]

When traffic smoothing, eco-driving, and platooning are combined, the resulting energy savings per vehicle-kilometer travelled could be around 20 percent. [14] There are, however, some human factors which might make it difficult to get the most out of these features (see **SECTION 2.3**).

2.2 Safety Gains and Vehicle Design Changes

Another category of gains from autonomous vehicle technology has to do with safety. The common claim, which has been backed-up by the track record of autonomous vehicles[1] is that they are safer than human drivers, and that the mass adoption of features such as collision radar and avoidance, lane-keeping assistance, and fully autonomous driving will result in not just fewer road deaths, but also several important knock-on effects that could influence car design and reduce energy consumption. [6], [14], [33], [34] This is a core component of "light-weighting": many analysts argue that safer cars will become lighter and therefore more efficient by removing safety features such as airbags and crumple zones.

There are, however, some problems with the basic idea that Level 1, 2, and 3 autonomous vehicles will improve safety on the highways. The first problem is behavioural adaptations. Research on both autonomous vehicles and other forms of autonomous technology finds that people adjust their awareness level and driving habits to autonomous safety technologies, and drive more unsafely as a response to the greater feeling of security that those technologies provide. [35]–[38] A similar issue is associated with the handover of Level 3 autonomous vehicles from the autonomous driving system to the human driver. The human driver may have become distracted during the time that the car was driving itself, and therefore might be unable to assume control safely, particularly on short notice. This could lead to an increase in the accident rate at Level 3 automation. [39]–[45] These vehicles could also be used inappropriately by people who are intoxicated, or who lack drivers licences: these groups would need Level 4 or 5 autonomous vehicles to be able to use cars independently (see **SECTION 4**). [46] Level 3 automation also poses issues for the training of new drivers, who might not get enough practice driving, and who thus might be unable to cope with an emergency when the car hands control over to them. [47]

Another uncertainty is how policy and car design would respond to a radical decrease in the accident rate. How much would the accident rate have to decline for motorists or politicians to be comfortable removing airbags or seatbelts? Would this ever be a politically viable proposal, given the blowback that would occur after even one road fatality that could have been avoided if the laws had not been softened? Even if politicians were comfortable taking the political risk of loosening vehicle safety regulations, would car companies take the commercial risk of designing cars with reduced protection for their occupants? Would the travelling public be comfortable buying these vehicles? If these safety features were removed, would car manufacturers replace them with other heavy features? These are complex political and commercial questions which are difficult to test, although perhaps historical comparisons could help us better predict their outcomes.

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1 Level-3 autonomous vehicles have only caused one fatality at time of writing, despite having been tested on city streets for several years now. [32]

If safety improvements do ultimately permit light-weighting, the gains are likely to be marginal: Analysts predict that they will result in improvements to fuel economy ranging from 4.6 to 11 percent. [6], [48]

2.3 Public Acceptability

Much of the research on platooning, eco-driving, and traffic smoothing finds that the benefits in terms of reduced traffic congestion and more energy-efficient driving patterns only materialise when two conditions are met. Firstly, the vast majority of cars on the road must be driven autonomously rather than by human drivers. [5], [49]–[51] Secondly, these cars should be networked together, sharing information and instructions, not just with each other but also with networked computer systems connected to the road itself—especially at intersections. [20], [29], [52]

The realisation of these requirements will be contentious. Eco-driving and traffic smoothing, for one thing, might conflict with the emotional experience of driving—something that many motorists value, and that a dedicated "hard core" of drivers already sees as a reason to avoid autonomous technology altogether. [44], [53]–[55] Another important concern is privacy: networked vehicles would produce a lot of data that could be harvested by governments or private companies. Surveys measuring the public acceptability of autonomous vehicles frequently find privacy to be one of the biggest public concerns associated with them. [54], [56]–[58] Finally, this kind of system could lead to increase economic inequality. Not only are autonomous cars likely to be considerably more expensive than manually-driven cars due to the computer hardware and sensor systems they require, but there are also already serious proposals for automated intersection controlling software that would require motorists to "bid" real currency for spaces in an intersection—a system which would explicitly prioritise wealthier motorists over poorer ones. [59]–[62] These potential objections to an autonomous road transportation system could undermine many of the efficiency gains promised by Levels 1, 2, and 3 automation. Not only would a group of motorists insisting on driving their cars manually undermine the efficiency gains of the system as a whole; they would also form a political bloc that would oppose dedicated autonomous vehicle infrastructure that would help maximise these efficiency gains.

If these objections are overcome, then driver assistance technology could bring about improvements in vehicle efficiency per kilometer travelled, which most researchers on the subject estimate to be between 1 and 5 percent, [14], [63] although Li et al's [64] estimate puts it at 15 percent. If these objections are not overcome, then the efficiency gains from this technology are likely to be marginal.

2.4 Rebound Effects

Assuming that driver assistance technologies do lead to reductions in congestion and to more efficient driving, there is a further question: will these efficiency gains stand, or will they result in more driving, which would in turn generate increased emissions? Several analyses have predicted that reduced congestion and fuel costs induce people to drive more, to live further from work, and to take longer road trips. [5], [13], [58], [65]–[68] Smith [69, p. 1401] compares the impacts of autonomous vehicles to those of road building in the middle part of the twentieth century—a development which was expected to radically reduce congestion, but which ultimately wound up increasing it due to the phenomenon of induced demand: "'Today we are well underway to a solution to the traffic problem.' That claim, made by Robert Moses in 1948, is as true today as it was then. Which is to say, not at all."

Safety improvements can create an additional rebound effect. If they can enable cars with fewer safety features, then they could also presumably allow faster driving, on the grounds that these higher speeds are safer when handled by autonomous vehicles. There might be pressure to revise traffic laws accordingly. This could result in as much as a 30 percent increase in the energy consumed per vehicle-kilometer travelled. [70]

If the pattern of induced demand that has historically been true for road expansions remains true for autonomous vehicles (which effectively promise a form of virtual road expansion), then the result could be that autonomous vehicles increase total vehicle-kilometers travelled by car, traffic congestion, and fuel consumption. Even if they do not increase these variables, rebound effects and induced demand could blunt the positive effects of efficiency gains that come from automation. These rebound effects could induce an increase in travel demand of between 3 and 27 percent. [65]

2.5 Conclusion

FIGURE 3 shows all the unanswered questions about the autonomous features discussed in this section, outlining for each one which outcome is the most likely, as well as the likely environmental consequences of different outcomes. It should be noted at the outset that this figure contains several major simplifications. For example, it represents the different pathways of autonomous vehicles as dichotomous choices. In reality most of these branching points include a spectrum of different outcomes, but this is difficult to represent graphically. The thicker arrows denoting more probable outcomes, however, still apply to non-dichotomous choices, indicating a clear pull towards one or the other sides of the spectrum of possible outcomes. As discussed in the introduction, these diagrams only trace the consequences of various scenarios specifically for carbon emissions.

The pathways most likely to occur in the absence of targeted intervention generally result in little change to the status quo, with the only major impacts being rebound and induced demand effects that might increase the total number of vehicle-kilometers travelled. All other impacts are marginal, and, in many cases, unlikely. It is not impossible that driver assistance, partial automation, and conditional automation could enable incremental improvements in the energy consumption and fossil fuel consumption associated with personal mobility, resulting in total potential energy savings of up to 50 percent per vehicle-kilometer travelled [6], [14], [48]. If, on the other hand, these developments lead to substantial rebound effects, then they could lead to little net change, or even to an increase in the energy used by personal mobility. Unfortunately, the preponderance of evidence suggests that rebound effects are likely. Thus, the moderate changes made possible by Levels 1, 2, and 3 automation will not on their own bring about the radical emission reduction needed to keep the global temperature increase below 2 degrees Celsius, much less 1.5.

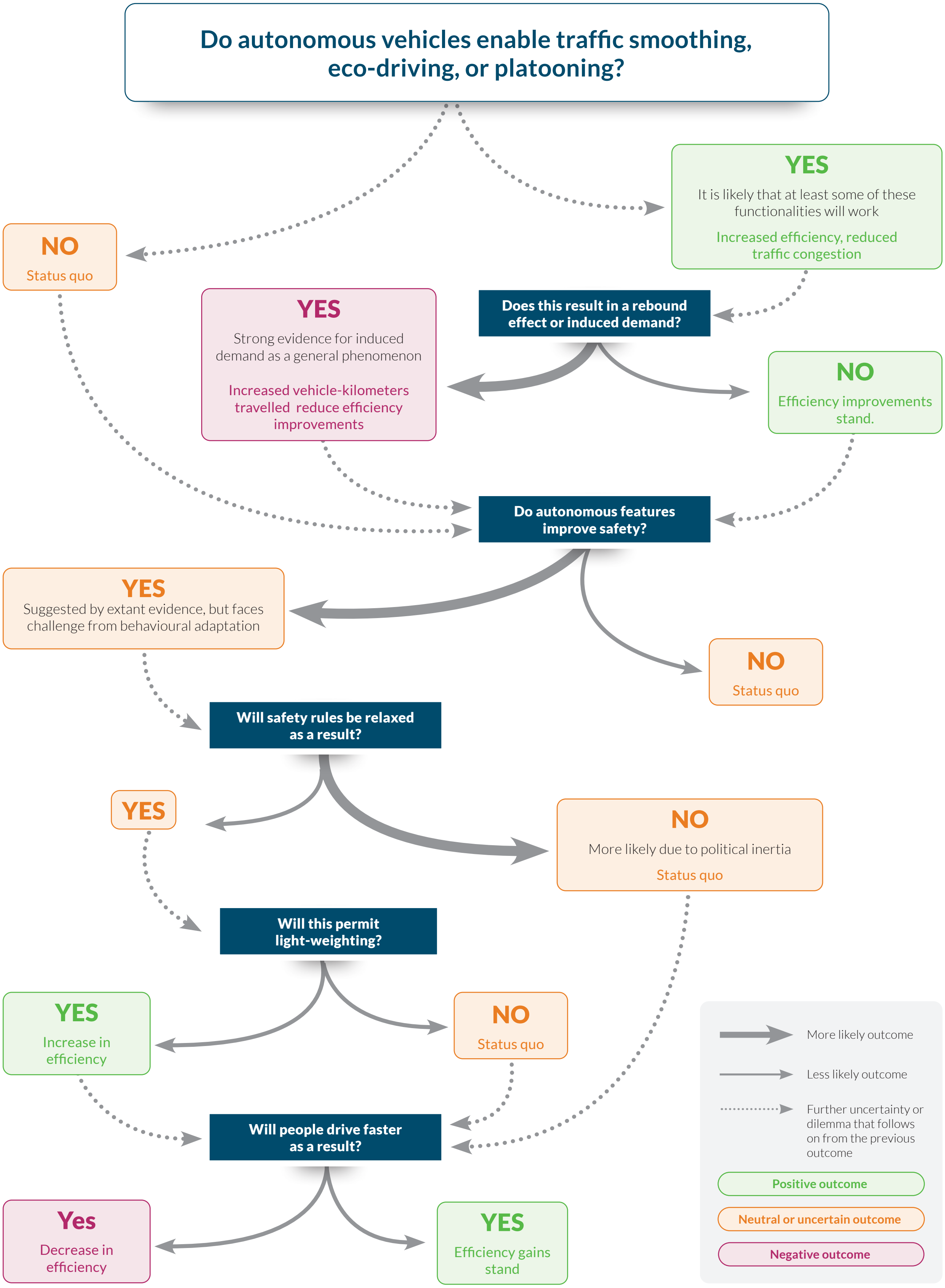

FIGURE 3. Flow chart summarising the possible outcomes in this scenario. Larger arrows indicate more likely outcomes, while dotted arrows indicate further dilemmas that occur as the result of particular outcomes. Italicised text describes results in terms of sustainability outcomes.

3 SCENARIO 2: FULL AUTOMATION

This scenario describes cars which are occupied by a human, who is responsible for setting the car's destination, and possibly has a role in some ancillary tasks such as navigation, but who does not need to monitor the driving task at all. These cars can handle all weather, traffic, and road conditions they might encounter,[2] and also respond to emergencies independently. This has far more dramatic potential impacts than the scenario described in **SECTION 2**. If motorists are no longer responsible for driving the car, or even monitoring the activities of the car as it drives itself, then it will completely change the economic, social, and psychological calculus of driving. This could lead to massive changes in people's patterns of travel. These vehicles would expand on the potential gains in efficiency, congestion mitigation, and safety described in the section above.

3.1 Rights to the Road

Fully autonomous vehicles will deepen the uncertainty about public acceptability of self-driving technology as discussed in **SECTION 2.3**, to the point that it winds up being manual cars that face challenges to their rights to use public roads. The ability of fully autonomous vehicles to drive themselves safely and efficiently in all situations might lead to bans of non-autonomous cars in some locations. [71] Doing so would lead to substantial gains in efficiency, as roads dominated only by autonomous vehicles could travel efficiently and smoothly, with cars whisking safely past each other at intersections with no need for red or green lights. As discussed above, this would require a big investment of political capital, and would face major obstacles from "hard-core" motorists, as well as from people concerned with privacy, autonomy, and economic inequality. One solution to this would be to have dedicated autonomous-only lanes on roads, while leaving the other lanes open for manual driving. This, however, would eliminate the efficiency benefits of autonomous vehicles at intersections, and would also require expensive infrastructural investments.

If these obstacles are not overcome, and autonomous vehicles wind up sharing the road with their manually-driven counterparts, then this is likely to reduce the efficiency gains they offer substantially, for the same reasons discussed in **SECTION 2.3.** [50] There is, however, a potential environmental harm on the other side of this equation as well: if infrastructure is reserved for autonomous vehicles, then this could also require closing it off to cyclists and pedestrians. Indeed,

2 Some Level 4 vehicles might be restricted to driving at certain times or places, such as a local neighbourhood or a time of day. See **Box 1** in Section 1.2.

these might be the first non-autonomous modes of travel to be eliminated from the roads, as autonomous cars have much more difficulty recognising pedestrians and cyclists than they do recognising other cars. [13], [71]–[75] Autonomous-only roads could therefore reduce the modal share of walking and cycling, thereby increasing vehicle-kilometers travelled. Whether this increase would be offset by the efficiency gains of autonomous vehicles (see **SECTION 2.1**) is a difficult question to answer.

3.2 Rebound Effects - Part 2

If fully autonomous vehicles are adopted en masse in a way that leads to big reductions in traffic congestion and increases in efficiency, then the next question concerns rebound effects, which in the area of road transportation tend to appear whenever traffic congestion is reduced, as people take advantage of faster roads to travel longer distances [15]. A road populated one hundred percent by cars using cooperative adaptive cruise control would increase the number of vehicles that can pass through it per hour by 102 percent [50]. Would this reduction in congestion encourage people to drive more? Lots of the evidence suggests that the answer is yes [13], [66]–[69], [76]–[83]. Induced demand is a very well-understood principle of traffic engineering: If you make it easier for people to drive somewhere (most often by building additional traffic lanes), then more people will choose to do so [15]. It would be very surprising if the traffic efficiency gains from autonomous vehicles do not lead to this outcome.

One of the specific ways that this increase in vehicle-kilometers travelled could happen is by people choosing to move further away from work in search of larger properties or cheaper mortgages, because less congested roads will enable them to cover a longer distance in the same commute time [76]. There is some debate as to whether this would occur. One survey of Texans found that most don't expect to move further from downtown if they buy autonomous vehicles [84]. Some analysts predict a radical increase in sprawl, however. Laberteaux [79] argues that historically, every increase in the speed and convenience of personal mobility has led to increased urban sprawl, and that in the United States, people's choices of housing location is driven mainly by cost and school quality, both of which tend to be better in the suburbs. This could create a powerful incentive to take advantage of autonomous vehicles by moving further away from the city, and therefore commuting further.

If these rebound effects do occur, then it is possible that the efficiency gains from autonomous vehicles will be washed out by an increase in total travel volume. While conservative estimates suggest this could amount to a 3 percent increase in total passenger vehicle-kilometers travelled [65], it could also see increases of up to 89 percent [14]. If these rebound effects do not occur, then the transportation system could see energy efficiency gains of around 48 percent. [14], [18]

3.3 Cultures and Practices

For many people, a car is more than just a means of travel. Driving has important emotional and cultural resonances, which have been widely documented by sociologists and anthropologists. [85]–[89] As discussed in **SECTIONS 2.3** and **3.2**, this might be an obstacle to any scheme to restrict roads to autonomous vehicles. But this emotional affinity for driving also influences the way cars are designed. The culture of recreational driving, for example, was a major reason why gasoline-powered cars won out over early electric vehicles. [90] The cultural affinity for driving has led car manufacturers to design and sell cars that give the motorist the best driving experience. References to aggressive handling, fast acceleration, and high top speeds are a staple of car advertising, which often depicts cars more as status objects or toys than as utilitarian conveyances.

Autonomous vehicles, if widely adopted, might change this. Once the driver is no longer directly connected to the experience of driving, the emotional incentive to buy a fast car with aggressive handling would weaken. Indeed, such a car might be less appealing for an occupant trying to sleep or work onboard [91], and could also induce car-sickness [92]. Passengers on trains, planes, and buses don't typically appreciate aggressive acceleration, and there is no reason why the occupants of autonomous vehicles would be any different. If this does result in changes to vehicle design, the likely outcome would be that manufacturers and car owners would prioritise efficiency and comfort over high performance. This could have profound effects on the energy demand from cars, as high-performance engines tend to be less fuel-efficient. If we go back to the acceleration capabilities that predominated in the 1980s, vehicle fuel efficiency could be increased by 23 percent [14]. This would only be relevant if the cars continued to be powered by gasoline, however. The impact of this effect on electric cars has not been thoroughly investigated.

3.4 Multitasking

The ability to multitask while travelling has been promoted as one of the greatest personal benefits of autonomous vehicles, enabling people to spend time with family, work, play, sleep, or simply relax while the car drives itself to the destination. There are some uncertainties about what this would mean in practice. Multitasking is often promoted as a way to recoup the value of time lost to travel, which would imply that people would spend at least some of their time in autonomous vehicles working [58], [93], [94]. Most potential users of autonomous vehicles, however, say that they would rather use the extra time to relax [95].

There are also technical uncertainties. Autonomous vehicles could create more motion sickness than manually-driven cars, which would make some activities difficult to perform onboard [92]. In order to permit effective multitasking, autonomous vehicles would have to accelerate, decelerate, and corner in ways more similar to a train than to a car [91]. This would put a damper on traffic efficiency, effectively washing out the congestion reductions that are often promoted as a key benefit of autonomous vehicles (see **SECTIONS 2.1** and **3.2**). If the choice is between traffic efficiency and multitasking there is some evidence that many motorists would choose the latter. A 2016 Boston Consulting Group study [96, p. 4] found that "increased productivity is the reason many drivers cite when they say they would consider buying or using an AV." It is also possible that the trade-off between traffic efficiency and multitasking could be managed on a vehicle-by-vehicle basis, with richer travellers paying extra for an autonomous road network that delivers a smooth and speedy ride, while those who cannot pay the premium must accept a ride that is more congested, less comfortable, or both (see the discussion of inequality in **SECTION 2.3**).

If multitasking does become commonplace, then it would likely have a net-negative impact on the environmental performance of autonomous vehicles. Firstly, it could cause people to reduce the value they ascribe to travel time. A two-hour commute in which you can work, sleep, or watch TV has less of a personal time cost than one in which you must keep your eyes on the road. This would add to the rebound effects discussed above, thereby increasing the total vehicle-kilometers travelled. [83], [97] The second way in which multitasking could increase the environmental impact of the transportation system would be to change the design of cars to better accommodate mobile offices, bedrooms, or living rooms. [34] There is already movement in this direction from car companies. Renault's SYMBIOZ concept proposes a car that parks right in its owner's living room (**FIGURE 4**). Their marketing description of the concept boasts that this car would be "no longer separate from your living space. It has been designed as a genuine extension of your home … Everything is designed

FIGURE 4. Renault's Symbioz concept. [100]

FIGURE 5. Honda's LeMobi Concept. From Alter [99].

so that you feel like you never leave your lounge while you are travelling. And when you do stay at home, your car becomes an additional room for your house." [98] Honda's LeMobi concept is similar: it integrates an autonomous vehicle into the very structure of a house (**FIGURE 5**). [99]

There is one way in which multitasking could reduce emissions. If the ride is comfortable enough, and the car is equipped with a bed, then overnight autonomous trips could substitute for short-and-middle-distance aviation. Since aviation emits more greenhouse gases per passenger-kilometer than road transportation, this would achieve a net reduction in emissions. At least one survey has shown traveller interest in this idea [101]. This scenario, however, would require both a very comfortable ride, and fairly large vehicles, which would result in increases to emissions per vehicle-kilometer travelled, as discussed above. It could also result in an increase in the total number of vehicle-kilometers travelled, as people take advantage of the additional comfortable mobility to take trips they might not otherwise take. Fully estimating the impact of this would require an assessment of aviation emissions, which is beyond the scope of this paper.

Multitasking is a very likely application of fully autonomous vehicles, which could result in major increases, both to the total distance travelled and to the energy consumed per vehicle-kilometer travelled. Estimates of the increase in total vehicle-kilometers travelled range from 20 and 160 percent [48], while new features could increase the energy-intensity of every vehicle-kilometer travelled by 10 percent [14]. This could be offset by a reduction in short-and mid-haul aviation, although it is difficult to estimate how many air-miles would actually be averted, since this represents a major and unpredictable change in people's travel habits.

3.5 Conclusion

FIGURE 6 shows that this scenario is more complex than the scenario described in **SECTION 2.1**, with many more dilemmas, and many more possible outcomes. As in the previous scenario, however, rebounds and induced demand remain a major potential environmental problem with autonomous vehicles. Multitasking in particular could lead to larger and possibly less efficient cars that are likely to travel longer distances on a daily basis. This is compounded by the fact that all the rebound and induced demand effects described in Scenario 1 would also apply here. This scenario is therefore also double-edged sword. The good news is that the evidence reviewed here suggests that several important efficiency improvements to automobile transportation could result from the wide adoption of autonomous vehicles. The bad news is that this might come with a significant increase in total vehicle-kilometers travelled, while also leading to a predominance of larger vehicles what could wash out the efficiency gains.

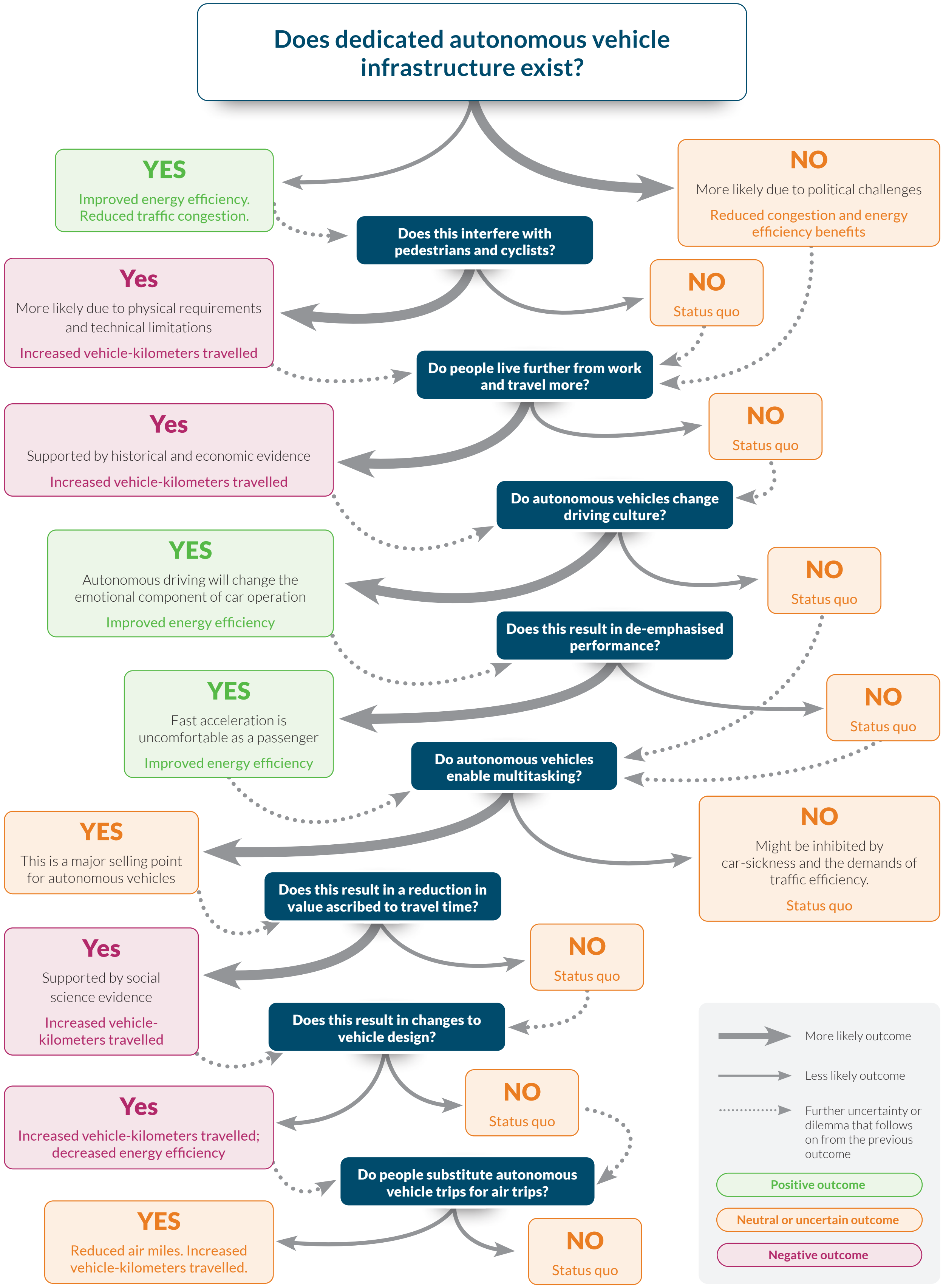

FIGURE 6. Flow chart describing possible outcomes from this scenario. Larger arrows indicate more likely outcomes, while dotted arrows indicate further dilemmas that occur as the result of particular outcomes. Italicised text describes results in terms of sustainability outcomes.

4 SCENARIO 3: FULL AUTONOMY

Autonomous vehicles could potentially travel with no human occupant at all. These vehicles would not only be able to handle the entire driving task, but would also to be able to independently plot and follow routes through cities. They could provide independent mobility for children or people with disabilities, while the cars could pick up packages and groceries, park, cruise for taxi passengers, or return home after a commute, all independent of any direct human guidance. This class of autonomous vehicles enables the most radical changes to the transportation system. They could be implemented as a system of zero-carbon electric autonomous taxis that disrupts the institution of car ownership, leading to an entirely new and potentially more sustainable mobility system. They might also be implemented as a massive fleet of private autonomous vehicles still powered by gasoline, which could significantly increase carbon emissions.

4.1 Vehicle Ownership Models

This is perhaps the most important and hotly contested question in scholarship on autonomous vehicles, with major implications for their impact not just on carbon emissions, but also on urban congestion, social equality, and safety. The essence of the dilemma is whether autonomous vehicles will be used collectively as part of a system of shared self-driving taxis, collective "cybercars," or autonomous buses; [51] or operated by individual car owners.

Most of the optimistic analyses of autonomous' vehicles impacts on carbon emissions pin their hopes on the former possibility. These analyses typically predict that autonomous taxis, since they do not need to pay drivers, will not only be cheaper per passenger-kilometer than conventional taxis or ride-sharing services, but also that they will financially out-compete even private vehicles. At least three major reports on the future of transportation have argued in favour of this outcome. [1], [2], [102] These studies typically model the various factors influencing the cost of a trip in an autonomous taxi, and then use that projected per-kilometer cost to model competition with conventional private vehicles. There is academic literature backing up this thesis. Some of the modelling exercises published in academic journals [103-105] show more interest in riding in autonomous vehicles than in buying them, and there is some evidence that points to the acceptability of shared autonomous shuttles, [106] although people in richer countries tend to be less interested.

	Estimate of cost per kilometer	Notes
Litman, 2015	$0.48-0.81	Considers cleaning costs, but not overhead.
Johnson and Walker, 2015	$0.24	Focuses on capital and operational costs. No cleaning or overhead.
Hazan et al, 2016	$0.46	Considers capital, operational costs, and overhead, but not cleaning.
Burns et al	$0.23-$0.47	Focuses on capital utilization and efficiency.
Bösch et al	$0.42-$0.57	Explicitly considers administrative overhead and cleaning.
Arbib and Seba, 2017	$0.08-$0.13	Focuses on advantages of shared autonomous vehicles over private cars, including vehicle utilization, longer lifetime mileage of cars, and cost reductions (finance, maintenance, insurance, fuel).
Dandl and Bogenberger, 2019	$0.36-$0.39	Considers capital, operational costs, and overhead, but not cleaning.
Bauer et al, 2018	$0.24-$0.50	Considers capital costs, operational costs, and administrative overhead, but not cleaning.

TABLE 1. Estimates of the cost of autonomous shared mobility. Note that in some cases units and currencies have been converted to CAD from those used in the original papers, based on exchange rates in October 2019.

	Cost per km of shared autonomous vehicles	Percentage of people willing to rely on the system entirely
Johnson and Walker, 2016	$0.81	10%
Bansal et al, 2016	$0.81	13%
Bansal and Kockelman, 2016	$0.81	7.3%
Bansal et al, 2017	$1.62	3%

TABLE 2. Willingness of survey respondents to rely entirely on shared autonomous vehicles, depending on the cost per-mile of the system. Values converted to CAD/km from other currencies and units of distance, based on currency exchange rates in October 2019.

There are reasons, however, to be suspicious of these optimistic forecasts. For one thing, the costs per kilometer might be higher than many analyses suggest, because they fail to account for expenses such as cleaning, repairs, and administrative overhead. [5], [107] Cost projections for autonomous taxis range from $0.08 per kilometer (an extremely optimistic estimate which includes no overhead, business administration, or cleaning costs), to $0.81 per kilometer (**TABLE 1**). There is more bad news when these numbers are compared with the results of surveys assessing people's willingness to give up private cars in favour of shared autonomous mobility (**TABLE 2**). Three separate surveys have found that at prices of $0.81 per kilometer,[3] fewer than 15 percent of motorists would give up their car for a shared self-driving alternative. [84], [108], [109] At $1.62 per kilometer, it would be less than 5 percent. A third survey suggests that even if the shared autonomous vehicles are completely free, a full quarter of motorists will still opt to use their own private cars (**TABLE 2**). [110]

3 Converted to Canadian dollars per kilometer from US dollars per mile, according to the exchange rate in October 2019. The figure of $0.81 CAD comes up frequently because at the time of writing it was equal to $1 USD.

One possible reason behind these findings could be the fact that people are not making a purely lowest cost economic calculation when they choose a mode of transportation. This is well-illustrated by Canadian mobility history. In the late 1970s, as the fuel crunch of the previous decade started to abate and gas prices came down again, Canadians opted for bigger and more luxurious cars rather than for reduced fuel budgets using cars of the same size. [111] This suggests that the fact that shared autonomous vehicles allow travellers to save money might not be persuasive all by itself. Much of the research shows that there are objections to shared autonomous vehicles that cannot be reduced to economic calculations. KPMG's [34, p. 25] 2013 study of autonomous vehicles finds that many people surveyed about autonomous taxis would still prefer the ready dispatchability and convenient mobile storage space offered by having their own private car in the driveway—something that shared taxis would not offer. A quote from one participant in their study illustrates this attitude well:

> **"I just kind of want my car all the time," she says. Why? She offers a couple of reasons. First and foremost, is safety: What if 'in the middle of the night...there's an emergency [and] I have to get to the hospital' she asks. Besides, her car is like her personal office with all her stuff inside. 'Like a large purse,' another female panelist interjects. "Exactly!" says Gail.**

Another participant in KPMG's study described her car as being like a mobile office. These concerns about safety, convenience, and storage space would be a big challenge for any disruptive autonomous mobility service to counter. Another challenge is mess and damage caused by passengers, which could be worse in the absence of a human driver. An autonomous taxi would have to be hardened against vandalism and mess, which would make it a less appealing to ride (**FIGURE 7**).

FIGURE 7A. A hypothetical autonomous microtransit vehicle, presented to participants in Nordhoff et al's [106] study of the acceptability of such systems.

FIGURE 7B. A hypothetical autonomous microtransit vehicle, presented to participants in Nordhoff et al's [106] study of the acceptability of such systems.

Litman [5, p. 6] describes what an autonomous taxi might be like for travelers:

> **To minimize cleaning and vandalism costs most surfaces will be stainless steel and plastic, and passengers will be monitored by security cameras, yet passengers may still encounter previous occupants' garbage, stains, and odors. There will be no drivers to help carry packages or ensure passenger safety.**

For many habitual motorists accustomed to immaculate interiors and comfortable upholstery, this would feel like a major step down. It would almost certainly make shared autonomous vehicles less competitive. There are also cultural reasons why people might reject shared autonomous taxis. First of all, there is the "hard core" of car owners, who are unlikely to like the idea of giving up the pleasure of driving or even just the satisfaction of owning a car [55], [85], [86], [112] (see **SECTIONS 2.3** and **3.3**). Even for non-car enthusiasts, empowerment concerns could work against shared autonomous vehicles, as they would be giving up direct control over their daily travel. [113]

With these considerations in mind, it is not surprising that several studies [34], [114] find that the presence of cheap shared mobility systems are more likely to make people reduce private vehicle use than to eliminate it entirely, while also showing that some people—potentially up to 15 percent according to one study [58]—would actually buy more cars! Other surveys show very little interest in eliminating private car ownership in favour of autonomous vehicles [67], [77], [95], [115], [116]. Hörl's [117] model of autonomous taxi adoption finds that a network of shared self-driving cars would only decrease private car modal share from 70 percent to 40 percent, but would cut much further into other, already-sustainable forms of transportation such as public transit and walking (see **SECTION 4.5**) (**FIGURE 8**).

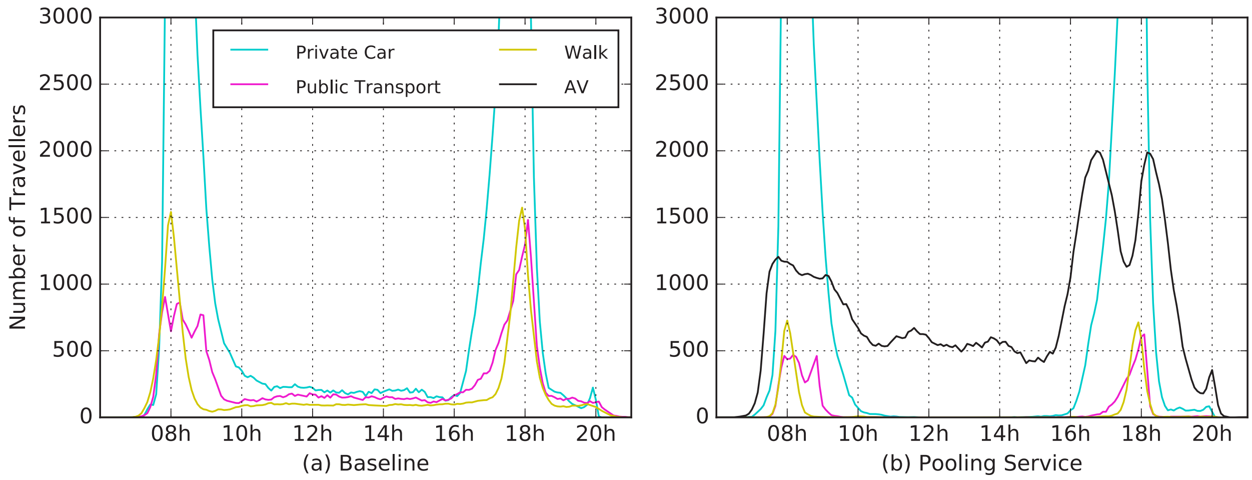

FIGURE 8. Results of Hörl's [117] agent-based model, studying the effect of an autonomous taxi service on the modal share of private cars, public transit, and walking.

There is also reason to speculate that there could be resistance to shared autonomous vehicles from the car industry, [34], [118] which needs to sell cars continuously. [119] The importance of this was illustrated by the 2008 financial crash: the slowdown in car sales resulting from the crash caused a big enough crisis in the industry that both the Canadian and American governments bailed out their auto sectors with public money. This is a difficult notion to test empirically, and public statements from car companies are inconclusive. Toyota claims it is shifting towards being a "mobility company", rather than a car company, [120] but Renault, which has developed some of the most ambitious and detailed concepts for autonomous vehicles, appears to be hedging its bets. While its "EZ-GO" concept, a front-entry autonomous electric taxi, plays into predictions of shared autonomous mobility, its Symbioz concept (see the discussion of multitasking in section 3.4) is a highly personalised private vehicle designed to erase the boundary between car and home. While it is possible that the car industry could re-orient its business model to incorporate a vastly reduced demand for vehicles, this would be a massive shift.

Unions might also reject shared autonomous mobility due to its impact on jobs in the car industry. One of the key benefits of shared autonomous mobility is that it might require a much smaller vehicle fleet for personal transportation (see Section 4.3). [121] This, however, would cause catastrophic job losses not only in the car industry, but in the many primary industries connected to it. [2], [122] Many unions (and politicians who depend on their support) might therefore prefer to avoid a transition to shared mobility altogether. As with the car companies themselves, however, this proposition is difficult to evaluate empirically.

The fact that the car industry is actively pursuing both shared autonomous mobility and private autonomous vehicles, and that large sections of the working class benefit directly from large-scale car production, suggests a future transportation system that blends both models of car ownership and use. One possible outcome of this could be that private autonomous vehicles would become status symbols—something that the upscale marketing for Renault's Symbioz concept seems intended to indicate. There is historical precedent for something similar. The early twentieth-century business model of General Motors under its CEO Alfred P. Sloan encouraged consumers to "climb the ladder", from the cheaper option to the more expensive. This proved extremely profitable. Whereas in the 1920s, General Motors encouraged car buyers to trade in their Chevrolet for a Buick, in the 2030s, Renault might encourage them to trade in their annual EZ-GO membership for a Symbioz vehicle. This would allow them to preserve their business model and maximise their vehicle sales, while still earning profits from shared autonomous mobility.

It is not possible to quantify the total impact of private and shared autonomous mobility systems at this stage of the argument, because there are many further uncertainties in both scenarios, which are explored further below. From a climate change perspective, however, shared autonomous mobility appears preferable to private self-driving vehicles.

4.2 Private Autonomous Vehicles

Academic literature assessing the prospect of private autonomous vehicles from a sustainability perspective often uses conspicuously un-academic language, including dramatic words like "dystopian", "nightmare", and even "hell." [6], [7], [14], [55] The evidence of the potential harms of this scenario is overwhelming. Private autonomous vehicles would dramatically increase the total distance travelled. They could also increase the energy consumption per vehicle-kilometer travelled, due to the changes they would engender in vehicle design. [5], [7], [65], [67]

The ways in which this would happen are diverse. First, one of the most commonly-cited benefits of fully autonomous vehicles, namely the additional accessibility they provide for children, the elderly, and the disabled, [76], [123], [124] would generate considerable additional traffic, with estimates suggesting a 16 to 40 percent increase in total vehicle-kilometers travelled. [76], [125] Multitasking (as discussed in Section 3.4) is another major potential contributor to this effect, while also potentially contributing to the development of less efficient vehicles as cars get larger to enable more onboard activities. [65], [66], [76], [77], [79], [83] The most radical way in which vehicles that can drive themselves independently would increase the total vehicle-kilometers travelled, however, is through empty vehicle-kilometers, which, for example, might occur when people send their cars home, or have them circle the block, rather than parking them. Owners of private autonomous vehicles might even send them to do errands by themselves, facilitated by new businesses designed to deliver products directly to autonomous vehicles. One experiment, which gave people personal chauffeurs to simulate fully autonomous vehicles, found that all participants in the study increased the vehicle-kilometers they travelled considerably. [78]

There are some potentially positive implications of private autonomous vehicles, although these tend to get washed out by the increase in vehicle-kilometers travelled. One interesting point here is the implications for parking. If autonomous vehicles (whether private or shared) can simply drive out of the city rather than parking, this will have two important beneficial effects. Firstly: It will reduce traffic congestion. In some cities, up to 74 percent of traffic could be created by motorists cruising for parking. [126] Eliminating this source of vehicle-kilometers would considerably improve inner-city traffic efficiency. Secondly, the removal of the need to build urban parking lots will free up urban land for other uses. This could help rejuvenate urban neighbourhoods, potentially bringing some goods and services closer to their residents, or creating more homes, whose occupants will be less likely to need cars. Yet it is unclear whether these outcomes could outweigh the harms of increased vehicle use.

The other environmental benefit that could materialize from these kinds of autonomous vehicles is the potential substitution of air-miles as discussed in section 3.4. This, however, would have difficulty making a big dent in the additional emissions caused by induced demand and empty vehicle-kilometers. Most models of private autonomous vehicle use predict radical increases in vehicle-kilometers travelled, in energy consumed per vehicle-kilometer travelled, and in greenhouse gas emissions from the personal mobility sector. Private autonomous vehicles could more than triple both energy consumption and vehicle-kilometers travelled by private cars (see **FIGURE 2** in the introduction).

4.3 Shared Autonomous Vehicles

Given the discussion in the section above, it is unsurprising that every scenario that predicts a net environmental benefit for autonomous vehicles also predicts that they will be shared as part of a mobility-as-a-service system. This, however, is not a magic bullet. For a system of shared autonomous vehicles to have a meaningful impact on greenhouse gas emissions from personal mobility, it would need to replace a large percentage of private vehicle-kilometers travelled, while also not reducing the modal share of public transit, cycling, or walking.[4]

That being said, shared autonomous mobility could have major benefits. If the technology is available and sufficiently widespread, electric autonomous taxis could radically decrease greenhouse gas emissions by 2030, [3] particularly due to 'right-sizing'. Autonomous taxi companies would have a financial incentive to fit the vehicle to the passenger, using small, cheap, one-or-two-seat vehicles for individual riders. But this outcome is not certain. For one thing, it cuts against the car industry's business model, which benefits from a small number of standard, multipurpose designs to maximise economies of scale. [119], [127] The operating costs of small vehicles, furthermore, are only slightly

4 Even with rapid uptake of autonomous electric vehicles, the total vehicle-kilometers travelled still needs to decrease.

lower than those of vans or midsized cars, which have more flexibility. Shared fleet operators might therefore opt for a one-size-fits-all solution, rather than risk having a car arrive and be unable to carry the passengers hoping to use it. [107] If right-sizing occurs despite these obstacles, it could result in energy savings of between 30 and 50 percent per vehicle-kilometer travelled. [3], [48]

A shared autonomous vehicle system would also mean a much smaller total number of cars on the streets. One model of a shared autonomous mobility system in Singapore found that such a system could meet that city's personal mobility needs with a vehicle fleet one third the size of the current one. [121] This would considerably reduce the embodied emissions resulting from new car production. In practice, however, this outcome could be extremely messy, both for the car industry and for the huge numbers of people who depend on it for employment. This would likely cause political resistance to shared mobility (see Section 4.1) If this resistance was overcome, and if it did not lead to additional rebound effects (discussed below) a shared autonomous taxi system could lead to reductions of up to 94 percent in the transportation system's total carbon emissions. [3] Shared autonomous vehicles would also benefit from the positive implications of autonomous travel for parking, as discussed in **SECTION 4.2**.

4.4 Ride-Sharing

The first question about shared autonomous vehicles is whether they are run like taxis, with individual travellers (or groups who all know each other) travelling from a single origin to a single destination, or like miniature buses, with different people, most of whom will be strangers, getting on and off at different points.

The most plausible way that autonomous taxis would reduce the total vehicle-kilometers travelled is by shared rides. Shared vehicles would actually increase the total vehicle-kilometers travelled, due to autonomous taxis circling to look for new passengers or driving unoccupied to a nearby parking lot while not in use. [68], [78], [80], [83] This effect has already been observed in practice with services such as Uber and Lyft, which actively recommend that their drivers circle to look for fares. This has already increased urban congestion. [128]–[131] It is likely that adding inexpensive autonomous vehicles to this scenario would make the situation worse. Many models of shared autonomous mobility thus predict that it would bring about an increase in total vehicle-kilometers travelled. [48], [132]

The solution to this problem is to instead opt for a shared-ride model, in which the autonomous vehicle operates more like a micro-transit vehicle and is therefore rarely if ever completely unoccupied. This model of autonomous mobility was acceptable to many respondents of one survey, although more so in developing countries than developed ones.[5] [106] Most of the social science research on

5 This is important, because residents of developed countries are responsible for a much higher proportion of global carbon emissions than residents of developing countries.

this kind of scenario, however, raises serious questions about its viability. There are, for one thing, major safety issues entailed in sharing an enclosed space with strangers, without the benefit or a bus driver or other human presence to ensure good behaviour. There are also privacy concerns. [96] The present-day manned mobility as a service provided by Uber has already given credence to these fears, with some reports of Uber drivers sexually assaulting their passengers. [133] One potential solution to these issues is to include security features in the shared shuttles, [5] including "private, glass-walled compartments, cameras, and other safety features." [96, p. 7] This, however, would make these autonomous taxis resemble the back seat of a police cruiser, which might make them less appealing for travellers. Shared vehicles might also conflict with the much-hyped ability to multitask while travelling (see **SECTION 3.4**). A shared shuttle would probably not be built with a desk, bed, or "mobile living room", as it would have to maximise passenger space.

There is one possible scenario in which shared vehicles, rather than shared rides, might decrease the total vehicle-kilometers travelled. This would happen if people, having abandoned private car ownership, become more likely to opt for non-car transportation options rather than calling an autonomous taxi. Social science research finds that car ownership is the most reliable predictor of car use: once people have a car in the driveway, they are likely to unconsciously choose to use it for most of their trips, even for short trips for which a car is not necessary. [134] Calling an autonomous taxi, however, might not trigger such a reflex, particularly since the financial costs it imposes are visible to the traveller with every trip. People reliant on this system might thus choose to walk, cycle, or use transit for many trips. This could result in a rejuvenation of local neighbourhoods as more businesses seek to capture this increased foot-traffic. This might be further encouraged by the parking benefits of autonomous vehicles, which would free up parking lots to be converted into denser housing or more local businesses. These feedback effects would reduce reliance on motor vehicles further still. In this way, autonomous taxis could sow the seeds of their own gradual decline. This is a utopian scenario: There is no serious empirical research that suggests such an outcome.[6] It is therefore not a strong argument in favour of the environmental virtues of autonomous taxis, although it might be as a direction to try and push the system if autonomous taxis emerge as a dominant form of mobility.

4.5 Impacts on Public Transit

Because shared autonomous vehicles will only be an environmental boon if they decrease total vehicle-kilometers travelled, it is important to consider their relationship not only to private vehicles (whether autonomous or manually-driven), but also to other forms of sustainable mobility such as public transit, cycling, and walking. There will be pressure to reduce total vehicle-kilometers travelled

6 This could be because such a hypothesis would be very different to test empirically as long as fossil fuels are associated in any way with mobility, whether they are consumed in the car's engine, in the power plant that provides an electric car's energy, or in the factory that produced the car. This means that even in an electric autonomous taxi scenario, there will still be a strong case to shift passengers from these vehicles to public transit and active travel, rather than vice-versa. In the most optimistic scenario, autonomous vehicles would have a synergistic relationship with these forms of mobility, providing a last-mile solution for public transit and enabling elderly people, people with disabilities, and people carrying heavy loads to travel independently and efficiently in a nearly car-free city [135]. This would increase transit ridership while also decreasing both total vehicle-kilometers travelled and total carbon emissions from personal mobility. As an additional bonus, a smaller number of large transit vehicles, such as buses and trains, might be easier to electrify than millions of private vehicles.

There are several academic studies that support such a scenario. Smith [16] might be the most convincing. He argues that due to persistent technical problems, autonomous vehicles are unlikely to be able to drive safely at full traffic speeds any time soon. An easy solution to this is to simply limit the speeds of autonomous vehicles, forcing them to be slow enough that a collision is unlikely to do very much damage:

> **While a two-ton car might not drive itself unsupervised through a city at 30 miles per hour any time soon, some truly driverless systems that are low-speed, low-mass, geographically restricted, and centrally supervised are actually nearing commercialization. These simplifying constraints help reduce both the risk and the broader uncertainty inherent in deployment: For most irregular occurrences, the system might achieve a minimal risk condition simply by stopping the vehicle and requesting assistance.** [16, p. 87]

Other scholars have made similar suggestions, proposing such vehicles as last-mile solutions for rail travel [96], [136], [137], or as a way to provide good, economical public transit coverage in places and at times when demand is low [138]. Eppercht et al [115] suggest building a living lab, possibly in a disused industrial area, to study this model and to build user acceptability for it. Existing experiments with manned micro-transit have a persistent problem with passenger numbers that are too low to pay the labour costs of driving the vehicle [139]. Making the vehicles autonomous could solve this by removing the need for a driver, thereby making these systems viable. Some European cities have already been experimenting with this. The city of Talinn, Estonia, for example, has already opened a driverless bus route, and the European Union-funded CityMobil project has provided valuable information about how autonomous shared micro-transit vehicles can function in urban environments [51], and [140].

Unfortunately, much of the scholarship on autonomous vehicles' interactions with public transit, finds that it will be more competitive than complementary [65], [67], [76], [80], [104], [107], [114]. The first line of evidence in favour of this comes from Uber and Lyft, which have already been shown to take more passengers from public transit than they do from private vehicles [130], [141], [142]. One study [68] calculates that to avoid this outcome, autonomous taxis would have to cost at least $1.33 per vehicle-kilometer.[7] This, however, would undermine these vehicles' ability to compete with private cars (see **SECTION 4.1**). If this analysis is correct, it suggests that there might not be a per-kilometer price that autonomous taxis could charge that would allow them to both compete with private cars, and to not compete with public transit. Hazan et al's [96] assessment of the threat posed by autonomous vehicles to railways finds that they will be a major competitive threat, and that the best way for railways to deal with this threat might be for railways to invest in autonomous vehicles themselves. Hörl [117] finds that shared autonomous vehicles would take far more modal share away from pedestrians and public transit than from private car use, meaning that they would have a net-negative impact on the transportation sector's carbon footprint.

The impact of autonomous vehicles on sustainable mobility could be particularly severe in the case of pedestrians and cyclists, which are currently the lowest-carbon form of mobility available. As discussed above (see **SECTION 3.1**), the need for traffic coordination with autonomous vehicles could lead to pedestrians and cyclists getting squeezed off the roads. How, for example, would pedestrians and cyclists fit in to the kind of reservation-based free-flowing autonomous intersections currently being modelled by computer scientists? [59]–[62] Because pedestrians and cyclists give autonomous vehicles' software and sensors more trouble than cars, there are already proposals to make the software's job easier by using physical barriers or aggressive law enforcement tactics to exclude pedestrians from the streets, or by requiring cyclists to carry signalling devices that will enable autonomous vehicles to more easily detect them. [73], [143] For cyclists and pedestrians, therefore, autonomous vehicles could provide both a carrot, enticing them into cheap self-driving taxis; and a stick, encouraging them to abandon more sustainable modes of transportation.

If autonomous vehicles compete with other forms of mobility in the way described in this section, it would pose a serious environmental issue. Competition between shared autonomous vehicles and public transit could add around 15 percent to the total vehicle-kilometers travelled. [48] If, on the other hand, they are able to complement public transit and increase ridership, then the effect could be more positive, possibly leading to a reduction in the energy intensity of the transportation system of up to 37 percent. [144]

4.6 Interactions with Electric Vehicles

A common argument advanced by proponents of autonomous taxis is that the people who own fleets of such vehicles would have little choice but to make them electric, due to the financial and commercial logic of fleet economics. Electric autonomous taxis, their analyses argue, are far cheaper

7 Converted to Canadian dollars per kilometer from US dollars per mile, based on exchange rates in October 2019.

per-kilometer than gasoline-powered ones, due to lower fuel costs. [1], [2], [145] This, however, rests on the assumption that fleet operators are more rational than individual motorists, which is not a sure thing. Operators of car fleets for large companies are sometimes reluctant to include electric cars as options for their employees for the same social and cultural reasons that many motorists shy away from electric cars, namely, unfamiliarity, regulatory barriers, and infrastructural hurdles. [146] Some of the same barriers might apply to the owners of autonomous taxi fleets. [147] This point is strengthened by the logistical barriers facing a rapid transition to electric mobility. [12]

Even if the taxis are electric, this would not bring about carbon-neutral transportation. Electric cars have higher embodied emissions than gasoline-powered cars, [148] and their emissions-per-vehicle-kilometer depend on the carbon emissions of the electricity which powers them. Currently, carbon emissions from electric vehicles in Canada range from 96 to 280 grams of carbon dioxide equivalent per kilometer travelled—a figure which does not include the embodied emissions.[8] [149]

4.7 Conclusion

FIGURE 9 shows that the environmental impacts of this scenario depend critically on whether autonomous vehicles are private or shared. From an environmental perspective, privately-owned autonomous vehicles may have serious environmental consequences. Shared autonomous vehicles, on the other hand, have a pathway towards significant environmental benefits, although this could be derailed by competition between shared autonomous vehicles and other low-carbon modes such as public transit and active travel. Unfortunately, most of the social science evidence with bearing on the question of who will own the vehicles currently points in the direction of private motorists. For a shared system to prevail, it would not only have to be cheap (cheaper than many forecasts suggest), but would have to overcome many of the complex social, psychological, and cultural reasons why motorists love their cars. There is therefore a big risk that in the absence of some kind of deliberate intervention in the development of fully-autonomous vehicles to encourage a sustainable shared use model, this technology would bring about an increase in vehicle-kilometers travelled, as car owners opt for private autonomous vehicles and transit users, cyclists, and pedestrians switch to shared autonomous vehicle systems.[9]

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8 This depends on the makeup of the electrical grid that charges the vehicle's batteries. The figure is highest in Alberta, Nunavut, and Nova Scotia, and lowest in Quebec, Manitoba, and British Columbia. Compare this with the average car, which, according to the United States Environmental Protection Agency, emits about 250 grams of greenhouse gases per kilometer travelled. [150]

9 As discussed in Section 2.5, Figure 9 simplifies complex uncertainties into dichotomous choices. In reality, for example, it is likely that there will be some use of both private and shared autonomous vehicles, although the research discussed in this paper suggests that private vehicles are likely to predominate.

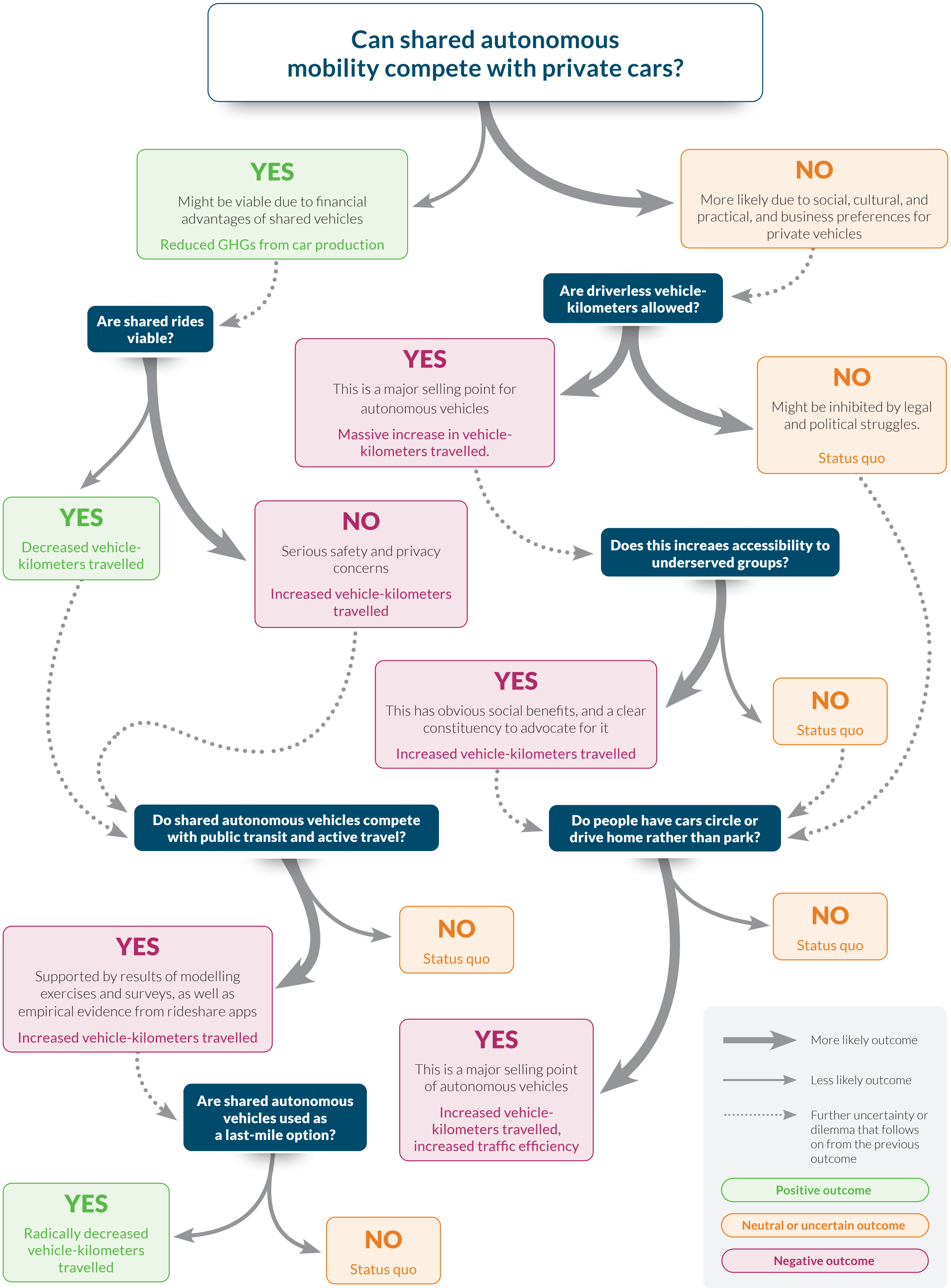

FIGURE 9. Flow chart representing different outcomes from this scenario. Larger arrows indicate more likely outcomes, while dotted arrows indicate further dilemmas that occur as the result of particular outcomes. Italicised text describes results in terms of sustainability outcomes.

5 CONCLUSION

The flow charts presented at the end of Sections 2, 3, and 4, when taken together, give a useful map of potential environmental implications of autonomous vehicles. In the first scenario **(SECTION 2)**, early autonomous driver assistance features such as lane-keeping assist and cooperative adaptive cruise control could produce a marginal increase in traffic and energy efficiency, but might alternatively increase emissions through induced demand and the rebound effect. In the second scenario **(SECTION 3)**, the increase to vehicle-kilometers travelled that comes about following the adoption of fully autonomous vehicles might again wash out efficiency gains, leading to a substantial increase in the environmental impacts of the road transportation system. In the third scenario **(SECTION 4)**, an outcome that perpetuates privately owned automobiles risks a dystopian nightmare of empty vehicle-kilometers and massively-increased travel distances. Even the more positive outcome of shared autonomous vehicles could still increase the total number of vehicle-kilometers travelled, unless these shared autonomous vehicles were used in a very specific way that complements transit, walking, and cycling.

It should be acknowledged that much of the discussion in this report relies on speculative leaps. This is an inevitable consequence of the subject matter: Autonomous vehicles are qualitatively different from any mobility technology currently in wide use, and could have profound and complex third-order consequences. Predicting their impacts is a very uncertain business, and it is possible that some of the conclusions reached in this report are overly pessimistic. What is true of this report, however, is also true of other literature which enthusiastically positions autonomous vehicles as a keystone technology for a future low-carbon mobility system. This literature also relies heavily on speculative leaps. The social science evidence cited here gives ample reasons why we should be concerned that, absent deliberate policy intervention, the adoption of self driving vehicles could produce serious environmental harms.

Autonomous vehicles are qualitatively different from any mobility technology currently in wide use, and could have profound and complex third-order consequences. Predicting their impacts is a very uncertain business.

This does not destroy the case for autonomous vehicles. Nor does it suggest their use or development should be resisted. The upside of the analysis is that at least two possible scenarios appear not just positive on balance, but positively exciting:

SLOW LAST-MILE SHUTTLES OR MICRO-TRANSIT. This application of autonomous vehicles, discussed in Section 4.5, sees them used deliberately to augment existing sustainable transportation systems. Small, slow, last-mile shuttles would roam neighbourhoods on flexible routes, picking up passengers on-demand and bringing them to stations on the nearest arterial public transit route. This would create an ideal solution to the last-mile problem that plagues public transit, greatly increasing its value proposition and allowing it to better compete with private cars. It would also improve accessibility for marginalised groups such as people with disabilities. It could be implemented by public transit agencies (in which case it would solve the labour cost problem currently faced by micro-transit schemes), by independent bodies, or by private companies. Perhaps its most interesting advantage is that it mitigates some of the technical hurdles of autonomous vehicles by implementing them in a form that can be effective and useful despite still operating at slow (and safe) speeds. It could thus be implemented very soon, and indeed there are already experiments with similar systems in Europe.

SHARED AUTONOMOUS VEHICLES UNDERMINING CAR USE. This outcome depends on an emergent effect of autonomous mobility that would be difficult to consciously design into the system. As discussed in Section 4.3, it could occur if shared autonomous vehicles disrupt established patterns of car ownership, which in turn results in a rapid decrease in car use, in favour of walking, cycling, or public transit. This is supported by the social science evidence that when people have cars, they tend to find ways to use them, which implies that without cars, people might change their mobility patterns on a fundamental level. This could have a self-reinforcing effect if it creates a new market for local businesses and services, and it could be accelerated by zoning changes which would further encourage this.

These two scenarios are not the only positive scenarios for autonomous vehicles. The point in including them here is not to present prescriptive guides for how autonomous vehicles should be implemented. Rather, it is intended to demonstrate two points: that there are positive plausible outcomes of autonomous vehicles from a climate change perspective; but also that plausible is not the same thing as probable. These scenarios are unlikely to materialise unless deliberate efforts are directed towards making them do so. On the flip side: If autonomous vehicles are adopted without any coordination, the result could be detrimental to efforts to combat climate change.

Any scenario in which autonomous vehicles reduce the carbon emissions from the transportation system will require not just disruption of personal mobility but directed disruption. Autonomous vehicles can be a massive environmental benefit if their development, adoption, and implementation is guided towards a positive outcome.

Charting a detailed path forward by which this goal can be accomplished is beyond the scope of this paper. But we can suggest some principles for discussion when considering a policy framework to orient the way autonomous vehicles are deployed:

IT SHOULD MAXIMISE THE EFFICIENCY GAINS OF AUTONOMOUS VEHICLES TO THE EXTENT THAT IS TECHNICALLY POSSIBLE AND POLITICALLY FEASIBLE. An important caveat to this is that efficiency gains from autonomous vehicles are the smallest of all their potential environmental benefits, so if some efficiency measures, such as dedicated autonomous vehicle lanes and networked intersections, prove too politically contentious to be widely implemented, the smart choice would be to abandon them in favour of winning more important battles down the road.

IT SHOULD MITIGATE REBOUND EFFECTS TO THE GREATEST EXTENT POSSIBLE. Reductions in congestion, efficiency gains, multitasking, and even safety improvements all might have the unintended consequence of making motorists drive further, drive faster, and drive larger vehicles. This is a common problem in transportation policy, which has long found the phenomenon of induced demand to be a major obstacle to reducing the environmental impact of the car-based transportation system. There is no one solution to this problem. Rebound effects will have to be handled by policymakers and transition practitioners on a case-by-case basis. But it is critical that at least until electricity systems are fully decarbonized autonomous vehicles be implemented in a way that durably reduces the total vehicle-kilometers travelled, energy per vehicle-kilometer, and ultimately the carbon footprint of the entire system.

IT SHOULD ENCOURAGE SHARED MODELS OF AUTONOMOUS VEHICLE DEPLOYMENT, RATHER THAN PRIVATE OWNERSHIP. This will be the most difficult to achieve. It will require careful commercial, technical, and political strategizing to overcome entrenched resistance, both from the automobile industry, and from drivers who do not want to part with their private vehicle. For this reason, shared rides, while beneficial, might be a bridge too far due to their major safety and privacy issues. Shared last-mile shuttles integrated into public transit networks might be an exception to this, however, as for now they appear the most beneficial form of autonomous mobility from a climate perspective.

IT SHOULD ENSURE AUTONOMOUS VEHICLES SHOULD DISPLACE PRIVATE CARS, RATHER THAN PUBLIC TRANSIT, CYCLING, OR WALKING. This means that infrastructure for autonomous vehicles must not come at the expense of good public transit and active transportation infrastructure. One ideal way to achieve this would be to offer slow, short-distance, last-mile micro transit, to connect with larger public transit networks. This would overcome some of the safety concerns associated with autonomous vehicles, and could also be implemented very quickly, without having to wait for the technology to be ready to safely operate autonomous vehicles independently at high-speed.

> The general principle is that autonomous mobility should be used as a force multiplier for forms of sustainable mobility that already exist.

The general principle here is that autonomous mobility should be used as a force multiplier for forms of sustainable mobility that already exist. It should be used to extend the reach of public transit networks, to provide a travel option for elderly or disabled people who cannot walk to their destinations, and to allow habitual bike commuters to carry large loads from time to time. If this is achieved, then autonomous mobility might well be the massive environmental boon that its most optimistic boosters promise. These goals, however, will not be achieve autonomously by the cars themselves, nor can we expect autonomous vehicle entrepreneurs or users to pursue them of their own accord. To get the best environmental benefits out of autonomous vehicles and avoid their worst environmental risks, societal institutions will have to steer them. In practice, this means active intervention in their development, adoption, and use. If this is done, then autonomous vehicles could indeed provide massive benefits for the health of the planet.

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TRANSITION ACCELERATOR REPORTS
Volume 3 • Issue 2 • April 2021

The Transition Accelerator

L'Accélérateur de transition