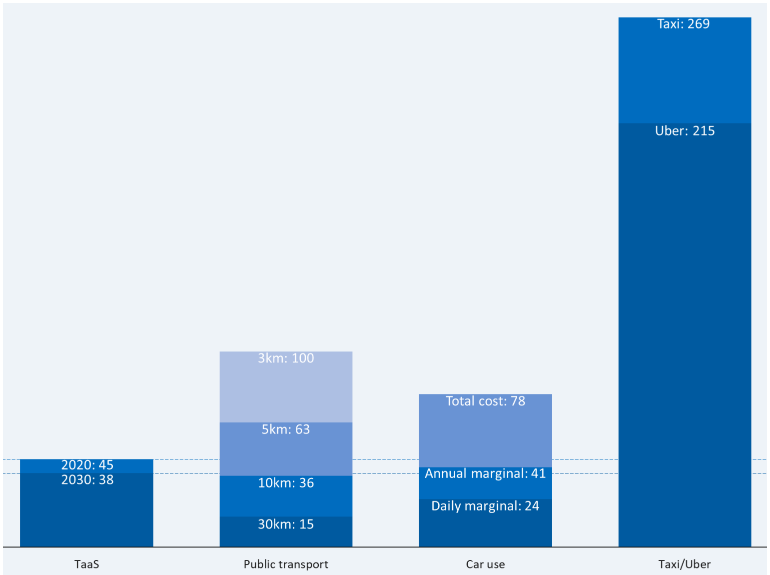
Autonomous vehicles – the clean energy technology we've been looking for?

In this discussion paper, we argue that autonomous vehicles (AVs) should be considered cleantech and could be one of the most disruptive technologies in the energy transition. At a minimum, we consider AV technology to be clean technology because it is likely to increase the energy efficiency of personal transport. However, of greater interest is the possibility that AVs will inadvertently and rapidly electrify Australia's vehicle fleet. The resulting increase in energy storage and flexible demand would help facilitate a transition to 100% renewable electricity.

AVs will enable a new business model – transport as a service (TaaS). This Uber-like service (sans-driver) could have a significant cost advantage over alternatives.

We have estimated the potential cost of TaaS in Australia to be below 50c/km. This would make TaaS not only cheaper than using a taxi, but cheaper than buying a car, and cheaper than even using public transport in some instances (Figure 1).

Figure 1: Cost of different transport options (AU c/km)



Due to its cost advantage, TaaS could quickly capture a large share of the personal transport market, on a passenger-kilometres basis. The most surprising result of our analysis is that TaaS could be comparable to the average annual marginal cost of

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About EnergyLab
We are Australia's leading platform for launching new energy businesses. Our Acceleration Program was the first in Australia to focus on energy startups and is currently available in four cities. To find out more visit energylab.org.au.

About EnergyLab's research
EnergyLab prepares discussion papers such as this to help facilitate productive conversation around clean energy innovation, and to promote and support clean energy entrepreneurship.

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owning a car. As a result, TaaS use could quickly displace the use of personal vehicles, possibly becoming the dominant form of transport within a decade.

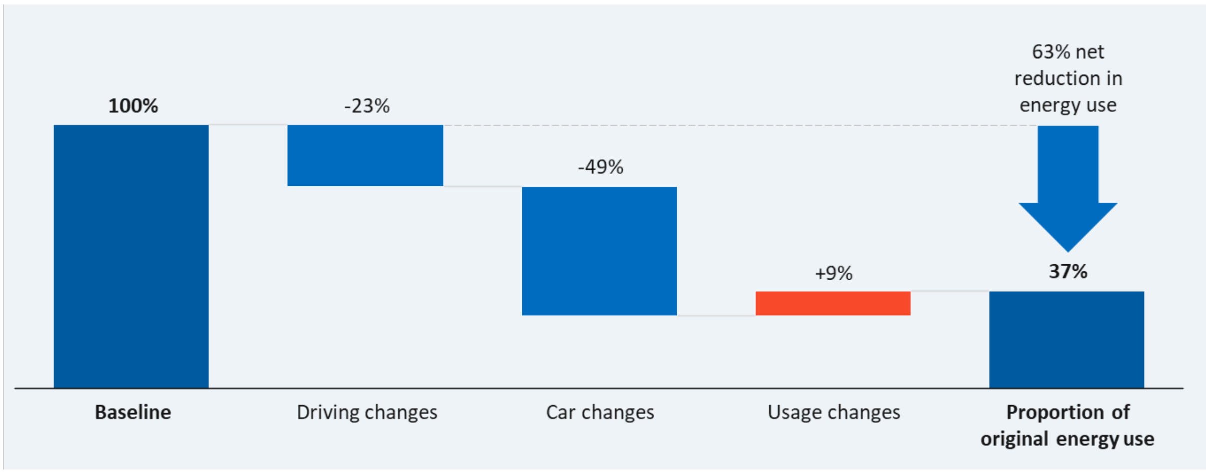
TaaS fleets are likely to be electric. TaaS providers, like all businesses, will minimise costs. In high-utilisation conditions, EVs have a lower total cost of ownership due to their lower running costs, and therefore are likely to be favoured by TaaS.

As a result, TaaS could electrify our personal transport systems much quicker than natural electric vehicle adoption. Currently, optimistic estimates have EV uptake reaching 90% of personal vehicles around 2085 under the normal model of personal vehicle ownership. One of the reasons for the slow change is that cars have high upfront costs and are retained for over a decade on average, resulting in a slow rate of turnover in the national fleet. TaaS won't suffer from this turnover brake, with the addition of a new commercial TaaS fleet bypassing the regular replacement process and lower barriers to consumer adoption. As result, some estimates project that TaaS could provide for 95% of all passenger-kilometres by 2030 – mostly with EVs.

Rapid electrification of transport is likely to help facilitate a transition to 100% renewable energy. The storage capacity that could be made available by a TaaS fleet would help balance out the intermittency of renewable energy. As a result, our grid would be able to handle a greater amount of clean energy, which in turn would decrease the carbon intensity of electric vehicle use. This dual potential to help decarbonise transport and the grid simultaneously makes TaaS highly significant for the energy transition.

Even if TaaS doesn't come to dominate, AVs could reduce the energy consumption of personal transport by about 60% compared to business as usual (Figure 2). These savings are due to driving with greater efficiency (~25% reduction), enabling cars to be redesigned to be more efficient (~50% reduction), but slightly offset by factors such as induced demand (~10% increase).

Figure 2: The impact of AVs on the energy footprint of personal road transport



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Introduction

Not all clean energy technologies are obvious. EnergyLab supports entrepreneurs commercialising technologies that will help Australia and the world transition to a 100% clean energy economy. Doing so necessitates forming a view of what technologies meet that criteria. Some are easy to spot, such as solar power, but determining the impact of other technologies is not as straight-forward. As a result, we spend a lot of time thinking about what a society running on 100% clean energy might look like, how we might get there, and what obstacles might lie along the path.

Australia's love of cars creates a potential roadblock to the clean energy transition, one that biofuels are unlikely to get us around. Most of our vehicle fleet runs on fossil fuels, with only 10% biofuel in the form of ethanol if you fill up with E10. One day we might be able to create a 100% biofuel mix that our cars can run on, but that day is likely a long way off. There are also many other problems with biofuels and, at present, it seems highly unlikely production will ever be able to keep up with our increasing demand for liquid fuels. Furthermore, if we are to decarbonise our economy, it is likely we will want to use the biofuel we do produce for other applications, such as aviation, rather than personal land transport.

Electrification is the answer to this challenge, according to most. Electric vehicles (EVs) can be charged with renewable electricity, and are getting cheaper, faster and capable of driving further on one charge. Furthermore, EVs increasingly promise to be a superior automotive technology to traditional internal combustion engines (ICEs) and may shortly be cheaper than their traditional counterparts. It's true that in most part of Australia anyone charging an EV will currently be doing so with electricity generated predominantly from coal-fired power stations. However, as the carbon intensity of our electricity mix decreases, so will that of EVs.

Furthermore, EVs will help facilitate a transition to affordable, renewable energy. One of the biggest barriers to higher uptake of renewable electricity is the intermittency problem – the fact that the sun doesn't always shine, and the wind doesn't always blow exactly when we want to turn on the kettle. EVs (which are just like household batteries while parked and being charged) can help solve this problem by storing electricity generated from renewables when we don't want it and making it available when we do. EVs also help address another problem with renewables – unpredictability. The grid operator carefully matches supply and demand of electricity within 5-minute intervals. But if a wind farm produces more than or less than expected during this period, there will be a mismatch (see our previous paper for more on this topic). EVs (if connected to the grid) can compensate for this by charging or discharging by just the right amount, almost as soon as the problem is detected. EVs and renewables are like gin and tonic – good individually, but better together.

Unfortunately, the uptake of EVs in Australia has been very slow to date. One of the least supportive policy environments in the world has led to a paucity of options for those interested in going electric. Australia has over 60 brands and over 350 models of ICE cars to choose from[1] but at the time of writing only three pure electric vehicles were available to retail customers, two of them Teslas. It's lucky Elon

[1] FCAI 2018 Price Comparison

likes us because otherwise there would only be one option on the menu for EV-enthusiasts, like a vegetarian in a suburban restaurant.

The situation is expected to get better, but not by much and not for a while. Even in the most optimistic scenario, with strong support from the government, EV penetration won't reach 90% for another 25 years. One of the reasons for the slow uptake is the pesky reality of mathematics. The Australian car fleet turns over once every 14 years,[2] so even in the highly unlikely scenario that 100% of new car sales are electric from now on, it would still be 2032 by the time close to 100% of cars are electric.

Recent research suggests autonomous vehicles (AVs) could change the game for EVs. A report by think-tank RethinkX drew our attention to the possibility we had missed an important clean energy technology. The authors argue that AVs will enable a new business model that could change the way we travel and that this new way of getting around could be so disruptive that it becomes the dominant form of transport within a decade. They further argue that the AVs catering to most of our needs in this scenario would be electric, leading to a faster electrification of transport than currently thought possible.

In this discussion paper, we evaluate these claims and assess the extent to which AVs could be considered cleantech. We start by assessing the impact of AVs on energy use as a standalone technology – if all our cars suddenly become autonomous, would energy use increase or decrease? We then evaluate the claims made by RethinkX, updating their analysis for the Australian context and assessing the significance of AVs for the clean energy transition.

[2] Credit Suisse 2016 She's electric (just not for a very long time)

AVs could increase the energy efficiency of personal road transport

Letting our cars drive themselves could reduce energy consumption in personal transport by 60% compared to business as usual. The benefits would come from a range of sources, from optimised driving and purpose-built cars to coordination between vehicles and an increase in car sharing. These benefits are offset somewhat by increased travel made possible by AVs and could be made even worse by the ability of AVs to drive safely at higher speeds. However, on balance, it appears that AVs will decrease the energy consumed for each kilometre travelled.

The analysis that follows is largely based on the excellent work of Wadud, MacKenzie & Leiby,[3] supplemented by several other sources. For a detailed and nuanced understanding of the environmental impact of AVs, see Wadud & Co's work. For a more digestible summary, read on.

Tweaking how we drive would save a lot of energy. This has been proven by Australian startup GOFAR, who provide drivers with live feedback to help them drive more efficiently. A subtle light on the dashboard glows red when you're burning more fuel than necessary – accelerating too aggressively, breaking too hard, or driving too fast. GOFAR claims drivers using their system reduce fuel consumption by 9.8% on average and by up to 30% for the most dedicated fuel misers.[4] These claims are backed up by academic studies that found drivers provided with dynamic advice reduced their fuel use by 10-20%[5] in real-world conditions and up to 31% in a simulator.[6] The problem is, most people don't want to drive efficiently because, well, it's boring (sorry GOFAR).

AVs will be able to achieve the energy-efficient driving heights that we can't be bothered reaching ourselves. AVs won't get bored (and hopefully won't be programmed with a need to demonstrate their masculinity); they are likely to pay meticulous attention to accelerating and braking to maximise efficiency while maintaining comfort and safely getting to the destination on time. A smooth ride is an efficient ride, and therefore perfect for an AV. Let's assume that as a consequence of this behaviour AVs will reduce energy consumption by 20%. Given that humans – who get distracted and occasionally feel the need for speed – can achieve 30%, this seems realistic. But eco-driving isn't where the savings end.

Figure 3: The GOFAR display glows blue when you're driving efficiently and red when you're not

Cars might start to look different once we're no longer driving them ourselves. The engines will likely be tuned for comfort and efficiency, rather than performance characteristics like acceleration. Such fine-tuning could reduce energy consumption by an additional 23%. As AVs are likely to be much safer than human-driven cars, many of the safety features our cars currently possess might no longer be needed once humans are no longer behind the wheel (probably once *no* humans are behind the wheel). These

[3] Wadud, MacKenzie & Leiby 2016 Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles
[4] GOFAR 2018 Fuel Saving
[5] Barth & Boriboonsomsin 2009 Energy and emissions impacts of a freeway-based dynamic eco-driving system
[6] Wu, Zhao & Ou 2011 A fuel economy optimization system with applications in vehicles with human drivers and AVs

features add significant weight to the car, the removal of which would improve efficiency by 6%. Taking this a step further, when the AV revolution really gets going, we might be comfortable being driven around in compact, light-weight cars, rather than taking comfort in the safety (for those in the car) of driving huge 4WD vehicles on perfectly good roads. This could increase efficiency by 18%. However, some design changes could also decrease efficiency. We might decide to add more features to our cars, like televisions and reclining seats, which apparently could add enough weight to the car to reduce energy efficiency by 11%, offsetting some of the other benefits.[7]

More savings are possible once there are a lot of AVs on the road. AVs will be able to safely travel much closer together than human drivers because computers have faster reaction times than us. Tailgating improves car performance (like in Mario Kart) by reducing aerodynamic drag. Estimates of how much 'platooning' as such reduces energy use range from 3-25% so for illustrative purposes we've taken an average of 14%. By coordinating at a city-level, AVs could also reduce congestion by optimising the overall flow of traffic. This is in addition to reducing the number of accidents, a major cause of congestion. By improving the flow of traffic, efficiency could be increased by an additional 4%.[8]

"AVs will radically alter the way people interact with cars" – Accenture

Furthermore, a high penetration of AVs may lead to a change in how we use cars, further reducing energy use. The ability to drive themselves will make it easier for us to share our cars through platforms like GoGet, Car Next Door and EnergyLab's EV-only alternative, Eveeh. Shared AVs will be able to come to you (rather than require you to walk to them) and relocate to a more convenient location or somewhere with cheaper parking when not being used.[9] One study found that people reduce the distance they travel by 27% after joining a car-sharing scheme.[10] If car-sharing becomes sophisticated enough, it could provide the perfect car for every occasion. Instead of sending a five-seater station wagon to the solo-commuter, it could send a two-seater hatchback instead. Such 'right-sizing' of vehicles could reduce energy consumption by an additional 45%.[11]

It is worth noting that the increased access to mobility made possible by AVs could lead to significant rebound effects. The improved convenience and reduced cost of travel will likely induce people to do so more often. People may also choose to live further away from their workplaces, increasing their commuting distance, and therefore energy use by as much as 60%.[12] AVs should also make car travel accessible to more people, such as those with disabilities that prevent them from driving and those too young or too old to drive. Overall improved access could increase travel and therefore energy use by an additional 14%.[13]

However, the presence of rebound effects does not usually disqualify a technology from being considered clean. The tendency for savings from energy efficiency measures to lead to increased energy use is common knowledge. One study found that the rebound effect for more efficient vehicles is 18-21%

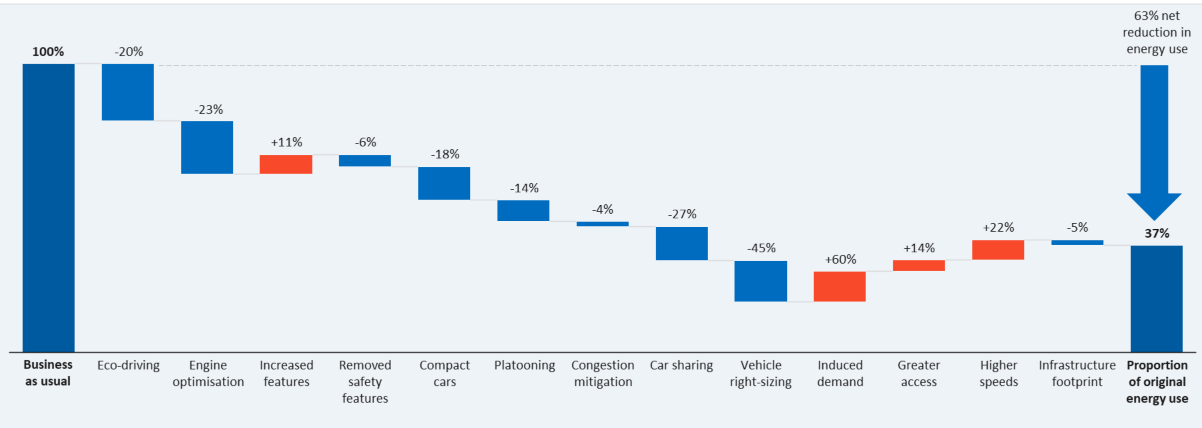
[7] Wadud, MacKenzie & Leiby 2016 Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles
[8] Ibid
[9] Fagnant & Kockelman 2014 The travel and environmental implications of shared AVs, using agent-based model scenarios
[10] Martin & Shaheen 2011 Greenhouse Gas Emission Impacts of Carsharing in North America
[11] Wadud, MacKenzie & Leiby 2016 Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles
[12] Ibid
[13] Harper et al 2016 Estimating Potential Increases in Travel with AVs for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions

and 5-8% for more efficient appliances.[14] Few would argue that the rebound effect disqualifies energy-efficiency technology from a cleantech classification. However, the sheer level of the potential rebound caused by AVs may lead some to see it as an exception to this rule. Fortunately, AVs have other environmental benefits that could dwarf everything discussed in this section, which will be covered in the following section.

Government policy will have a significant impact on the overall energy savings from AVs. For example, governments may increase speed limits on highways, considering AVs will be able to handle higher speeds safely. While this will save people time, and therefore potentially be a politically popular move, it would be a setback for energy efficiency. Driving cars at high speed increases the energy consumed per kilometre and could increase overall energy consumption by up to 22%. Conversely, regulators can reduce the over energy footprint by optimising infrastructure. Lanes for AVs don't need to be as wide, reducing the amount of material needed to build the road, and therefore the embodied energy in transport infrastructure by up to about 5%.[15]

Overall energy use could be reduced by about 60% compared to business as usual, taking all these effects together. The following waterfall chart shows the cumulative effect of each factor. Please note that the total percentage saving doesn't equal the sum of the percentage savings from each individual measure, because maths.

Figure 4: The impact of AVs on the energy footprint of personal road transport



The actual energy impact of AVs will depend on a range of factors. In general, we have taken the higher end of the estimates available (both positive and negative) for our analysis. NREL conducted a similar exercise to produce several combined estimates, which range from 90% energy savings to a 250% increase.[16] In the best-case scenario, we could enjoy benefits much higher than described in this section by capturing the full benefits while mitigating the downsides. In the worst-case scenario, AVs could increase energy use, if we end up driving more, at higher speeds, in cars kitted out with luxury features. The reader can pick and choose from the factors in Figure 4 to draw their own conclusions. In our opinion, if AVs increase energy consumption it will only be because they have enabled us to do more, not because the technology itself is less efficient.

[14] Murray 2011 Income dependent direct and indirect rebound effects from 'green' consumption choices in Australia
[15] Wadud, MacKenzie & Leiby 2016 Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles
[16] NREL 2013 AVs Have a Wide Range of Possible Energy Impacts

Of course, most of this section assumes a somewhat business-as-usual approach to personal transport. The next section will argue that this is not a given, with a complete disruption of the personal transport model possible.

AVs could disrupt the personal transport sector, accelerating the use of EVs along the way

AVs will enable a new business model: transport as a service

New technology enables new business models. We all bought software on CDs until the internet came along and enabled the now-dominant software-as-a-service business model. Likewise, we've gone from purchasing movies and music on physical media to subscribing to all-you-can-eat services like Netflix and Spotify. The smartphone made the ride-hailing business model popularised by Uber possible by providing the technology necessary to link people needing a lift with those who have a car and time to spare.

The introduction of AVs will also make new ways of doing business possible. Instead of owning cars, we'll be able to summon an autocab to take us where we need to go. The business model underpinning this has been dubbed 'transport as a service' (TaaS). This new business model isn't all that different to existing options; it's effectively the same as taxis and ride-hailing services like Uber, but without the driver. However, the cost reductions possible when using AVs puts it in a different league and makes it deserving of its own buzz-word.

> *"The rise of automated mobility services could be one of the most interesting and complex disruptions of the modern era."*
>
> – Rocky Mountain Institute

TaaS providers are likely to use EVs to reduce costs

At present, it doesn't make much sense to buy an EV in Australia. They're more expensive, there aren't many to choose from, and the driver must constantly think about where to charge the vehicle rather than just using the service stations we're all accustomed to. The one advantage EVs do have is lower running costs, but for most people that isn't compelling enough to overcome the other factors.

Buying EVs will make a lot more sense for TaaS providers. Australians drive about 15,000 km per year on average,[17] but TaaS cars are likely to be used an order of magnitude more. Taxis are driven an average of 155,000 km per year,[18] so you can expect cars in TaaS fleets to drive at least as many kilometres. Once utilisation rates reach that level, operating costs become vital and EVs will have an edge over ICEs. In addition, TaaS providers won't suffer from range anxiety, because they'll just program the cars to drive themselves to a charging point when needed (probably without a customer onboard).

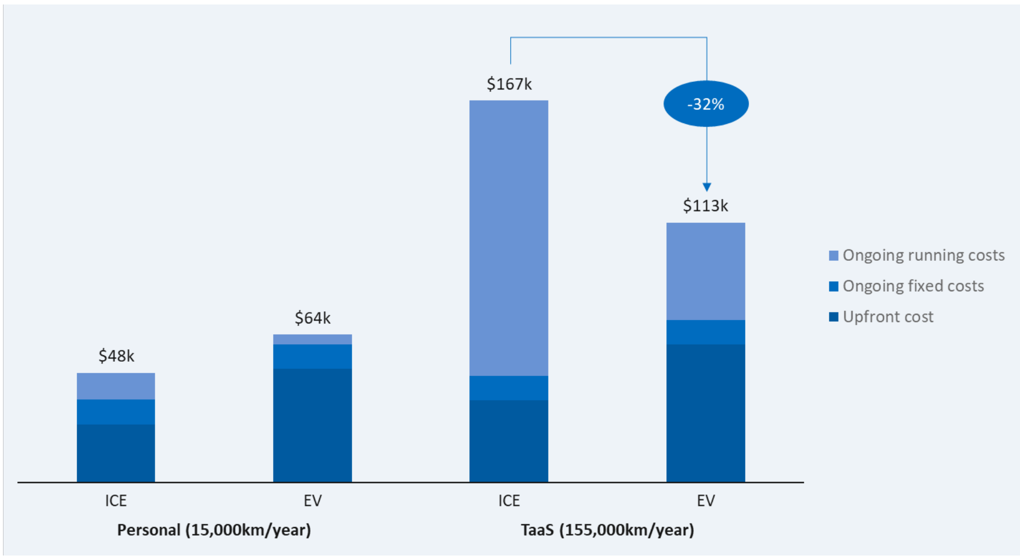
As an example, let's compare a Toyota Corolla Ascent with a Hyundai Ioniq Electric. Both are five-door hatchbacks with the Corolla being one of the best-selling cars in Australia and the Ioniq one of the EVs

[17] Roy Morgan 2013 Australian motorists drive an average 15,530km per year
[18] ATIA 2014 Taxi Statistics

expected to be available in Australia in 2018.[19] A Corolla has an on-road price of about $25,000[20] and the Ioniq is assumed to cost twice that at $50,000, the higher end of the estimates found online.[21] The Ioniq has an energy efficiency of about 15.5 kWh/100km.[22] With an electricity price of 25 c/kWh and a round-trip efficiency of 90% that equates to 4.3 c/km. By comparison, the Corolla consumes 7.7 c/km of petrol and cost 7.2 c/km in maintenance.[23] EVs are widely believed to have up to 90% lower maintenance costs (even with battery replacement costs), but let's assume the Ioniq's is just 50% lower than the Corolla's at 3.6 c/km. If these two cars are driven 15,000 km/year (about the Australian average), then it would take the Ioniq 24 years to make up the increased upfront cost of $25,000. However, if the two cars are driven 155,000 km/year, then it takes only two years to pay off.

Over a five-year period, choosing electric could reduce the cost of TaaS fleets by at least 30%. To produce Figure 5 we've taken the numbers from above and added the cost of tyres to get the ongoing running cost and added annual costs such as registration and insurance. For simplicity, we've assumed the cost of tyres and annual costs are the same for both vehicles and have omitted the cost of capital and resale value. For the TaaS scenario, we've added the cost of AV equipment for both vehicles. As you can see, the EV costs a bit more when used for personal purposes, but a lot less when used in a high-utilisation TaaS model.

Figure 5: Comparison of five-year costs for ICE and EV for personal and TaaS use



The economics for EVs are likely to look even better from a TaaS provider's perspective. The assumptions used in the previous examples are quite conservative. If the Ioniq is charged on off-peak rates or with a large business tariff, and the full 90% maintenance savings are realised, then the payback period for the increased upfront cost of the EV comes down to about a year. In addition to this, EVs are expected to last longer than ICEs; the above example assumes one vehicle can last 775,000 km, which is

[19] RACWA 2017 Charge your drive: The five new electric car models coming to Australia
[20] RACQ 2017 Car running costs; RACV 2017 Car running costs
[21] My Electric Car 2017 Hyundai Ioniq Electric; RACWA 2017 Charge your drive: The five new electric car models coming to Australia
[22] US DoE & US EPA 2018 Compare Side-by-Side; Lima 2016 Electric cars: range and efficiency comparison
[23] RACQ 2017 Car running costs; RACV 2017 Car running costs

very generous for an ICE but increasingly appears to be realistic for an EV.[24] Finally, the upfront cost of an EV isn't likely to be double that of an ICE for very long.

The cost of EVs is coming down quickly. As battery prices fall and production volumes rise, the upfront cost of EVs will fall. UBS predicts that EVs will reach consumer total cost of ownership parity with ICEs between 2018 and 2025, depending on the country – and that's without incentives or subsidies.[25] ING estimates the upfront cost of purchasing an EV will be equal to that of an ICE sometime between 2023 and 2028, depending on how big a battery consumers want.[26] The Australian Government pegs 2025 as the year EVs will match ICEs on upfront price Down Under,[27] which is consistent with estimates by Morgan Stanley and Bloomberg New Energy Finance.[28]

TaaS use could grow rapidly as soon as it becomes available

TaaS could be so cheap that it quickly out-competes other forms of transport. Almost as soon as TaaS is introduced it should be cheaper than taxis, ride-hailing services like Uber and car share schemes like GoGet. It should also be cheaper than short public transport trips. However, the tipping point for TaaS adoption could be when people consider renewing their registration and insurance for another year. At that point, it might make more sense for many people to leave their car in the garage and use TaaS instead. The same is even more true for purchasing a new car – such a decision could soon be considered a luxury. Therefore, within a surprisingly short period of time, we could be using TaaS for most of our travel.

Picking the right metric is important when comparing the cost of different forms of transport. In this discussion paper, we've followed the lead of others and used a distance-based measure: $/km. All monetary values in this paper are stated in Australian dollars and have been converted as necessary.

By our estimates, it could initially cost about $0.45/km to use TaaS, falling to about $0.38/km in ten years. For illustration, we've chosen 2020 as the year that TaaS becomes available, so these estimates are for 2020 and 2030 respectively. To arrive at these figures, we conducted a bottom-up analysis, calculating the final cost to the consumer from estimates of component costs. These costs include depreciation, interest, insurance, maintenance, electricity, tax, and a healthy profit margin. Most costs are expected to decline over the next decade, although tax is expected to jump as governments adapt to the new transport model. This analysis was inspired by the seminal work of RethinkX and draws on the detailed work of others to modify assumptions for the Australian context. A lengthy discussion of the assumptions we've used – which we consider quite conservative – can be found in Appendix A.

TaaS could quickly replace taxis, ride-hailing and car sharing (Figure 6). Almost as soon as it's available, TaaS is likely to be significantly cheaper than catching a cab, using a ride-hailing service like Uber, or even using a car sharing scheme like GoGet. Australians spend $6 billion per year on taxis and limousines[29] and

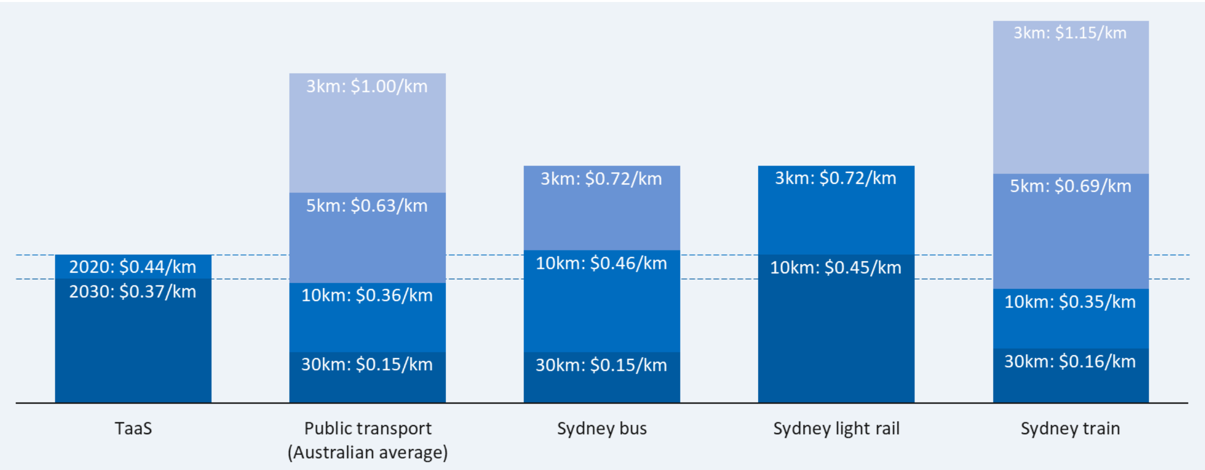
[24] Electrek 2016 Tesla battery data shows path to over 500,000 miles on a single pack
[25] UBS 2017 Evidence Lab Electric Car Teardown – Disruption Ahead?
[26] ING 2017 Breakthrough of electric vehicle threatens European car industry
[27] Australian Government 2016 Australia's emissions projections
[28] Morgan Stanley 2017 Electric Vehicles - On the Charge; BNEF 2017 Pretty Soon Electric Cars Will Cost Less Than Gasoline
[29] IBISWorld 2017 Taxi and Limousine Transport in Australia: Market Research Report

therefore stand to save about $1 billion per year by switching to TaaS. Uber and GoGet[30] are both pushing to become TaaS providers themselves, rather than be disrupted.

Figure 6: TaaS cost compared to GoGet, Uber and taxis (see Appendix B for underlying assumptions)

TaaS could become the default option for people who currently commute less than 10 km on public transport. Travelling a short distance by public transport in Australia, such as a 3 km trip across the city, cost about $1/km. A TaaS ride could cost less than half of this and will take you directly to your destination, rather than the closest stop to it. In general, we estimate trips less than 10 km in length will be cheaper than TaaS, although anything longer will probably still be cheaper via public transport. As a result, it is likely that public transport will only be used within CBD areas when the roads are congested (which, admittedly, is a lot of the time).

Figure 7: TaaS cost compared to public transport

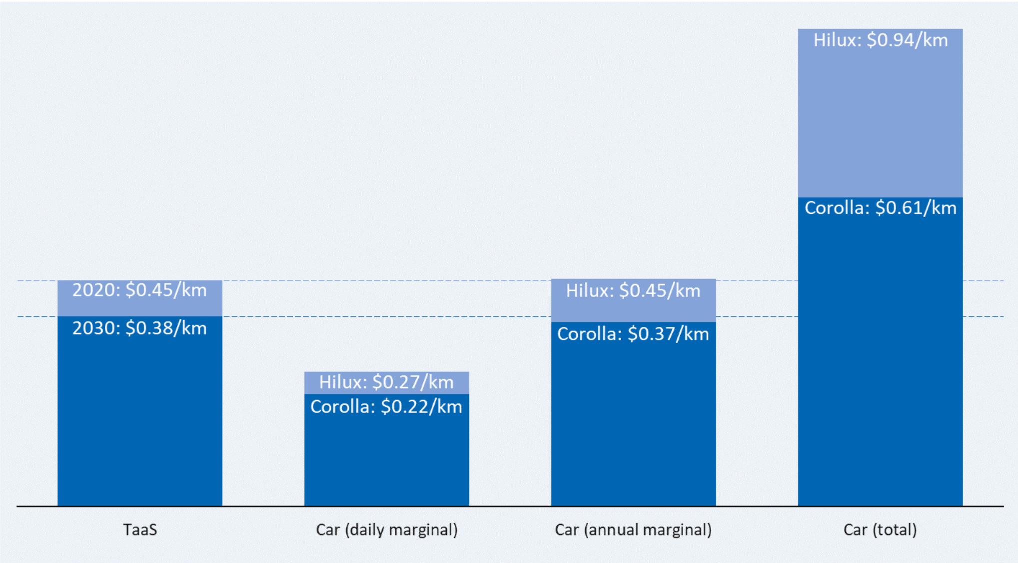


TaaS services could start to eat into personal car usage within a year. If you already own a car, with the registration and insurance paid, then it will probably be cheaper to use it than order a lift with a TaaS provider. Fuel and wear-and-tear cost about $0.25/km, significantly lower than even our 2030 TaaS estimate of $0.38/km. However, when it comes time to renew registration and insurance, many might hesitate. Considering these costs increases the rate to a comparable level to our TaaS estimate. These rates assume the car is driven 15,000 km per year and increase significantly with lower usage. That means that cars that aren't used very often, such as second cars, could be particularly uneconomical to keep registered and insured. However, the real impact comes at the point that people would normally buy a

[30] GoGet 2017 Will driverless cars be in your future?

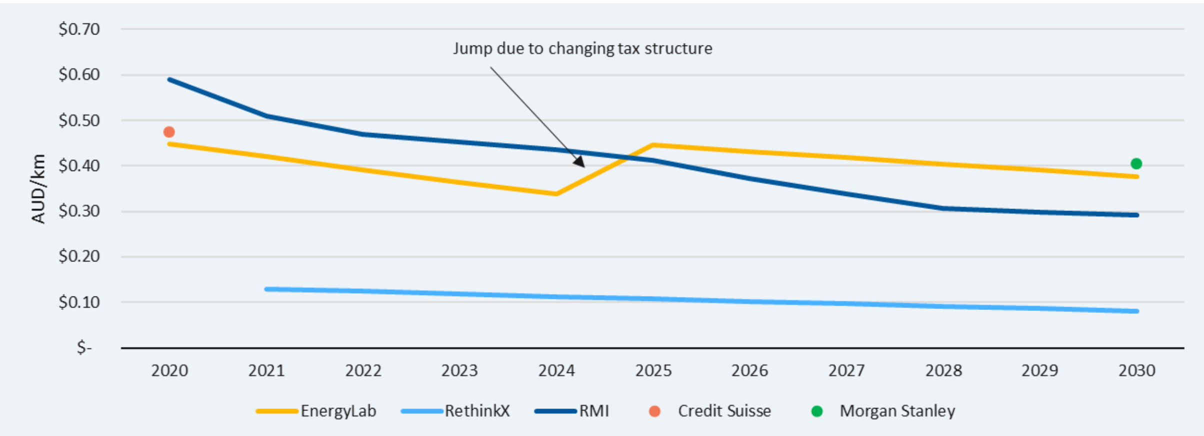
new car because adding the upfront cost of a vehicle makes it significantly more expensive than using TaaS. For the illustration in Figure 8, we've chosen the Toyota Hilux and Toyota Corolla – two of the most popular cars in Australia – as examples.

Figure 8: TaaS cost compared to personal car use



Our estimate is in-line with others and more conservative than some. Our 2020 estimate is slightly lower than that made by Credit Suisse,[31] and our 2030 estimate is slightly lower than Morgan Stanley's.[32] RMI's estimate is similar, but starts higher at $0.60/km in 2020 and ends lower in 2030 at $0.30/km. RethinkX's estimate is much lower, at about $0.10/km. RethinkX even claims that TaaS could become free, subsidised by other revenue streams such as advertising and data monetisation.[33] Our cost trajectory is also less regular than most, as we're conservatively assuming at some point Australian governments will change the tax structure to be less favourable to TaaS providers.

Figure 9: EnergyLab's TaaS cost estimate compared to others



[31] Credit Suisse 2017 A choice of revolutions: efficient, electric or autonomous?
[32] Morgan Stanley 2016 Shared Mobility on the Road of the Future
[33] RethinkX 2017 Rethinking Transportation 2020-2030

TaaS could be just around the corner

Some companies are already trialling TaaS offerings, and others are on their heels. Waymo, Google's self-driving car company, began operating AVs on public roads in the US city of Phoenix in October 2015, albeit with a human ready to take over if necessary. Two years later, in November 2017, they took the human out of the car and have been operating completely driverless cars in public since then. They now have plans to launch a public TaaS offering in early 2018.[34] NuTonomy, an MIT spin-off, also plan to launch a TaaS offering in 2018 after starting trials in Singapore in 2016.[35] Uber has been using AVs on public roads with real customers since September 2016, albeit with a driver that takes control occasionally when needed.[36] In September 2017 Lyft announced it would start doing the same.[37] General Motors have also announced they plan to launch a robot taxi service, although have set themselves a more sedate deadline of 2019.[38] In 2016 the Rocky Mountain Institute predicted that 2018 would be the year TaaS arrived,[39] and it looks like they could be right, or at least not far off.

Estimates for when AVs will enter mass production range from "they're already here" to 2025. Tesla announced in October 2016 that all cars they produce from then on will have the hardware required to drive themselves and just need an over-the-air software update to transform them into AVs. Similarly, by 2020, Australian start-up A2emCo are planning on manufacturing EVs capable of driving themselves when regulations allow it and consumers are ready.[40] Ford, on the other hand, "will have a fully autonomous vehicle in operation by 2021", as their website boldly claims.[41] These vehicles will be specifically designed as fleet vehicles for TaaS providers and available in volume.[42] Baidu, China's Google, have announced they plan to start mass production of AVs around 2021.[43] But GM might beat everyone (except maybe Tesla) to the punch because they already have a mass-producible AV ready to go.[44] Analysts at Black Rock and IHS are more sceptical but nonetheless still believe AVs will arrive by 2025.[45]

Legislation could still slow down AVs. It is currently unclear whether existing laws in most countries allow AVs, requiring clarification from lawmakers. However, the response from lawmakers so far has varied widely. Ahead of the pack are our Kiwi cousins – with AVs already legal in New Zealand (if only through a regulatory loophole[46]). Close behind is the UK Government, who are progressing legislative changes to allow AVs on public roads, as well as to clarify questions relating to insurance and liability.[47] The US was on track to implement a national law allowing self-driving vehicles,[48] but a Californian senator has put a spanner in the works.[49] China has taken a more cautious approach, only allowing AVs to be tested on

[34] Wired 2017 Waymo has taken the human out of its self-driving cars
[35] TechCrunch 2016 MIT spinout NuTonomy just beat Uber to launch the world's first self-driving taxi
[36] Reuters 2016 Uber debuts self-driving vehicles in landmark Pittsburgh trial
[37] Wired 2017 Lyft is launching a fleet of self-driving cars in San Francisco
[38] The Verge 2017 GM says it will launch a robot taxi service in 2019
[39] RMI 2016 Peak Car Ownership
[40] RenewEconomy 2017 Plans brewing for Australian gigafactory and A-EV manufacture
[41] Ford 2017 Looking Further: Ford will have a fully autonomous vehicle in operation by 2021
[42] Ford 2016 Investor Day
[43] Engadget 2017 Baidu plans to start mass-producing AVs around 2019
[44] Cruise 2017 How we built the first real self-driving car (really)
[45] IHS 2014 Autonomous Cars - Not if, but when; BlackRock 2017 Future of the vehicle
[46] AFR 2017 New Zealand loophole to make it a driverless car mecca
[47] Herbert Smith Freehills 2017 UK Government Wants to See Fully Driverless Cars On UK Roads By 2021
[48] Reuters 2017 U.S. Senate panel puts self-driving cars in fast lane
[49] Recode 2018 A bill to put more self-driving cars on U.S. roads is stuck in the Senate

certain roads, under certain conditions.[50] Other countries are openly hostile to AVs, with the Indian transport minister declaring that AVs won't be allowed on their roads to protect the jobs of taxi drivers.[51]

Legislators in Australia are on track to legalise AVs. According to Clayton Utz, there are currently legal barriers to AVs in Australia, such as a requirement to have a human driver with their hands on the wheel.[52] However, Australian transport ministers have agreed to a phased reform program allowing AVs on Australian roads from 2020.[53] In the meantime, guidelines have been put in place for testing AVs in public.[54]

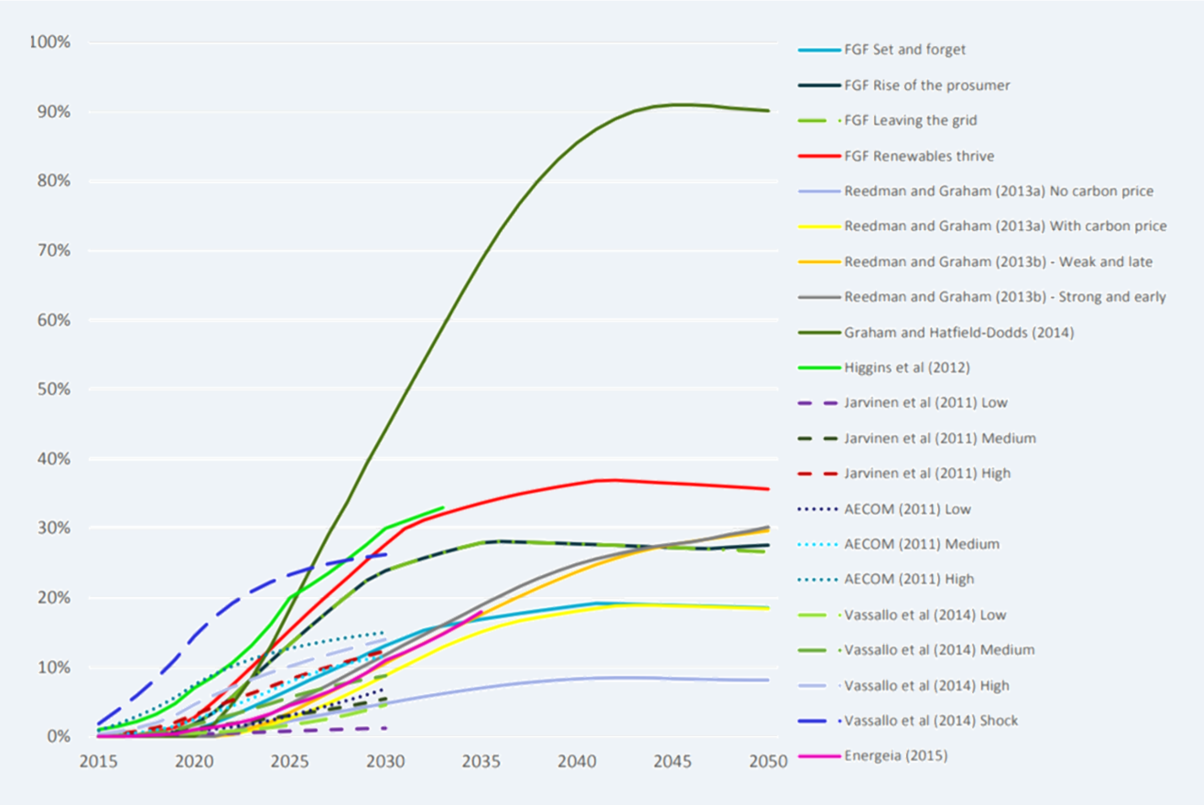
There is a surprising level of political support for AVs in Australia. The reforms just mentioned were initiated in November 2015 when the Transport and Infrastructure Council asked the National Transport Commission to clarify whether there were regulatory barriers to AVs. By November 2016 – just a year later – a set of recommendations for changing policy and regulations to support AVs had been drawn up and approved by transport ministers, sped along by bipartisan support.[55] This pace of reform is a breath of fresh air for anyone who has lived through over a decade of climate policy gridlock. Perhaps the road to AVs has been smooth so far because the topic hasn't been tarred by the climate brush, in which case it might be prudent not to send this paper to any politicians…

[50] Engadget 2017 China will allow self-driving car tests on public roads
[51] BBC 2017 India says no to driverless cars to protect jobs
[52] Clayton Utz 2016 Driving into the future: Regulating driverless Vehicles in Australia
[53] NTC 2017 Automated vehicles in Australia
[54] NTC 2017 Automated vehicle trial guidelines
[55] Drive 2016 Politics and cars: Where do the parties stand?

Adoption of EVs via TaaS could outpace the current trajectory

There is a wide range of forecasts for EV adoption in Australia. Fortunately, CSIRO & Energy Networks Australia (ENA) have done the hard work of compiling these estimates for us (Figure 10).

Figure 10: Projections of electric vehicle fleet penetration in Australia[56]

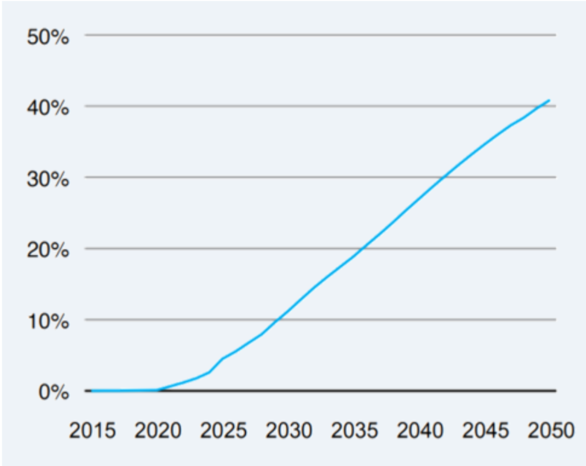


EV penetration in Australia will be less than 40% in 2050, according to most. Only one of the estimates compiled by CSIRO & ENA has EV penetration increasing more quickly. This projection was developed as part of a scenario for reducing Australia's net greenhouse gas emissions to zero by 2050 (the 'Australian Deep Decarbonisation Pathway' proposed by ClimateWorks) and represents close to the maximum possible adoption rate. The remaining projections don't come anywhere close to this one, with the next most optimistic scenario having EV penetration in 2050 at 36%.

[56] CSIRO & ENA 2015 Future Grid Forum – 2015 Refresh: Technical report

CSIRO & ENA estimate EV uptake will be 41% in 2050, based on a consolidated model with relatively optimistic assumptions (Figure 11). This projection was developed by combining those in Figure 10, assuming government policy is implemented by 2018 to support light vehicle emissions standards. Such a policy is being considered, but progress has been slow. A discussion paper was released in February 2016 with the consultation period closing over a year later in March 2017.[57] Since then the proposal has been labelled as a carbon tax on cars (go figure) and progress appears to have slowed.[58] Even yet, this scenario is probably the most rigorous projection available, if on the optimistic side.

Figure 11: Consolidated projection of the share of electric vehicles in light vehicle road transport in Australia



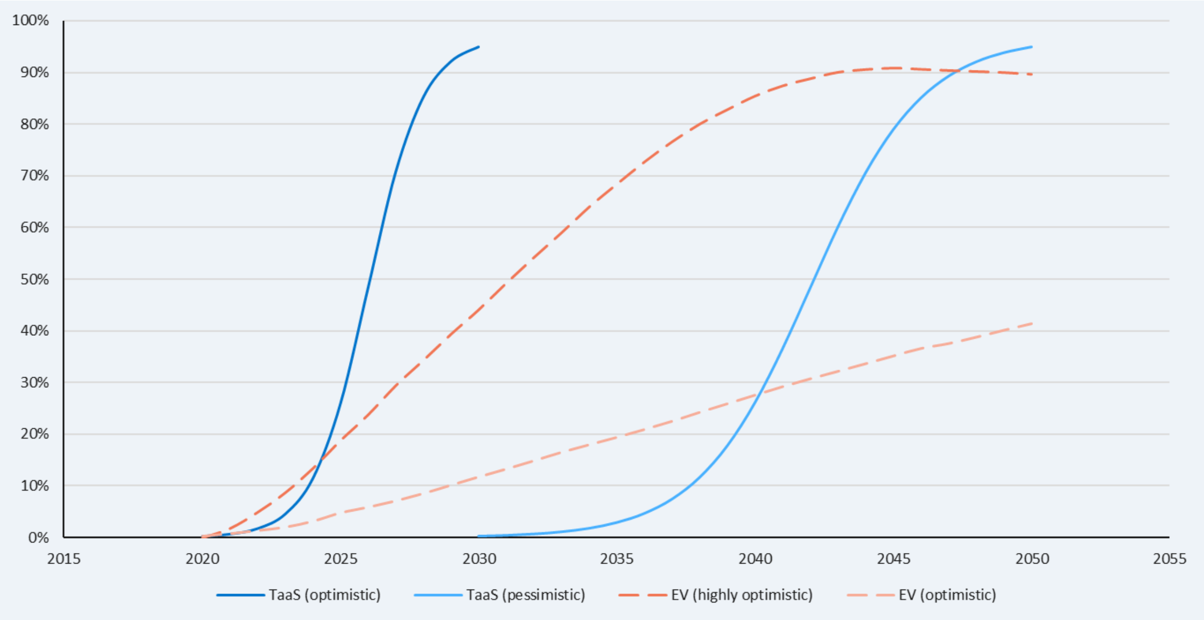
Few attempts have been made to estimate TaaS uptake speeds, but it could only take ten years to become the dominant form of personal land transport. RethinkX predicts that TaaS (and therefore EVs) will provide for 95% of passenger-kilometres in a jurisdiction a decade after being legalised, which is consistent with RMI's 'Fast Growth Scenario'. RethinkX's estimate is based on very low costs, but even the authors have been surprised by the speed of progress since publishing – many of the developments we saw in 2017 weren't expected until 2021. As such, if they were to publish today they might revise their estimate downwards. While higher, our cost estimates are lower than most transport options and comparable to the marginal annual cost of personal car use. If people are rational, they won't buy another car after TaaS becomes available. Despite the uncertainty, these data points provide adequate information to build potential uptake scenarios.

> *"Of course, there will be a transition period. Everyone will have five years to get their car off the road or sell it for scrap…"*
>
> **–** Bob Lutz, former Vice Chairman, General Motors

We've compiled four different scenarios to provide a sense of the relative speeds with which TaaS could electrify transport compared to current EV adoption forecasts. Figure 12 contains two scenarios for TaaS and two for EVs in a world without TaaS. The 'highly optimistic' EV scenario is the most optimistic projection from Figure 10, consistent with net zero emissions by 2050. The 'optimistic' scenario is the one from Figure 11 that relies on vehicle efficiency standards. By comparison, the 'optimistic' TaaS scenario involves AVs becoming available in 2020 (broadly consistent with plans from auto manufacturers, tech giants and regulators) and TaaS providers approaching maximum market share within ten years. The 'pessimistic' TaaS scenario assumes that AVs don't become available until 2025, the upper end of current estimates, with regulators not allowing AVs on Australian roads until 2030, a whole decade after current estimates. Adoption then takes twenty years, double the optimistic assumption.

[57] Australian Government 2017 Ministerial Forum on Vehicle Emissions
[58] ABC 2017 Fuel emissions decision that would cut costs, greenhouse gases lags despite 'almost universal trends'

Figure 12: Comparison of passenger travel electrification in Australia under different TaaS and EV scenarios



The pessimistic TaaS scenario does not consider global dynamics. Australia may delay legalisation of AVs, but there will be at least one country that legalises AVs early. Companies like Uber will probably perfect their TaaS offering in these jurisdictions and arrive in Australia fully-formed as soon as AVs are legal here. In this state, the service should be cheap and providers able to move quickly, increasing the speed of adoption.

TaaS results in electrification at least a decade earlier than otherwise expected, based on these scenarios. If extrapolated, 90% of personal vehicle travel will be electrified around 2085 in the optimistic EV scenario. The optimistic TaaS scenario hits this target 56 years earlier. Even the pessimistic TaaS scenario beats the optimistic EV scenario by 37 years.

TaaS results in faster electrification because it's based on technology uptake, rather than capital stock turnover. There will be limited barriers to switching to TaaS; you'll be able to try it once, then slowly increase your usage as you become comfortable with it. Buying an EV, on the other hand, is a big decision that requires considerable capital outlay. Most people only consider it seriously when they need to buy a new car, which isn't very often. Therefore, the uptake rate of TaaS is likely to more closely resemble the uptake of Netflix, which a quarter of Australian homes were using within two years of being launched in Australia.[59] (Some are already concerned about future 'TaaS and chill' fads[60]).

[59] nScreenMedia 2016 Netflix Australia penetration hits 25% in 20 months
[60] ABC 2017 Sleep pods, dog deliveries and sex behind the wheel: how we'll use driverless cars

When it comes to AVs and EVs, you can have your cake and eat it too. The previous thought experiment pits an EV ownership scenario against a TaaS scenario, but they're not mutually exclusive and supporting one will boost the other. An increase in either will result in more charging infrastructure, to the benefit of both models of vehicle ownership. Likewise, an increase in production volume, regardless of the cause, will help drive prices down, which will improve the economics for TaaS providers and car owners alike.

Conclusion

This paper was inspired by RethinkX's report on the looming disruption of the transport sector. While their argument that AVs would soon be catering to our every transport need was interesting, what really caught our eye was the claim that all these vehicles would be electric. We are big fans of EVs for the important role they play in transitioning both transport and stationary energy use to renewable sources. However, we acknowledge that at the current rate of uptake it will be decades before a significant share of Australia's vehicle fleet is electric. Therefore, RethinkX's claim that AVs could result in the electrification of personal land transport within ten years really caught our attention.

Given the possible significance of AVs and TaaS for transport electrification we decided to test RethinkX's claims in the Australian context. This has been undertaken before,[61] but we were interested in undertaking the analysis purely from a cleantech perspective and updating it for recent developments. Having chosen reasonably conservative assumptions, our estimate comes out considerably higher than RethinkX's but slightly lower than that produced by other Australian analysts. In any case, at less than $0.50/km our estimated TaaS cost was surprising and highly significant for potential TaaS uptake.

It's hard to escape the conclusion that robotaxis could be cheap enough to quickly gain a large share of the transportation market. The current taxi and Uber fleet would quickly be replaced, as it is very unlikely they could ever compete with TaaS providers. The impact on car ownership is less certain but still appears likely to be significantly impacted. If nothing else, the argument for owning more than one car could quickly fall over. For low-utilisation vehicles, it might be cheaper to just leave them in the garage and hail an AV. Buying a new car will become uneconomical by our estimates, which we believe will have at least a similar impact as the price of EVs suddenly dropping to half that of an equivalent ICE vehicle.

Of course, it is entirely possible that this scenario won't come to pass. History is littered with amusing anecdotes of technological predictions turning out to be completely wrong. AVs are clearly coming, but it's possible that it takes decades rather than years. And maybe when they do arrive we'll use them the same way we've always used cars – buying one or more each, keeping them parked most of the time, and only occasionally sharing them with others.

Even if AVs don't disrupt transport, we still consider them to be cleantech on efficiency grounds. Our analysis shows that on balance, AVs are likely to significantly decrease the energy consumed in personal transport compared to business as usual. Our central estimate is a 60% reduction in energy use once all vehicles are autonomous. It's worth noting this conclusion holds even if all autonomous cars end up being powered by fossil fuels, as they'll be using less fuel than if those cars were driven by humans.

Overall, we think it's important to acknowledge that autonomous vehicle tech is cleantech, and possibly one of the most significant technologies in the clean energy transition. When many people think of clean energy, they usually think first of solar and wind power. However, it will take a wide range of technologies to help us transition to a 100% clean energy system, and it's not always clear what those technologies are. We wrote this paper to make sure that entrepreneurs interested in clean energy, and those who want to support them, don't miss the potential of AVs to accelerate the modernisation and decarbonisation of society's energy systems.

[61] Credit Suisse 2017 A choice of revolutions: efficient, electric or autonomous?

Glossary

AV	Autonomous Vehicle
ENA	Energy Networks Australia
EV	Electric Vehicle
ICE	Internal Combustion Engine
RMI	Rocky Mountain Institute
TaaS	Transport as a Service

Appendices

Appendix A: TaaS cost modelling assumptions

Distance: As in RethinkX, it is assumed that the EVs used for TaaS (including the batteries) last 800,000 km before being retired, which appears realistic given current data.[62] It is assumed autonomous taxis travel 155,000 km per year (like current taxis[63]), which is conservative considering taxis drive up to 250,000 km.[64] Therefore TaaS fleet vehicles last just over five years before being replaced.

Efficiency: To minimise operating costs, it is assumed that TaaS providers will initially purchase the most energy-efficient vehicle available. At the time of writing the Hyundai Ioniq had that title,[65] with an energy efficiency of about 15.5 kWh/km.[66] As per the beginning of this paper, it is assumed that AV's initially use 20% less energy per kilometre due to eco-driving. Based on our analysis, if TaaS providers optimised their cars and software enough, they could reduce energy use by 80%. It is assumed that they achieve half this target by 2030.

Electricity price: The cost of electricity for TaaS providers is based on an AEMO forecast for large businesses.[67] It is possible that TaaS providers will be able to reduce their effective cost of electricity with demand side participation (see our previous paper, 'Restoring the balance - opportunities for entrepreneurs in Demand Side Participation').

Insurance: Insurance costs for AVs are generally expected to be 60-90% cheaper, mostly due to fewer accidents, 90% of which are estimated to be due to human error.[68] However, in EnergyLab's experience, insurance costs are often more expensive initially due to Australian insurance companies being wary to provide novel products. Therefore, it is assumed that the insurance cost is initially twice today's value, and then dwindles by 90% over a ten-year period. A base premium of $5,000 is used, as per an Allianz quote for a BMW i3 kitted out with $10,000 of AV equipment and used for ride-sharing purposes.

Interest rate: It is assumed that TaaS fleets are financed by debt at an interest rate of 6%.

Maintenance: An initial maintenance cost of 1.74 c/km for tyres and 6.79 c/km for service and repairs is assumed, as per the BMW i3 figures reported by RACQ (Hyundai Ioniq values are not yet available).[69] The impact of subbing in estimates from other states (or countries[70]) was not material. Considering Tesla effectively charge about 4 c/km for their maintenance plan (not including tyre replacement),[71] the value

[62] Electrek 2016 Tesla battery data shows path to over 500,000 miles on a single pack
[63] ATIA 2014 State & Territory Taxi Statistics
[64] IPART 2014 Review of maximum taxi fares and review of annual Sydney taxi licences
[65] CleanTechnica 2016 Hyundai Ioniq Electric Steals Energy Efficiency Title From Toyota Prius Prime
[66] US DoE & US EPA 2018 Compare Side-by-Side; Lima 2016 Electric cars: range and efficiency comparison
[67] AEMO 2016 National Electricity Forecasting Report
[68] RethinkX 2017 Rethinking Transportation 2020-2030; Credit Suisse 2017 A choice of revolutions: efficient, electric or autonomous?; Wadud, MacKenzie & Leiby 2016 Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles
[69] RACQ 2017 Car running costs
[70] AAA 2017 Your driving costs: How much are you really paying to drive?
[71] Tesla 2017 Maintenance Plans

chosen is likely conservative. RethinkX claim that service costs of A-EVs are at least 80% cheaper than for ICEs. Half this savings is assumed after five years.

Margin: A 30% margin on top of other costs is assumed, which is 50% more than that taken by Uber, according to RMI.[72]

Tax: According to the Australian Government's 2016 Infrastructure Plan, the average vehicle registration cost $263/year.[73] To be conservative, it is assumed that the AV equivalent is initially ten times this amount. It is assumed that five years after TaaS becomes available (which is taken as 2020 for the purposes of this note), that taxes shift to a per-kilometre basis, as recommended in the Infrastructure Plan. The per-kilometre tax chosen assumes that total funding received is initially the same and based on the average kilometres driven per vehicle as reported by the Australian Bureau of Statistics.[74] This assumption significantly increases the cost of TaaS.

Upfront cost: The cost of a Hyundai Ioniq is assumed to be $50,000 upfront, which is the higher end of the estimates found online.[75] It is assumed that a TaaS provider purchasing a fleet of these vehicles could negotiate a 15% discount, which brings the price down to $42,500. It is assumed that the cost comes down 32% between 2018 and 2030, in-line with Bloomberg New Energy Finance estimates for medium EVs.[76] RethinkX uses a similar, if slightly more optimistic, assumption. The equipment needed to make the EVs autonomous will initially cost about $11,000 extra, according to IHS, dropping to about $4,500 ten years later.[77] These cost estimates do not consider the fact that over time custom-designed vehicles are likely to be made for TaaS fleets that are cheaper, stripping out some of the performance features.

Utilisation: It is assumed that 75% of the distance travelled by a TaaS car is driven while a paying customer is onboard. This is halfway between the most optimistic assumption of 100% utilisation and the most pessimistic scenario of a car having to travel back to its origin after each trip (e.g. dropping someone off to the suburbs and then driving back to the city), resulting in a 50% utilisation.

Appendix B: Basis for cost comparisons

GoGet: The per kilometre rate for GoGet is based on the rates published on their website,[78] assuming the driver takes out GoFrequent membership (providing access to the cheapest rates), uses a mixture of the cheapest two cars, drives an average of 10 km for every hour the vehicle is hired (the assumption GoGet appears to use[79]), and drives 15,530 km per year (the national average according to Roy Morgan[80]). Using GoGet less frequently significantly increases the cost per kilometre. Conversely, using GoGet more frequently does not materially decrease the cost per kilometre.

[72] RMI 2016 Peak Car Ownership
[73] Infrastructure Australia 2016 Australian Infrastructure Plan
[74] ABS 2016 9208.0 - Survey of Motor Vehicle Use
[75] My Electric Car 2017 Hyundai Ioniq Electric; RACWA 2017 Charge your drive: The five new electric car models coming to Australia
[76] BNEF 2017 When Will Electric Vehicles be Cheaper than Conventional Vehicles?
[77] IHS 2014 Autonomous Cars - Not if, but when
[78] GoGet 2017 Rates
[79] GoGet 2017 Young drivers get going with GoGet
[80] Roy Morgan 2013 Australian motorists drive an average 15,530km per year

Public transport: The average cost per kilometre for public transport in Australia is taken from a University of Sydney study.[81] For bus, light rail and train figures, costs in Sydney were used because the tariff structure was most conducive to being translated into a consistent cost per kilometre. These figures were taken directly from the Opal website.[82]

Taxi: The per kilometre rate for taxis is simply the average cost per trip in Australia divided by the average distance, as reported by the Australian Taxi Industry Association.[83] These prices were last updated in 2014, but even a significant reduction doesn't change the conclusion of this paper.

Uber: The cost of using Uber is taken to be 20% cheaper than taxis. This is based on a Deloitte report commissioned by Uber and based on August 2015 data.[84] You might assume this report would exaggerate the benefits, but a Choice study conducted around the same time found taxis to be 40% more expensive.[85] It is commonly thought that Uber's prices have been creeping up over the years, but some research by Finder in 2018 found that Ubers are comparable to taxis even with 1.4x to 1.9x surge pricing,[86] implying Ubers without surge pricing are at least ~30% cheaper than taxis. Overall, 20% appears to be a realistic and conservative number. Again, the conclusions drawn are not sensitive to this number.

[81] University of Sydney 2015 are public transport fares more expensive in Australia than anywhere else?
[82] NSW Government 2018 Opal fares
[83] ATIA 2014 Taxi Statistics
[84] Deloitte 2016 Economic effects of ridesharing in Australia
[85] Choice 2017 Behind the wheel
[86] Finder 2018 When is a taxi cheaper than an Uber in 2018?