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Context and methods for improved velomobiles

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Abstract

This article discusses future transport emphasizing the aerodynamic cycles called velomobiles. Along with bicycles and ebikes, velomobiles are low energy transport which could displace cars as our commonly owned vehicles. Velomobiles are discussed in the light of emerging 3d printing, solar and structural battery technologies which could allow them and other cycles to be more useful and go further for less energy.

Development and use of these technologies in velomobiles would benefit transport options and the technologies themselves, allowing beneficial and practical demonstrations in practical machines. Velomobiles using new technologies could be simpler and more relatable than cars and aeroplanes using the same technologies.

The article aims to promote velomobiles and emerging solar, battery, and 3d printing technologies through their use in velomobiles. It highlights Australian researchers and manufacturers. Discussion includes the author's electric leaning trike which has timber panels replaceable by panels containing batteries or solar cells.

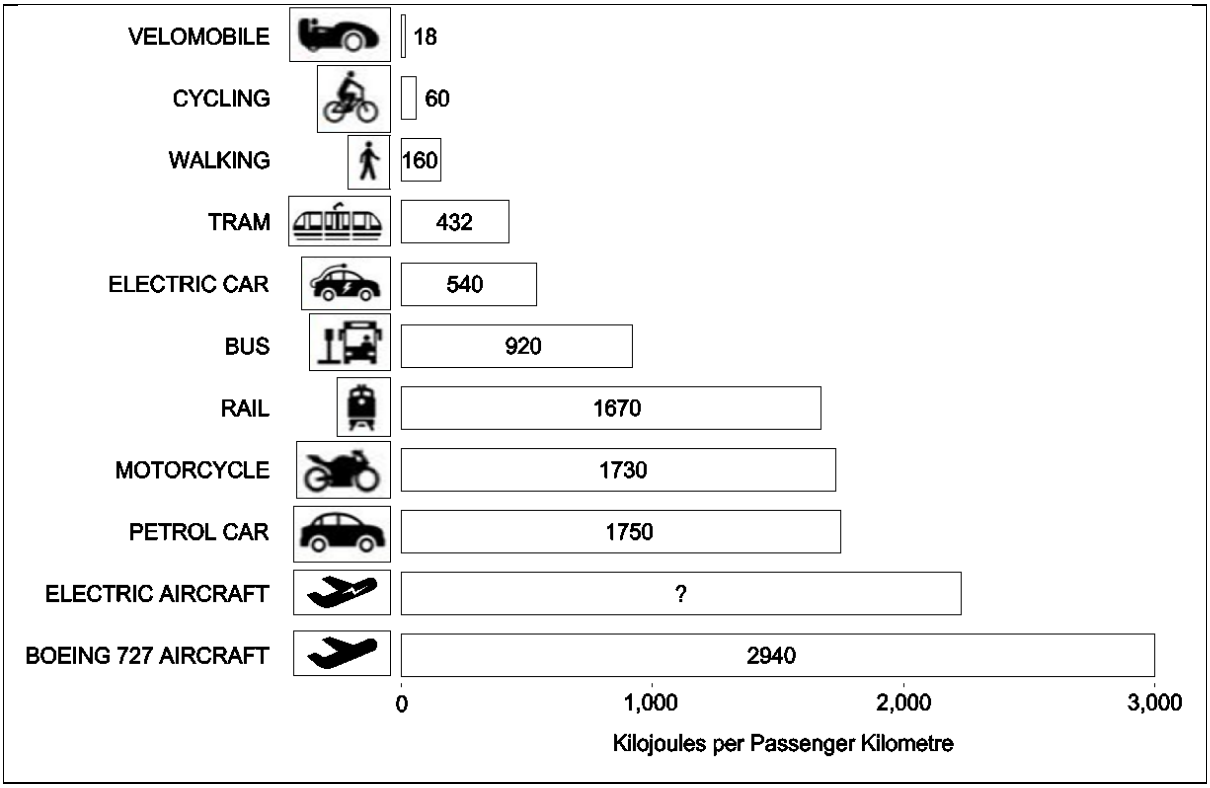
1 Introduction

Creatures are not naturally wasteful, however with technological progress humans have become wasteful. Waste accumulation harms environments and other creatures, and our Earth is sickening from pollutants and carbon dioxide. We can choose to alter our technological mastery and acknowledge some expedient technologies are unacceptable, or to live in an uncomfortable dump.

Assuming we choose not to live in a dump, our future will involve reduced waste including transport waste. This waste reduction will include low energy vehicles driven by human power or renewably sourced electricity, not by fossil fuels. Our vehicles should use the least amount of energy to do their job, and it can be seen in Figure 1 that electric cars use less energy than petrol cars and that bicycles use comparatively little energy.

However bicycles may not be personally sustainable as owned vehicles, and improved cycles such as electric bikes and load carrying, weather protecting velomobiles could fill needs for lightweight, energy efficient, owned vehicles (Cosgrove 2012).

Figure 1: Energy use in transport, adapted from Povkh and Ferreira (2018)



1.1 Personal and environmental sustainability

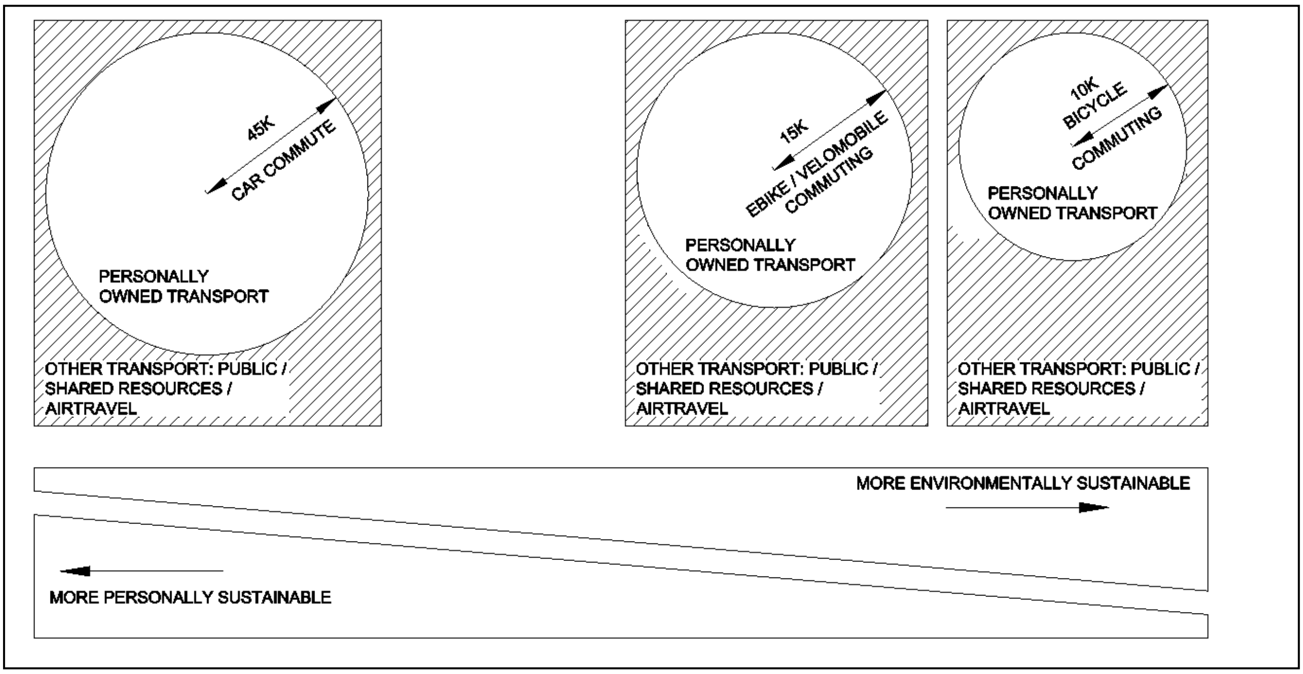
In cities we have transport choices, and to get from home to Richmond Station 5km away, I can go by foot, bike, bus, train or car. Walking or running might take too long or be exhausting. The bus is direct, but unfamiliar, and the train is indirect, involving changing trains en route. By car, I can take luggage and passengers, but would have to find a park when I get there. By bike I get exercise but can't carry passengers or much load but this would be my normal transport option.

Transport options change when going further and for the 120km to Anglesea, the bicycle trip could be too long and tiring. Like the 5k walk or run, this trip might not be *personally sustainable* and I would usually travel by car. On a 17,000km trip to Europe, flying by aeroplane becomes the default option.

This describes my mobility, and my mobility combines with yours and the facilities we use to become city-affecting transport systems. Resource consumption, greenhouse gas emissions and use of space mean transport systems also affect the planet, and can be *environmentally sustainable* to different degrees. Private ownership of vehicles is part of sustainability and transport systems.

Owning a car means accommodating it at home, in transit and at destinations. Businesses for car sharing and short-term use have proliferated recently, and their familiarity and support is simplifying car-free living as shown in Figure 2. With sufficient support, a bicycle or other human powered vehicle can become our only owned vehicle, with electrically enhanced or other improved cycles making this more personally sustainable (Apostolou 2018, Dijk 2013).

Figure 2: Personally owned vehicles and sustainable transport (Author's diagram)



1.2 Introducing velomobiles

Human powered vehicles include recumbent bicycles, recumbent tricycles and faired recumbent tricycles or *velomobiles* as shown in Figure 3. Just as ebikes can have better commuting range and hill climbing than bicycles, human powered vehicles can have better stability, aerodynamics, load carrying and weather protection (Cox 2008, Vittouris 2014).

Figure 3: Author's recumbent bicycle, recumbent tricycle, velomobile (author, Smith 2014, McAdam 2018)

Frederick Van De Walle (2004) discusses the 365 Fiets competition where competitors needed to carry luggage and average more than 35km/h in windy, rainy weather. Due to difficult conditions and speed requirements, only recumbents qualified for the event, and the winner was an Alleweder velomobile.

Van De Walle is enthusiastic about velomobiles, and so is Dillon Hiles (2014). However Hiles is realistic about velomobile uptake in a time when electric bikes are becoming more affordable. He states that like velomobiles, ebikes travel further for less effort, but believes velomobiles will never become mainstream. This is because of velomobiles' extra weight, cost and size, and because unlike velomobiles, ebikes provide motive assistance on hills and during acceleration. He acknowledges that velomobiles can have electric assistance too, and includes the solar electric Elf velomobile in his list of iconic machines (Organictransit 2019).

Bicycles and velomobiles were included in a transport energy map (Figure 1) compiled by Povkh and Ferreira. Within this map we should move towards sustainable alternatives to preserve resources, prevent pollution, and ultimately have better lives. Energy and pollution intensive aeroplanes and cars should become more *environmentally* sustainable, and lower powered transport should become more used by becoming more *personally* sustainable, useful, acceptable and affordable.

Regulatory assistance may be needed to drive change. For example Norway's tax incentives favouring sustainably fueled electric cars resulted in 58% of new vehicles purchased in March 2019 being electric (Npr.org 2019). Norway have also mandated that all flights within its borders be made by electric plane by 2040 (Bbc.com 2019) which will drive clean emission technology development (Adam 2018, 1).

Having better electric and aerodynamic bikes is already achieving sustainable transport: Melbourne cyclist Peter Wells reported changing from public transport to a Valka Vista electric bike for his 17k commute, finding it reliable, useful and inexpensive but heavy (Wells, 2019). Although my family still owns a car, it can sit unused for days with most trips for visiting family, shopping and study done on aerodynamic cycles I have designed and built, including a trike with a 250W pedelec electric motor. This trike is used for a 20k round trip to nightschool and has proved reliable and easy to own and use. Being very accustomed to pedaling my trikes, I use the motor mainly for hills or starting at traffic lights (Nurse 2019).

Figure 4: Valka Vista e-bike with lights but no inbuilt luggage storage, Author's aerodynamic pedelec trike with lights and 50 litre of storage behind seat (Wells 2019, author)

1.3 Velomobiles in context

Improved cycles should include not only electric bikes but also statically stable trikes and weather protecting velomobiles to make cycling an always-acceptable short-distance option for most people (Cox 2006, Richardson 2010). Velomobiles can complement other cycle types to make a diverse low energy cycle fleet, and together, low energy cycles could become our default owned form of transport.

A velomobile can combine features from an electric utility cycle and a record breaking speedbike. The *electric utility cycle* has load capacity, is easy to mount and can replace short car journeys. Compared to unassisted bicycles, they carry more further with less effort, and compared to cars use less road and parking space while providing useful exercise.

The *speedbike* is altogether different, designed only for going fast. To do that, aerodynamics and low frontal area are emphasized above all else including easy vehicle access. Although impractical for everyday transport, their aerodynamics can be applied to their velomobile-practical-cousins to achieve improved speeds independent of motors.

Figure 5: Top: Electric utility cycle and speedbike, and bottom: Velomobiles (Velo-ads 2018, Russo 2019, Hasebikes 2019, Velomobiel.nl 2019, A1AA1A 2017)

Velomobiles are most commonly based on recumbent tricycles with the rider close to the ground, so can be both statically and dynamically stable. They cover and insulate the rider, so can be used in a wide range of weather conditions (Ferrari 2013). “Auntie Helen” is an English cyclist living in Germany who has a prosthetic arm and blogs about Germany and velomobile culture. She commutes by velomobile in all weathers including snow and rain, routinely covering between 300 and 1220 kilometres per month in electric and non-electric velomobiles (Helen 2019).

Australian velomobile manufacturers include Trisled and Gtrikes who make velomobiles for road use and for the schools sport of Pedal Prix endurance racing. Pedal Prix velomobiles are different to roadgoing machines because they must accommodate a team of riders of different sizes and heights, and because they must have seatbelts, roll cages and other safety requirements.

Australian roadgoing velomobiles include Trisled’s Rotovelo. It was introduced in 2011, and has a thermoplastic rotomoulded shell which is more robust than most thermoset-plastic velomobile shells. Costs start at $6500: an electric motor assisted version is advertised for $9500 and a lighter carbon-fibre-shell version is $10900 (Ball 2012, Trisled 2019)

In 2019, Gtrikes bought the rights to produce the Greenspeed-developed Glyde velomobile. Gtrikes development team includes contract aircraft builder Brett Turner, and they aim to produce the Glyde in shell-as-frame / monocoque form. Greenspeed's Glyde production included a steel frame (Turner, 2019, Velomobile facebook group 2019).

Some Australian race series are part of education and development of sustainable transport. One focusing on secondary education and use of alternate energy sources is the Energy Breakthrough series where schools incorporate electric motors into pedal prix velomobiles. This is held annually in Maryborough, Victoria (Pedler 2018).

An event held every two years is the World Solar Challenge with the next edition running between Darwin and Adelaide from October 13 2019. Universities from around the world compete. Although the event does not include human energy as a power source, it features practical solar vehicles and light aerodynamic solar-electric vehicles with composite bodies. Developments first trialed in the World Solar Challenge include axial flux electric motors used on Avanti e-bikes (World Solar Challenge 2019, Charles Darwin University 2006).

1.4 Scope and technologies

Although many technologies can be applied to improved cycles and velomobiles, this article concentrates on several encountered through my 3d printing and cycle design practice, reading, and contact with research groups and manufacturers. The technologies *3d printing, solar cells and structural battery cells* seemed underexposed in relation to velomobiles, and as a method of selection I have focused on local manufacturing and research with potential velomobile applications.

Other technologies which could improve velomobiles include hydrogen fuel cells which have been researched by the University of New South Wales and the German Fraunhofer Institut (Aguey-Zinsou, 2015, Fraunhofer 2019), and series hybrid electric drivetrains (Nurse 2018, Fuchs 2014). These technologies are out of scope. Fuel cells are complete systems encompassing fuel, energy conversion and electric drive, and could be used in conjunction with the 3d printing discussed here. Series hybrid electric drives have all their energy output delivered through a motor but can take energy from human power, batteries, solar panels and other sources. All the technologies discussed in this paper could be apply to series hybrid velomobiles.

Velomobiles may be new to many readers, and I have already introduced them. However further analyzing velomobile use, commuting distances, cycling and velomobile uptake, benefits in Australian weather, off-vehicle solar charging, and how velomobiles could relate to Australian greenhouse gas emission goals is out of scope. Suggested reading on these topics is Helen 2019 (velomobiles in everyday use), Van De Walle 2004 (velomobile overview) and Cosgrove 2012 (Australian velomobile uptake and potential for greenhouse gas abatement).

1.5 Aims

The article aims to provide a thorough introduction to velomobiles and their characteristics with an emphasis on their role as sustainable transport. It aims to promote emerging solar, battery, and 3d printing customization technologies by showing their use, potential, and contributions in sustainable velomobiles. It hopes to promote interaction by highlighting Australian researchers and manufacturers.

Discussion includes the author's electric leaning trike which has swap-out panels which could be repurposed as batteries or solar cells.

2 New velomobile technologies

Velomobiles must be light to be carried easily, accelerated or propelled up hills by the power supplied by humans and small electric motors (Van de Walle 2004, 100). According to Van de Walle they are the most efficient form of transport. Despite this, they share requirements for light weight with passenger aircraft, the least efficient vehicles. The driver for light weight in passenger aircraft is fuel use: each kg of weight saved in an aircraft can save approximately 3.8 tonne of aviation fuel (Appendix 1).

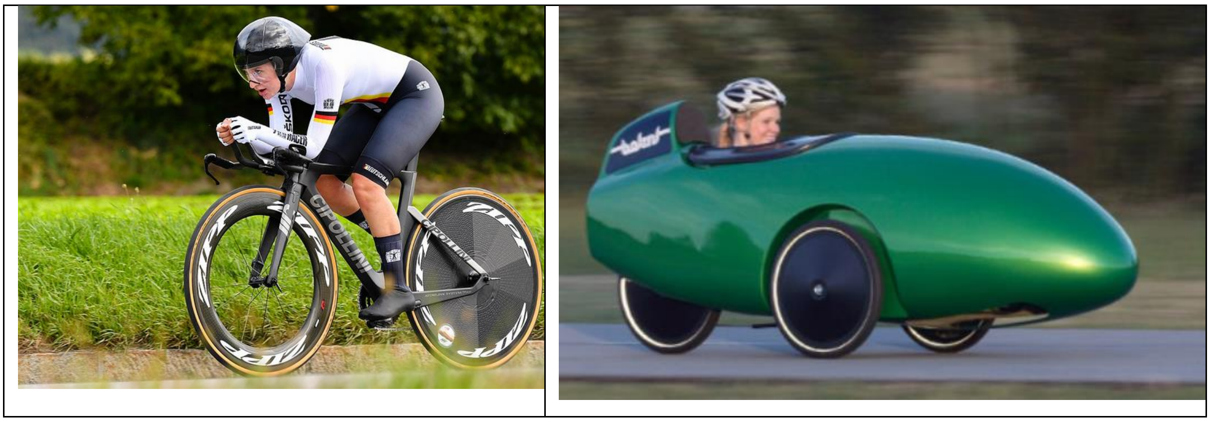
Velomobile technology already overlaps aeroplane technology in that both use strong, lightweight materials including carbon fibre, and rely on aerodynamics for performance. The following sections deal with technology for improving velomobiles: solar power, right sizing and simulation through 3d Cad and 3d printing, and incorporating batteries into structural materials. 3d cad and printing can make improvements independent of any electrical assistance, while solar and battery technologies could improve electrical assistance.

2.1 Custom 3d printed velomobiles

It is hard to imagine road cycle racing without the aerodynamic clothing riders use. This clothing gives cyclists speed advantages of 6 -10% compared to street attire by being slick and tight which improves the pattern and minimizes the volume of air disturbance. Cyclist posture also influences racers' frontal area, with riders reducing area and effort by bending low when travelling at high speed (Kyle 1986).

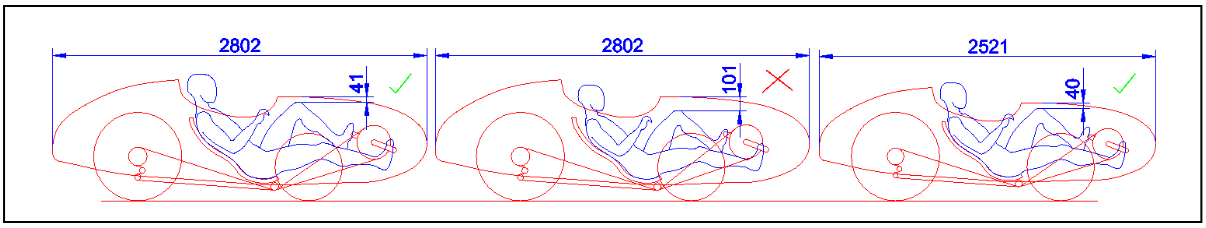
Velomobiles are cycles which minimize air disturbance patterns using a fixed low-profile body position and aerodynamic covering. However minimizing the area of air they disturb could use more attention. This is because velomobile shells are routinely made in moulds determining shell size with only one or two shell sizes available.

Figure 6: Cyclist's frontal area: Determined by posture and clothing of racing cyclist but fixed for velomobile rider. (Granada 2018, Trisled 2019)



Consider a velomobile designed for a person up to 180cm (5'11") high and weighing 100kg. The velomobile works well for a person of that size, with snug clearances between rider and body shell ensuring the velomobile has minimum size and frontal area, and design ensuring components are strong enough for combined vehicle and rider weight. Now consider a 163cm (5'4"), 60kg person in the same machine, which may be the smallest available from a manufacturer's moulds. Because clearances and component strengths are greater than necessary, the rider carries unnecessary frontal area and overweight components. Assuming the velomobile height and width can be changed in proportion with rider height, the frontal area can be reduced to 82% of the original resulting in 6% more speed on the flat at 20 kph (Figure 7, Appendix 2). Reduced size and weight mean the velomobile shell would weigh less, and components could be less strong and weigh less, enabling better hill climbing, acceleration and making lifting it safer and easier.

Figure 7: a) 180cm rider in correctly sized velomobile shell. b) With 163cm rider in the same machine, the shell is oversized and the rider carries extra weight and wind resistance. c) correctly sized shell for 163cm rider. (Author's sketches)



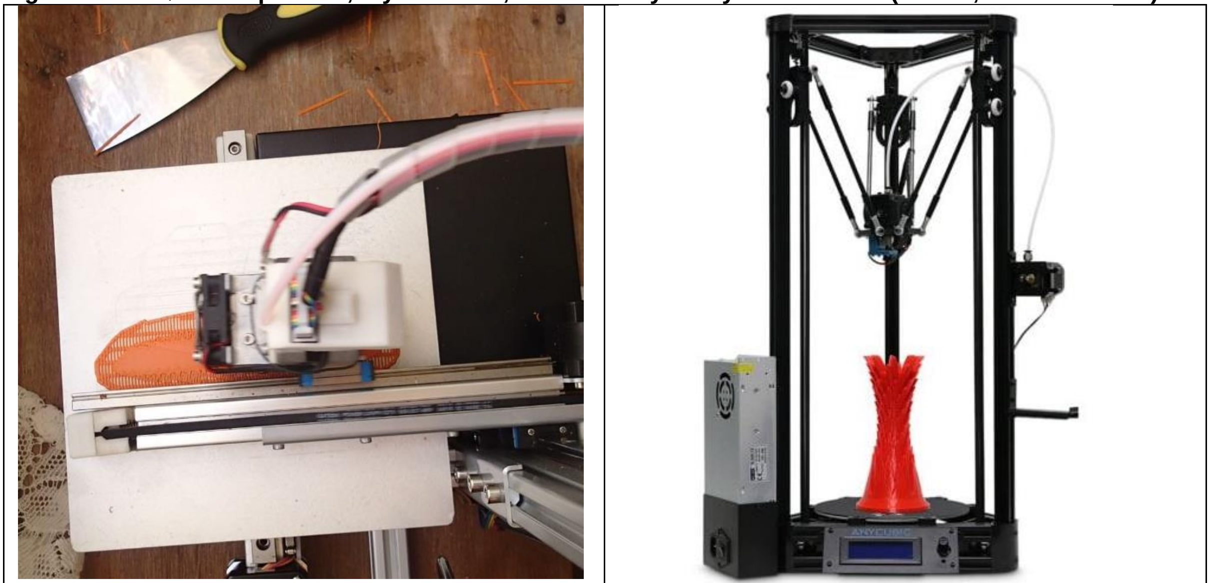
a) **b)** **c)**

This-right-sizing of velomobiles for occupants should be possible by 3d printing components including the shell. 3d cad, adjustable mock-ups, virtual reality and scanning technologies could be used to size, visualise, prototype, evaluate, design and advertise these new machines. One off velomobile shells could be printed to suit a rider and their need to carry luggage.

3d printers have proliferated in the last 10 years with growth rates of 30% per year since 2010, and are used for production to the extent that "Additive Manufacturing" has become a term describing their use (Bourell 2016). 3d Printers are robotic construction machines which interpret computer files describing 3d shapes as print head movements to deposit material. The accumulated path of deposited material results in real-world objects independent of casting moulds or material removal. 3d printing can be carried out using biological, metal, concrete, ceramic, plastic, and reinforcing fibre materials (Wu 2016) on scales from nanometres (=<0.01mm) to house size (=>5m).

As well as a range of materials, 3d printing works with a range of coordinate systems. My home 3d printer uses a 3 degree of freedom XYZ coordinate system. Another home printer, the Anycubic Kossel uses the Delta system of 3 vertical, parallel, linear rails to produce a 3 degree of freedom print head motion. More expensive printers such as those from Australian Spee3d and Arevo use industrial robots to provide motion. These robots can have more than 3 degrees of freedom, allowing material deposition from variable angles, not just to particular points.

Figure 8: Sub $400 3d printers, my Cetus 3d, and delta style Anycubic Kossel (author, Gearbest 2019)



3d printing technologies are scaleable, with human sized / cycle sized objects now being printed using Delta technology. Tractus 3d vertical printers make life size mannequins, and their largest model prints up to 2.1m high, just less than the lengths (2.4m, 2.84m) of the Rotovelo and Quest velomobiles (Hiles, 2014, Tractus 2019). Compared to traditional manufacturing methods, printing a velomobile could have customization advantages, not only minimising frontal area and weight but also providing luggage space, positioning mirrors and providing for use by other family members.

Figure 9: Large scale printers: Australian Spee3d metal printer, Tractus3d delta printer (author, Tractus 2019)

Far from being a future manufacturing method for cycles, US company Arevo is currently making 3d printed cycles which are vastly different from 3d printed bicycles produced in 2011(Daily Mail 2011, Frptitan 2018). Arevo see their cycles as relatable human-scale items that can be readily assessed in their own right. This relatability might not be present if the company were making (say) a car chassis. As well as making frames for electric bikes for Oechsler, they have speculated on human powered vehicle designs including load carrying bikes and a faired, tandem recumbent. Without needing moulds, Arevo claim product development times of 18 days, down from 18 months for composite products requiring moulds. Arevo have made Aerospace parts up to 2.5m x 1.5m (Daily Mail 2011, Frptitan 2018, Compositesworld 2018).

Figure 10: 3d printed bicycles in 2011 and 2018. (Daily Mail 2011, Frptitan 2018)

Being able to 3d print custom-sized velomobiles is one thing, but being able to size and market them is another. However existing technologies for capturing and visualising riders on bikes could be used. Wearnotch sensors are worn on the body to capture and display movement on smartphones and record movement as computer files. This technology could be used in conjunction with an adjustable recumbent exercise bike to capture motion, then calculate internal sizes for a velomobile.

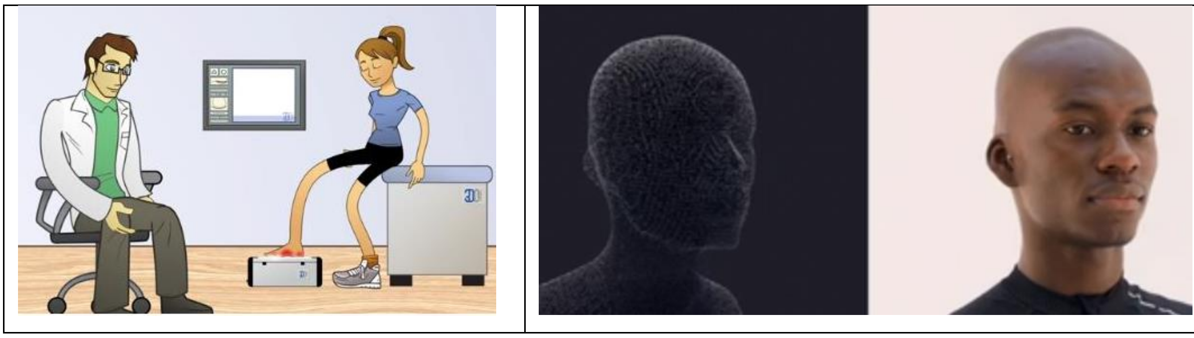
Figure 11: Monash University adjustable speedbike simulator, application and use of of Wearnotch sensors (Monash Human Power 2019, Wearnotch 2019).

An extension of Wearnotch technology would be to use its data to create virtual reality environments including a proposed velomobile shell. Further inputs could include pedal resistance to simulate riding and racing. These simulations could gamify and show the speed potential of custom velomobiles. “Marky D” is a Sydney velomobile user, and makes first person view videos from his Australian Rotovelo velomobile, the sort of vision achievable in this proposed velomobile virtual reality. Due to the aerodynamics of his machine, Marky will typically pass many, many cyclists in his videos (geek.com 2016, Marky D 2019, Wearnotch 2019).

Figure 12: Virtual reality in cycling, rider point of view from Marky D's velomobile, velomobile racing (geek.com 2016, Marky D 2019)

Measuring riders for correct velomobile size and strength, velomobile manufacture using 3d printing, and virtual reality velomobile simulation could form a tool set or *ecosystem* to encourage velomobile use. Ecosystems involving scanning, 3d printing and mobility already exist, and examples include 3dprintedorthotics.com.au (2019) who scan feet to produce printed shoe inserts helping customers walk and run, and hexr.com (2019) who 3d print custom bicycle helmets after scanning the customer's head.

Figure 13: Ecosystems involving body scans and mobility: 3dprintedorthotics.com.au orthotics and Hexr.com helmets (3dprintedorthotics.com.au 2019, Hexr.com 2019)



2.2 Solar

Solar power is a widely used renewable energy source. Solar energy is generated by rooftop photovoltaic cells for off-grid and grid power generation, and stand-alone photovoltaics for large-scale grid generation. Unlike base-load energy technologies such as coal and gas fired power stations, solar power is intermittent, site dependant, and changes on daily and yearly cycles. To provide constant electrical power, photovoltaics must be connected to a battery or other energy storage (Kabir 2018).

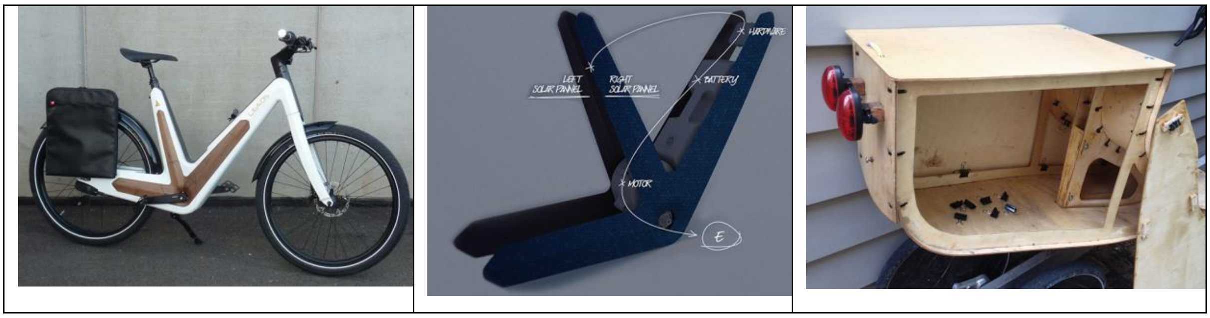
Despite this intermittency, solar power is being used in more direct methods for transport than simply supplying a grid which then charges electric vehicles. These include static photovoltaics powering bike-share rechargers and on-cycle photovoltaics (Gowrisankaran 2016). Static solar is out of scope for this paper, and this section discusses direct on-cycle photovoltaics.

As mentioned, solar power is intermittent, and cycle motion makes on-cycle solar panels even more intermittent than static panels (Apostolou 2018,10). However solar power has been used in a range of vehicles including e-bikes, boats and planes, and now velomobiles. Photovoltaics integrated into vehicles can be described as Product Integrated Photovoltaics and a Dutch survey has concluded solar assisted electric bicycles are effective transport (Apostolou 2018).

When mounted above a velomobile, photovoltaics can form a canopy and protect riders from sun, dust and cold. Configurations providing mainly sun protection can be set up as a flat panel roof which minimizes extra wind resistance. This is favoured in some solar bike races (Suntrip 2018).

However perhaps the factor most in favour of solar velomobiles and e-bikes could be that modest amounts of electrical energy can power them (Rose 2012). An example is an e-bike sold by Leaos with side-mounted solar panels transforming direct and indirect sunlight into electrical power. The bike is carbon fibre and Leaos claim it can recharge itself from sunlight only for daily rides of 15km (Leaos 2019). This recharging comes from approximately 17dm^2 of side-mounted panels. As a comparison, my e-trike includes a 14.4 dm^2 boot lid / top panel and 47.2 dm^2 side panels. This area is available for solar panelling and indicates my e-trike could be a good candidate for including photovoltaics (Appendix 3, Figures 4 and 14).

Figure 14: Leaos Solar electric bike and solar charging system, author's trike with side panel removed and removable boot lid. (Leaos 2019, author)



Trailers fitted with solar panels can carry loads while powering the electric / human powered vehicles they follow. Jürgen Burkholz designed a solar caravan for his trike for the 25,000 km "Suntrip" solar bike race and went on to incorporate panels into a load carrying trailer. Rob K's electric trike with solar trailer features on the Azub website and uses a 25% efficiency yachting solar panel (Burkholz 2019, Azub 2019). There seem to be no commercial solar bike trailers although DIY builds have been documented (travelbikesandstuff 2012). Commercial solar velomobiles include the Elf, Evovelo and the Pedilio (Organictransit 2019, Evovelo 2019, Pedilio 2019).

Figure 15: Solar velomobile, Pedilio solar electric quad bike (Pvvelo 2019, Pedilio 2019).

Solar film technology from CSIRO promises to make solar energy provision lightweight and able to be installed on a variety of surfaces. They have developed 19% efficient solar cells which could be applied to velomobiles to boost electric drives (CSIRO, 2018, Zuo 2018).

2.3 Battery technology

Velomobiles are generally heavier than bicycles because they include aerodynamic fairings and an extra wheel. With batteries, motors and controllers, electric velomobiles are heavier still. Velomobile weight reduction will improve performance, and weight has been cited as a reason why e-bikes are more common than velomobiles (Hiles 2014). For a cue as to how electric assist velomobiles can be made lighter, aeroplane technology can be observed. Just as carbon fibre was used in bicycles after being manufactured for aircraft, (Roberts 2007) structural battery technologies proposed for aeroplanes will benefit e-bikes and velomobiles.

Aerospace use and optimization of strong, lightweight carbon fibre material is now standard, however new technologies promise to make aircraft lighter and more efficient. Specific applications are to give unmanned aircraft greater range, and to enable production of larger electric passenger aircraft. Research is now at aimed at commercializing multiple simultaneous uses of carbon fibre material, or multifunction composites. As well as providing structural strength these composites can be self-healing, variable in surface roughness, thermally conductive, electrically conductive, sensing, vibration damping or used for electrical energy storage (Jay 2015). Whatever the new materials' advantages, their after-original-design-life uses and recycling should be established. Without this, the new materials could be solving one waste problem only to create more (McDonough and Braungart 2010).

This section concentrates on electrical energy storage. Adam, Liao, Petersen et al (2018) list five multifunction composite energy storage technologies and document their advantages for use in electric aircraft. They see flight range extensions of up to 66% being possible through multifunction composites. Legault (2019) uses the term "composite structural supercapacitors" to describe multifunction composite batteries and considers that although their first application will be in military drones or unmanned aerial vehicles they could one day power cars or trains.

If multifunction composites were used in electric assisted cycles or velomobiles, some of the battery weight could be subsumed in the frame or shell weight. As well, cycles or velomobiles could make good early, simple, visible, relatable, useful applications for multifunction composites.

The first lightweight supercapacitor batteries may be available as panels, suitable for installation into frameworks such as that on the author's trike (Figures 4, 14) This type of battery panel was researched by Volvo in 2010 (Asp 2015). Later developments will increase complexity but improve strength and allow incorporation into monocoque frames.

Swinburne university has a composite battery research department, with a paper by Chan (2018) reviewing progress in the field. This paper discusses the strength and storage capacity of novel materials, however Shirshova (2014) discusses working prototypes of structural composite batteries. It seems actual use of structural composite batteries is still years away.

3 Discussion

All new cycles have relied on individuals and researchers including counter-cultural advocates, early manufacturers, champions and demonstrators of new technologies' effectiveness (Cox 2015, Richardson 2010).

After demonstrations of effectiveness, commercialization and widespread adoption of technology can follow. However while I have ridden recumbent cycles on the road for more than twenty years, I cannot see any increased uptake in recumbents or velomobiles. Despite this, e-bikes and freight bikes *have* seen beneficial growth, at least partly because mass-manufacture has brought prices down and because they are effective (Wells 2019, Cox 2015).

Further work to promote velomobiles could include development of printable designs for velomobile shells, development of generic designs for velomobile solar / battery panel integration, and cost and technical analysis of technological combinations in velomobiles. These combinations should include technologies outside the scope of this report including fuel cell and series hybrid drivetrains.

However for more widespread adoption of recumbents and velomobiles of all sorts, my advice is for openness in design and research, and the application of new technologies in relatively simple human powered vehicles. Peter Cox (2015) cites the low barriers to making, fixing and adapting cargo bikes as reasons for their continuous use in Europe throughout the 1970's. The barriers for adaption of new technologies that will assist velomobiles should be kept low as well, with the use of technologies by students or anyone who could become advocates as important as any other aspect of research.

4 Conclusions

New technologies including 3d printing, virtual reality, structural batteries and flexible solar cells could add significantly to the speed, usefulness and adoption of cycles including velomobiles. Increased velomobile uptake would be a significant move toward more sustainable transport.

Simultaneously cycles and velomobiles could showcase these new technologies in applications which are simpler and more relatable than their use in cars or aerospace.

The highlighted technologies should be developed individually or in parallel to enhance low energy transport. This development should not be limited to formal research in universities: it is our role as researchers to encourage the wider use and seeding demonstration of technologies we work on.

Acknowledgements

Thanks to Doctor Tim Corbett and my wife Christine for reading and commenting on an early version of this paper.

Appendix 1: Fuels savings from lightweighting aircraft:

From Huang (2016): "Each 100 kg reduction in the weight of an aircraft is estimated to save 13.4-20.0TJ of fuel over the course of a 30 year life of an airplane" This translates to each kg saving an average of 167,000 Mj. Aviation fuel energy content is approximately 43.5 MJ/kg (hypertextbook.com 2015). So approx. *3840kg* of fuel are saved per kg of aircraft weight reduction.

Appendix 2: Speed increase with reduced cycle front area:

On flat ground and ignoring rolling resistance, the equation governing speed of a cycle is $Pr \times (n/100) = Vr \times (0{,}5 \times rho \times Cd \times A \times (Vr + Vw)^2)$, refer Van De Walle 2004

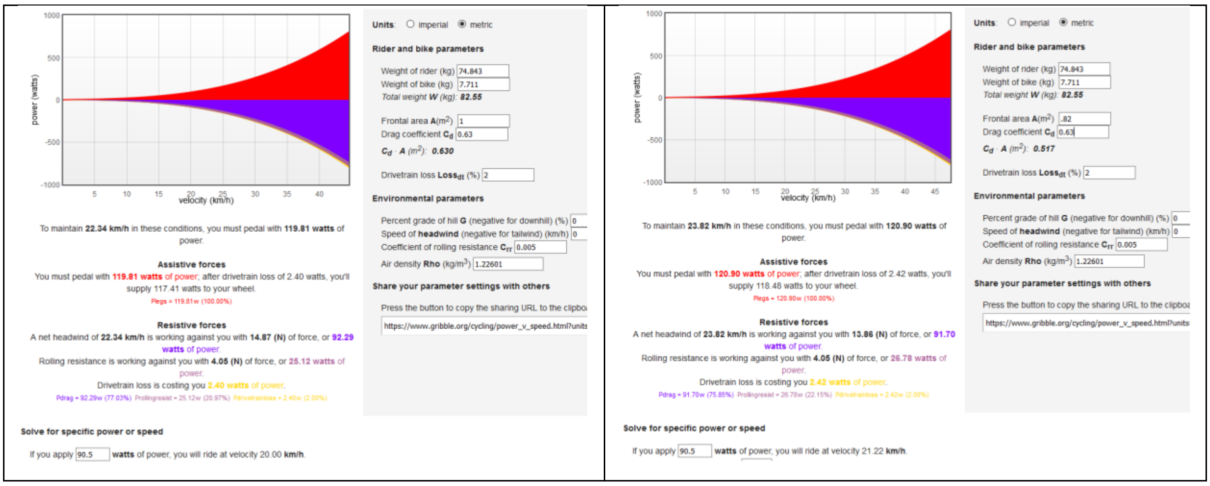
where Pr = power delivered to overcome wind resistance (at pedals) (W), n = power transfer efficiency (%), Vr = vehicle speed (m/s), rho = air density (kg/m3), Cd = drag coefficient, A = frontal area (m2) and Vw = wind speed against riding direction (m/s)

Assuming zero wind speed, and using a constant K to represent constants and changed units, this can be reduced to:

$K/A = (Vr)^3$, and for Vr = 20 kmh and A = 1 unit, K = 8000, then for 0.82A,

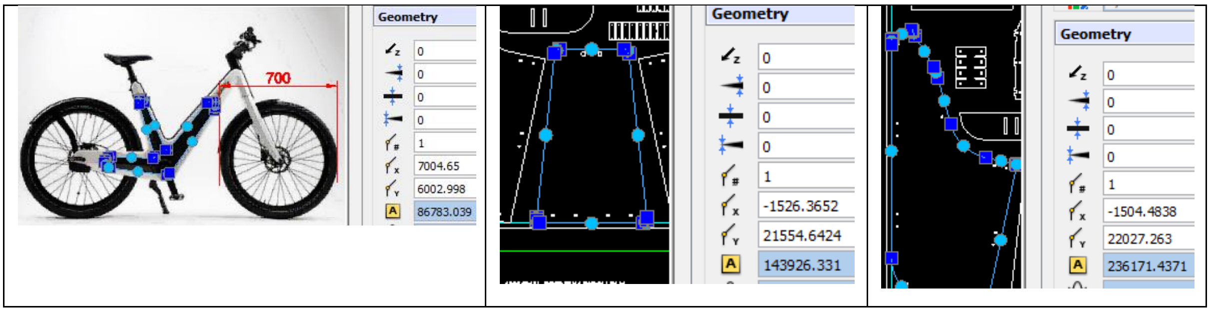
$8000 / 0.82 = (Vr1)^3$, and Vr1 = 21.3 km/h

An online calculator (Gribble 2019) confirmed this, under otherwise unchanged conditions a frontal area reduction from 1 to 0.82m^2 showed a cycle speed increase from 20 to 21.2km/h



Appendix 3: Area estimates for panels

As shown below, my 2d cad tracing of the Leaos Solar panels uses the wheel size to obtain scale & indicates there are (2 x 8.7dm^2 or) 17.4 dm^2 of side-facing panels on the e-bike. Cad data from author's bike shows 14.4 dm^2 top panel and (2 x 23.6dm^2 or) 47.2 dm^2 side panels totalling 61.6 dm^2.



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