Do Mountainbikers Require Dedicated Commuting Bicycles? A Systems Approach

Abstract
This portfolio outlines analysis of the question “Do Mountainbikers require a dedicated Commuting Bicycle?” Anthropometric, time, energy, materials and economic approaches are taken. Quantitative analysis is completed throughout, alongside qualitative analysis of perceptions of the question. System aspects including maintenance, time, energy use, congestion, environmental impact, user comfort and safety are considered throughout. This analysis is then fed into a comprehensive analytical model of the system which is tested/verified based on survey results. Optimization of this model is also considered alongside qualitative considerations. The paper concludes that the model produced is a reasonable method of determining economic choices for individuals and that mountain bikers are often in a favourable position in buying a second (road) bicycle to commute.

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Introduction

Mountain biking is a highly popular sport for many reasons. Studies have shown that mountain biking offers fantastic health benefits, such as increased bone density, muscle mass and strength (even more so than road cycling) (McVeigh et al., 2014), while also offering an exciting and engaging sport for people of many ages. Furthermore, recreational cycling is positively correlated to increased rates of cycling for the purpose of commuting (Kroesen and Handy, 2014). It has also been established that those who undergo "active commuting" such as riding a bicycle to work, express feelings of heightened mood throughout the work day and to the greatest extent in comparison to other forms of commuting (Morris and Guerra, 2014).

Due to these relationships, it is of great interest as to whether or not those who Mountain Bike recreationally require a specialised bicycle for the purposes of commuting. Commuting bicycles and mountain bikes have very different design features which make them suitable to the respective use cases. Mountain bikes often have design features such as stronger and therefore heavier frames, suspension, hydraulic disk brakes, wider handlebars, and larger wheels with deeper tread. Road and commuting bicycles are often designed with lightweight frames, small, narrow wheels, narrow handlebars, wire-controlled wheel rim mounted brakes and rarely have suspension, all of which are designed to improve speed, ease of maintenance and ease of use for use on smooth roads and cycling paths. It remains in question as to whether the perceived benefits of these design features justify the costs (economic and otherwise) which come from buying a second bicycle.

Hybrid bicycles are designed to be a "half way" between mountain bikes and commuting bicycles, often having design features from both disciplines, such as moderately thick tires, flat handlebars, limited suspension and disk brakes. It is yet to be fully established if hybrid bicycles truly meet the design requirements of either commuting or mountain biking to a great extent. Particularly, this is of question as hybrid bicycles often have higher starting prices and can even become as expensive as two lower priced, specialised bicycles (Giant, 2014). This portfolio attempts to use Systems Engineering Analysis techniques to answer the overall question by looking at the question using multiple perspectives.

1.0 System Scoping

Use Case: A casual mountain biker who wishes to know if it is reasonable (economically, and otherwise) to buy two dedicated bicycles for mountain biking and commuting, to buy a hybrid bicycle or to buy only a mountain bike. It is assumed that the cyclist does not perform any extreme mountain biking that would preclude the option of a hybrid.

Stakeholders: Bicycle owner, transport authorities, town planners, commuters

Exclusions from system scope: Factors which are highly unpredictable and based on personal preference will be largely excluded. This includes factors such as the probability of theft, the desire to maintain bicycles in given configurations or set ups, cycling attire and geographical considerations. For the purposes of the report, it will be assumed that the client lives in an area where sufficient infrastructure is present should the client decide to use a commuter/ road bicycle. It is also assumed that the individual wishes to invest in a good quality bicycle for future use.

2.0 Quantitative and Qualitative Analysis

2.1 Estimations of Energy use for Different Cycles

Estimations were completed in order to determine the energy use of an individual per km when using a mountain bike, hybrid bicycle and road cycle on a stretch of flat road. This was done in order to establish the potential energy trade off that is associated with each cycle.
The power input required to move a bicycle at a given speed on a bicycle is calculated using equation 1.

$$P = gmV_g(R + s) + KV_a^2V_g \qquad (1)$$

Where "P" is power, "g" is gravitational acceleration, "V_g" is velocity relative to the ground, "V_a" is the velocity relative to air, and "s" is the grade, given as a ratio, "R" is the rolling resistance coefficient, "K" is the air resistance coefficient. In the case of this paper, the velocities relative to air and ground are considered to be equivalent, as if the air was stationary (no wind). The gravitational acceleration is assumed to be $9.81ms^{-2}$ and the grade is assumed to be zero, as if the rider is on flat ground. The rider is assumed to have a mass of 70kg. With these assumptions equation 1 simplifies to equation 2.

$$P = V_g(gmR + KV_g^2) \qquad (2)$$

This estimation has many associated errors. Firstly, the friction in moving components is not taken into account. This may be a large factor when comparing bicycles of different costs, as more expensive, lighter and newer bicycles will have far lesser losses in the drive chain and bearings of the bicycle. As noted, the estimation excludes grade and wind, which may be important in bicycle choice, particularly when a commute has particularly large hills, or if there is a consistent wind. Pointedly, when climbing a hill, wind resistance has a reduced effect, due to the reduced velocity and as a result of the cubed power which influences the term for wind resistance. Thus, on climbs, aerodynamics becomes far less important to the rider. On downhill rides, however, this factor is reversed, with rolling resistance having near-negligible effects. Any value which is chosen for the coefficients "R" and "K" present some error, due to permutations of individual riders, including their preferences such as wearing a back pack, different helmets and different clothing. Equation 2 is explored in more detail in Sections 5.2 and 6.2.

2.2 Survey

A survey was designed to gauge the opinions, attitudes and choices surrounding the question of interest. The survey attempted to focus on two main questions: Why do people commute on bicycles, and what are trends amongst this group? Do those who commute on bicycles have a dedicated bike for this purpose? The survey was publicized targeting members of the Australian National University Mountaineering Club (ANUMC) (although it was made public, and was not restricted to ANUMC members), as it was thought that these respondents would have a higher probability of being mountain bikers, thus within the scope of the question, and would also be from the Canberra region, thus largely removing geographic position as a variable.

The survey questions and raw data collected can be found in ANNEX A. Questions 1 and 2 were demographic questions, questions 3 and 4 determined if respondents were mountain bikers, and if they cycled to work, questions 5, 7 and 8 determined why respondents did or did not commute to work, including a multiple choice for distance to work. Questions 5 asked if respondents had a dedicated commuting bike, and 9 asked regardless of whether or not they commuted; what their choice would be between dedicated bikes, a mountain bike and a hybrid. Reasons for answers were asked. Question 10 asked the net worth of respondents bicycles, to gauge the economic position (in regards to willingness to spend money on bicycles) of respondents.

As noted, the survey was deliberately advertised and targeted to mountain biking enthusiasts, as they are the clientele of interest. Some confounds still remain. For example, respondents were not screened, to determine if they would be suitable as example clients. Questions 5, 7, and 8 were used to identify possible non-client respondents and remove them from data. Another confound arises from proposed answers to questions. Multiple choices was used to reduce survey time and increase the number of respondents, but sacrificed the possible detail and range of possible responses, limiting qualitative analyses.

2.3 Survey Results, Distributions and Coding

A total of 23 responses were gained. Generally, respondents were of the ages 20-30, and male. This was expected from the targeted audience. The 3 respondents who answered that they did not mountain bike recreationally were removed from the results. Approximately 70% of respondents commuted to work on a bicycle most days of the week, with an additional 15% which commuted on a bicycle once or twice per week. Results of distance to place of work/ study fit a bell curve, with a peak at 5-10km and extremes of <1km and >50km. 70% of those who commuted to work on a bicycle claimed to have a dedicated bicycle for this purpose. Of the three respondents who claimed to not commute, 1 claimed to walk, and another claimed to be planning to commute on a bicycle in the near future. All respondents who commuted on a bicycle claimed fitness as a key reason, with economic reasons, speed and environmental sustainability, traffic, parking and enjoyment as provided other reasons, which agrees well with the research by Morris *et al.* (2014). In answer to the question "…Would you buy a second bike for commuting, use a hybrid or commute on your mountain bike?..." 80% of respondents responded that they would have two bicycles, providing reasons such as efficiency and speed of commuter bicycles and reduced maintenance of the mountain bicycle as another common reason.

Some qualitative results were gained from feelings expressed by the respondents. Points which influenced decision making included differences between bike types such as gear ratios, geometry, suspension configurations and the idea that each activity can only be enjoyed with a specialized bicycle. Some respondents expressed concern about having their expensive mountain bike stolen. Respondents, who decided that riding the mountain bike to commute was a better option, gave few reasons outside the personal preference to have only one bicycle. Only the respondents who claimed to not mountain bike recreationally (who were removed from the survey) answered that a hybrid was the best option. Claiming that this indicates that no mountain bikers would be comfortable on a hybrid would likely be a misattribution of causation as a result of the small sample size. A common trend amongst all responders was that commuting bicycles were generally far cheaper or older than their dedicated mountain bicycles and road cycles, although this was generally coupled with fears of theft. For the purposes of this analysis, it is assumed that the user is looking to invest in new, good quality bicycles.

3.0 Human Factors

3.1 Anthropometrics

Anthropometrics is the study of the dimensions of the human body. Bicycles have a large amount of customizability in order to fit the individual rider as comfortable as possible. However for two individuals of the same height and leg length, road cycle frames tend to be approximately 18% larger, and mountain bike cranks (which attach the pedal to the cog) tend to be approximately 6% larger (Burke, 1994). This indicates two factors. Firstly, the force requirements for each riding situation are different. Larger cranks are likely used in mountain bikes due to the higher moment that can be produced, which may be required to quickly accelerate the bike. The smaller frame size in mountain biking is likely due to the fact that mountain biking often requires riders to stand out of the saddle, while road cyclists spend more time sitting. This clearly indicates that anthropometrically, the two bicycle types favour different riding styles, indicating that specialized bicycles may be required over long distances as discussed in Section 3.2 (J.C. Martin, 2001).

3.2 Ergonomics and Comfort

Multiple studies have investigated the ergonomics of cycling. In terms of muscle fatigue, it has been established that bicycle posture is a great contributing factor for fatigue and strain injuries amongst cyclists (Balasubramanian et al., 2014) . It has been established that saddle design, frame shape and handle bar design are considered to be the largest contributors to comfort in terms bicycle subsystem design, with rider posture, as seen in Figure 1, being the largest contributor to safety in terms of system design (Ayachi et al., 2014). These factors will be discussed here.

Saddle design and frame shape do not significantly alter between the three bicycle categories being considered. However, handlebars and rider posture do vary. Road cycles, mountain bikes and hybrid bicycles adopt different stances according to their different handlebars. Road cycles generally move a faster pace, and therefore have greater aerodynamic considerations, leading to lower "dropped" handlebars. This produces greater back strain (Ayachi et al., 2014). In contrast, mountain bikes often require the user to stand out of the seat and to produce greater turning moments, with far less aerodynamic requirements; therefore mountain bike handlebars are higher and also wider than those of road bikes. Hybrid bicycles may take either handlebar configuration depending on personal preference and model (Giant, 2014). Multiple studies have looked into alterations of bicycle design that may be used to reduce discomfort. Raising the height of the handlebars has been reported to help to reduce back pain (Balasubramanian et al., 2014). Rear Suspension has been shown to significantly reduce fatigue in the upper and lower spine (Balasubramanian et al., 2014).

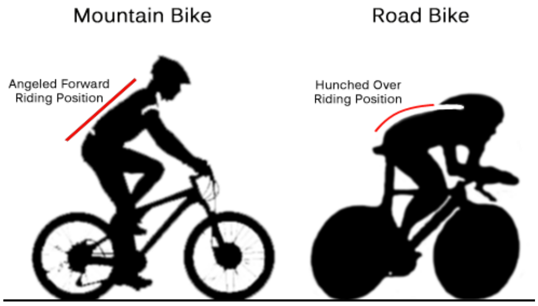

Figure 1 Schematic of different riding postures (BeachBikes, 2013)

In these simple cases, a key trade-off is established in terms of ergonomics and comfort. Mountain bicycles have suspension and a riding stance which are conducive to greater rider comfort, and this stance is often adopted by hybrid bicycles. However, the aerodynamic benefits of the road cycle riding posture may outweigh these factors if total riding time is significantly reduced. The choice would be based on user preference.

Another factor to be considered is temperature, which is a key motivator for rider comfort (Heesch and Sahlqvist, 2013). In the aims of producing an analytical model as outlined in Section 8, it could be established within what temperatures an individual would be willing to commute on a bicycle. An estimation of 10 to 30°C could be made, which for the hours of 7:00am and 6:00pm could be married with climate data for the Canberra region to estimate the number of days per year an individual would be willing to ride to work. Due to the large error associated with such estimates, instead, in the model, a question is posed to the client. We can however postulate from Section 5.2 that road and hybrid bicycles would lead to higher user comfort in terms of temperature by virtue of the lower human power output requirements of riding these bicycles.

4.0 Time Analysis

4.1 Queue Theory

In order to address the question of interest, both the bicycle system itself, and the commuting system into which cyclists fit must be considered. Queue theory may be applied in analysing the operation of bicycle queues on cycle paths during peak periods. The main focus of this analysis is the "service time", the time in which the cyclist slows to a stop, waits and then accelerates up to top speed may be compared. This can be calculated by equation 3, where "$\overrightarrow{\Delta V}$" is the change in velocity between the velocity of travel and the velocity of crossing (zero for waiting at a stop), "t_{wait}" is the time waiting for lights or cars, "m" is the mass of the user and their bicycle and "F_b" and "F_a" are the forces of braking and accelerating respectively.

$$Service\ Time = \left|\frac{\overrightarrow{\Delta V}m}{F_b}\right| + t_{wait} + \left|\frac{\overrightarrow{\Delta V}m}{F_a}\right| \qquad (3)$$

By reducing service time period, the maximum number of bicycles that can be serviced within a given waiting period increases, reducing congestion. Equation 3 is an arbitrary number which has large associated error if it were to be integrated into the model; however it does indicate what variables would affect wait times. By reducing waiting periods, individuals can reach their place of work sooner, meaning that the economic pay back investigated in Section 7 becomes more pertinent. This may be important to riders who have a large number of stop/ start cycles in their riding journey. Generally, lightweight bicycles with strong braking power and long crank lengths (higher force in acceleration) may be preferred. This describes a hybrid bicycle. This said, the equation does not take into account the fact that a larger number of stop/ start cycles would potentially reduce the cyclist top speed, reducing the aerodynamic influences discussed in Section 4.2. However, the mass of bicycles is largely related to their cost, so investment costs of a light weight hybrid may overcome any benefits.

This also highlights that information of the proportion of commuters using different bicycle types may be of interest to engineers constructing bicycle paths. If riders have a lower service time, it can reduce the need for multi-lane queues, thus reducing the need for wider paths, and hence reducing cost and environmental impacts.

4.2 Gantt Chart

By use of equation 2 the top speed attainable for an individual given a certain power output can be calculated. Assuming an average power output of 200 Watts (an estimate based on cycling measuring power output on a stationary bicycle during easy to moderate riding) and solving equation 2 for velocity, a cyclist on a mountain bike would be able to maintain 5.03ms^{-1} or 18.1kmh^{-1}, a cyclist on a hybrid bicycle would be able to maintain 5.48ms^{-1} or 19.7kmh^{-1}, and a cyclist on a road bicycle would be able to maintain 5.93ms^{-1} or 21.35kmh^{-1}. The results are collated in a Gantt chart for simple comparisons.

Figure 2 Gantt Chart of Everyday commuting

As can be ascertained from Figure 2, there are only 5 given steps in commuting on a bicycle. There is little that bicycle choice does to dictate the time taken to change into riding clothing and preparing the bicycle, as these factors were excluded from the scope of the system. It is possible that the time taken in the "ready bicycle" stage may be increased if one chooses not to have a dedicated commuting bicycle, such as adjusting suspension and changing seat height (as mentioned in Section 3), but likely to a negligible degree. The main process of importance is the time represented by "x" in Figure 2. In Figure 2, in the region which is dedicated to commuting time, each division represents 0.1 time steps of the total commuting time. The Gantt chart shows that in comparison to the road cycle (where 10 steps are used to represent a standard commute time) the hybrid will take approximately 1.1 of the commute time and mountain bicycle will take 1.2 of the commute time, as based on the above values of velocity. This application does not take into account the waiting time periods discussed in Section 4.1.

4.3 PERT Chart

The PERT chart seen in Figure 3 can be used to show a maintenance regime for two different bicycle types. There are different critical paths for different bicycles as a result of the unique components that are required for each type. The Red line indicates steps required for a mountain bicycle, the Green represents steps for a Road Cycle and the purple represents common steps. A hybrid would likely require the same steps as for a mountain bicycle, due to the overlap in components such as suspension and disk brakes.

	Activity	Duration (minutes)
A	Remove Accesories	5
B	Clean Bicycle	*
C	Flip or Mount Bicycle	1
D	Check Wheel Rims	2
E	Check Disk Brakes	2
F	Adjust Disk Brakes	15
G	Check Caliper Brakes	2
H	Adjust Caliper Brakes	5
I	Lubricate Chain	2
J	Check and Adjust Suspension	10
K	Check and Adjust Derailleurs	#
L	Check Gear Function	5
M	Check Tire Pressure and Pump Tires	10

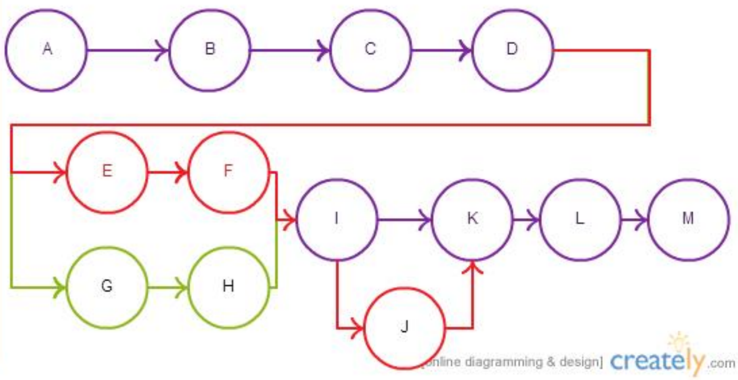

Figure 3 PERT Chart of Bicycle Maintenance for road and mountain bicycles. Unique steps required for a mountain bike and a road bike are seen in red and green respectively.

Note that in step B (clean bicycle), * indicates that the time varies between two types of bicycle. Cleaning is a longer process for mountain bikes, by simple assumption that they may be dirtier with an estimate close to 20 minutes, whereas a road cycle may only take 5 minutes to clean. Similarly in step K, the derailleurs on a mountain bike take longer to check and adjust, as there are generally more gears, meaning it can take up to 20 minutes, whereas the same job may only take 10 minutes on a road bicycle.

Figure 3 indicates that maintenance is generally a longer process for mountain bikes than for road cycles. This is a result of several factors, including the increased duration required in steps B and K as mentioned, alongside the longer duration of steps E and F in comparison to G and H. Finally step J is unique to mountain bicycles, thus increasing maintenance time. Overall, table 1 summarises the length of the critical path of bike maintenance.

Table 1 Maintenance critical path requirements of different bicycle choices

Choice	Iterations Maintenance per year	Duration Maintenance (Minutes)	Total duration maintenance per year (Minutes)
Mountain Bicycle	6	92	552
Hybrid Bicycle	8	92	736
Specialized Bicycles	3	150	450

This application does have some large associated errors, particularly as a result of the estimates being based upon limited personal experience. Generally estimates will vary according to the condition and age of the bicycle and personal experience and aptitude, as discussed in Section 9.2. This PERT chart also assumes that there are no major issues with the bicycle that are found during maintenance. This data could be supplemented by interviews with professional bike mechanics, but time and availability did not permit this.

Overall, it can be ascertained that maintenance of mountain bicycles takes approximately 50% longer in time. This has several implications for the cyclist. Firstly, if one choses to use a mountain bike for both commuting and recreational mountain biking, then the individual can expect that their mountain bike will require maintenance more regularly. It is difficult to ascertain how much more often this would be required, and would depend on both personal preference and the duration of the commute. If one was to use a hybrid bicycle, they could expect to maintain the bicycle as often as if they were to choose to use a mountain bicycle if not more, as a result of the higher wear on components which are not highly specialised to off-road cycling. The estimate of 8 times may however be an unreasonable expectation for an individual. Again, this is a factor that is difficult to quantify meaningfully. Finally, if one were to have specialised bicycles they would be required to maintain both bicycles, but the frequency of maintenance would likely reduce by at least one half.

5.0 Energy Analysis

5.1 I = PCT Equation

The I = PCT equation allows for the impact of a technology on the environment to be calculated. The equation is a rough estimate, with the most useful application being comparisons between technologies. Equation 4 can be applied to the project to determine the environmental impact of the three possible design choices:

$$Impact = Population * Consumption * Technology$$

$$\frac{Embodied\ Energy}{Year\ lifespan} = Number\ of\ Bikes\ Chosen * \frac{Embodied\ Energy}{Bicycle} * \frac{1}{Lifespan\ of\ Bicycles} \quad (4)$$

The first term takes into account the number of bicycles for each design choice, which is a scalar, the second term takes into account the energy expended by manufacturing a bicycle, which is relatively standard and can be determined using the materials audit seen in Section 6. The final term takes into account the lifespan of the bicycles.

This application attempts to take into account the fact that having a higher number of bicycles will increase the lifespan of given bicycles, as they will be used for their intended purposes. This of course weighs against the more significant upfront "energy costs". Using data from Section 6 one can graph the amount of embodied energy that is represented in a bicycle over its lifespan as seen in ANNEX B. The graph clearly indicates a rectangular hyperbola relationship, which is to be expected.

This analysis obviously indicates that initially, the choice of buying two bicycles has twice the "impact" than buying a single bicycle. However, as time progresses, the values converge somewhat, because of the rectangular hyperbola relationship. In fact, the difference becomes less than 100MJ within 8.5 years. This indicates that after some time, the impact cost of having two bicycles becomes negligibly different to the impact of one bicycle.

Another way of viewing the data is by estimating the probable lifespans of each bicycle based on their respective uses. We could say that a single mountain bicycle would have a lifespan of 5 years, whereas having two dedicated bicycles may result in each bicycle having a lifespan of 10 years. Using Figure 4, we can see that the impact for both one bicycle lasting 5 years and buying two bicycles which last 10 years respectively is 340MJ/year. So, the effect clearly is negated, by the factor of two. The question then becomes whether or not this simple assumption on lifespans is reasonable. To ascertain a more accurate assumption would require surveys of bicycle lifespans and knowing the patterns of use of those bicycles. Alternatively, one can postulate that a hybrid bicycle, if exposed to the stresses of mountain bicycling, would have a shorter lifespan than a mountain bicycle used in the same capacity. Because of the rectangular hyperbola relationship, we could deduce that this option has the highest impact. With the assumption that off-road cycling results in higher wear than road riding, one could also postulate that a dedicated road cycle would have the longest possible lifespan of all bicycles. Hence, as an individual bicycle its impact may be the least. Herein lies a problem with the analysis, as it is difficult to quantify just how significant the differences between wear on components is between off road riding and on road cycling, which would lead to a better analysis overall. This analysis also does not consider the need for replacement components.

5.2 Sankey Diagrams

Sankey Diagrams allow engineers to visualize where energy is expended by a rider. This can be calculated by use of equation 2. By assuming a given speed of $15kmh^{-1}$ ($4.167ms^{-1}$) and by determining the coefficients of rolling and air resistance, equation 2 can be used to determine the power output required to maintain the speed for different bicycle types as seen in table 2 (Tribiology, 2010).

Table 2 Power required for different bicycle types

Bicycle Type	Coefficient of Rolling Resistance (R)[1]	Coefficient of Air Resistance (K)[1]	Resulting Power Required (W)	Proportion Air Resistance (%)	Proportion Rolling Resistance (%)
Road Cycle	0.003	0.9	73.69	88.35	11.65
Hybrid	0.005	1.1	93.88	84.76	15.24
Mountain Bike	0.01	1.3	122.65	76.67	23.33

The Sankey diagram seen in Figure 5 informs design choices by indicating that at acceptable commuting speeds, air resistance becomes a real issue. Road cycles clearly have a higher benefit in this aspect which indicates that possible design optimization options such as having interchangeable wheels to reduce rolling resistance and wear on a mountain bike would be little benefit, as rolling resistance becomes negligibly small in its contribution at high velocities. This optimisation is further considered in Section 9.1. Another consideration is that using a mountain bicycle for commuting at $15kmh^{-1}$ requires 66% more power to the pedals applied than a road cycle. This is a relatively slow commuting speed, and would be encountered moving on bike paths, but on roads, this factor would become even larger, as can be appreciated by the cubic relationship seen in equation 2.

[1] TRIBIOLOGY. 2010. *Coefficient of friction, Rolling resistance and Aerodynamics* [Online]. Engineering-abc. Available: http://www.tribology-abc.com/abc/cof.htm#rolweerstand [Accessed 14/9/14 2014].

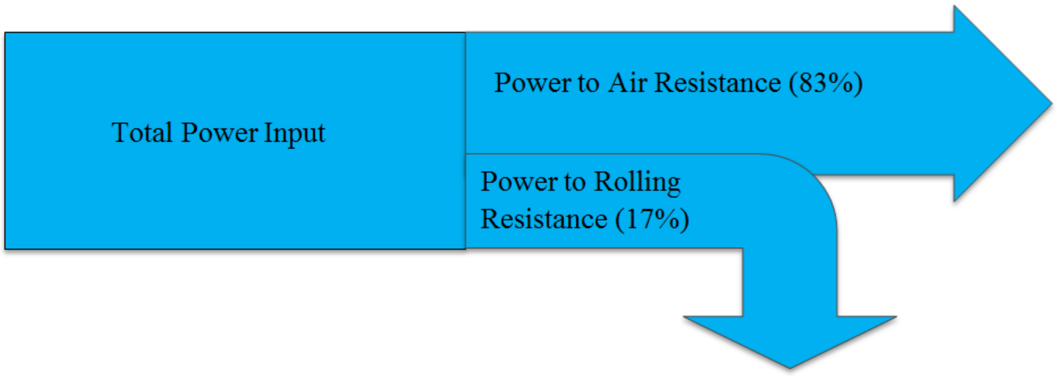

Figure 4 Sankey Diagram of approximate power use during constant cycling at 15kmh^{-1}

One may also consider the differences that bike tire pressure makes. Increasing tire pressure leads to a reduction in rolling resistance, which can allow the power required on the mountain bicycle to be reduced. However, on rough mountain biking tracks, the rider is generally advised against high tire pressures, as they can lead to rider discomfort and reduced traction (Macdermid et al., 2014). Thus if an individual were to increase tire pressure when commuting, and reduce pressure when riding recreationally, this would increase total commute time, as analysed in Section 4.2, (as this would be incorporated into the Gantt chart) and increase maintenance energy requirements, thus the total embodied energy of the device as seen in Section 6. Furthermore, the potential pay-off is small, as indicated by the Sankey Diagram in Figure 5.

5.3 Energy Mass Balance

By consideration of energy-mass control volume analysis of the bicycle at steady state operation, we can consider the energy flows of the system. The work rate input (power) which was calculated in Section 5.2 could be used to analyse the road and hybrid bicycles. If we assume the same input power of 122.65W, then we can say that for the hybrid and road cycles there is a power excess of 28.77W and 48.96W respectively. The energy mass balance diagram can be found in ANNEX E. Full USB power is 5V and 500mA, or 2.5W, indicating that either of these bicycles could easily be used to power a dynamo (even considering efficiency limitations), to charge a USB device such as a GPS. Dynamos typically have conversion rates of 70%, meaning that a Hybrid would be capable of powering approximately 2 10W lights, whereas a road bike could be used to power 3 10W globes (Alee, 2012). A higher amount of illumination may be a priority for clients, as it can be directly related to rider safety, particularly in winter months where commutes may be performed under darkness, and therefore user comfort. This would indicate that investing in a hybrid or a second bicycle is a good choice for safety, if use of hub dynamos for lights or devices is a client preference.

6.0 Materials Analysis

6.1 Materials Audit, Embodied Energy and End of Life Issues

The materials analysis of a generic bicycle was used to determine the potential environmental impact of different choices. This analysis was completed such that it could be integrated into Section 5.1, which allows for clear comparison between the three potential choices by taking into account the factors of life cycle length and number of bicycles. The analysis is in the form of a materials audit and embodied energy calculations as seen in table 3. The components list is significantly shortened from the potential list of components which would integrate minor components. It is assumed that components small in size will not greatly contribute to Embodied Energy; hence they are omitted for clarity and simplicity sake. The material choices assumed for components and estimated masses are based off industry trends amongst mid-range bicycles (Giant, 2014). Values of specific embodied energy and specific carbon output (used in Section 8) were sourced from the

Inventory of Carbon and Energy ('ICE') from the University of Bath (UK) (Hammond and Jones, 2006). The complete table is found in ANNEX C.

Table 3 Materials Audit table with embodied energy calculations for a generic bicycle.

Component	Material	Estimated Total Mass (kg)	Specific Embodied Energy (MJ/kg)	Embodied Energy (MJ)	End of life Destination
Chain	Steel Alloy	0.1	20.1	2.0	Recycled
Crank Set	Aluminium	0.5	155	78.8	Recycled
Fork	Aluminium	1.8	155	279.0	Recycled
Frame	Aluminium	1.5	155	232.5	Recycled
Handlebar	Aluminium	1.7	155	262.8	Recycled
Pedals	Polycarbonate	0.5	112.9	54.2	Recycled
Wheel Rim	Aluminium	1.9	155	293.0	Recycled
Saddle	Nylon	2.6	120.5	311.8	Recycled
Spokes	Aluminium	0.2	155	33.1	Recycled
Tires	Rigid Rubber	1.2	91	109.2	Recycled
Cassette	Aluminium	0.3	155	46.0	Recycled
		12.3		1702.4	

Several factors affect the transferability of this analysis to all the bicycle types. Saddles tend to vary in size, with larger saddles on hybrid bicycles in order to improve comfort. Wheels also vary in size, with mountain bicycle wheels being wider with greater definition in tread and high diameters for greater rolling momentum (Macdermid et al., 2014). Crank sets also very widely based on desired gear ratios. Frames vary by size, thickness and composition widely, being the main component where individuals choose to invest in lightweight materials such as carbon fiber. Tires are normally made from a rubber/ Kevlar composite for which the embodied energy and percentage weight of Kevlar could not be found. Instead, rigid rubber was assumed, likely underestimating energy requirements.

It should be noted that high performance bicycles would likely use carbon fiber components. Using calculations similar to table 3, we can determine that the embodied energy total would be approximately 1958.9MJ, which is somewhat larger than that of the aluminium bicycle, despite the comparatively low density of the material. This calculation, based on a table found in ANNEX C, assumes that each material choice is in equal quantity and does not take into account the relative strengths of the materials, as carbon fiber has a strength approximately 2 times that of aluminium (Hibbler, 2005). Overall, it is likely that the embodied energy of the two choices is comparable, with carbon fiber possibly having lower impact. The energy costs of manufacturing carbon fiber components is likely higher however, due to the difficulties associated with mass production of composite components, and the possibly custom components for very expensive bicycles. Thus, the overall lifecycle energy requirements of composite bicycles are likely higher than those for aluminium.

Table 3 outlines the end of life destinations for the various components of a bicycle. Bicycle components are unlikely to be reused, due to the wear and fatigue of the components. However, all materials used can be recycled at varying levels of efficiency following significant investment in dismantling the device and components.

7.0 Cost Analysis

7.1 Life-Cycle Cost Analysis

In the case of bicycles life-cycle cost analysis can be broken into three main phases being Acquisition, Maintenance and Refinement/ disposal costs.

Using estimates based on “sport” level bicycles, Acquisition costs can be simply calculated A mountain bicycle at $1400 (“Talon 1”), a road bicycle at $1050 (“Defy 3”) and a hybrid at $1550 (“Roam XR 0”) (Giant, 2014). However, this is based upon a strong estimate of a loosely defined “Class” of bicycles, with bicycle costs ranging from $100 to $5000. It should also be noted that from survey results, few people would be content to ride a hybrid on single track mountain bike trails, implying that a highly expensive hybrid is a more likely choice.

The maintenance of bicycles is generally considered to be economically favourable, having little to no cost outside of potential costs associated with replacing parts. As noted in Section 5.3 however, there is an associated cost with the time spent performing maintenance over the course of a year, a mountain bicycle alone has a “cost” of 9.2 hours per year, a hybrid bicycle 12.3 hours, and specialized bicycles, 7.5 hours per year. Getting professional maintenance (which could be considered part of the Refinement stage) can cost between $100-200 per session (Giant, 2014). It is not unusual to have professional maintenance on a bicycle annually. The average weekly salary of Australian adult full time employees is $1516.9 per week, with maximum full-time hours being 38 hours per week, this is equivalent to $40 per hour (Australian Bureau of Statistics, 2014). It should be noted that these estimates are based off very regular, high levels of maintenance of all bicycles involved as outlined in Section 4.3, which many individuals would not be accustomed to performing. Furthermore, such high level maintenance would likely reduce Refinement Costs.

Results are summarized in table 4. It should be noted that this model likely overestimates the value of one’s time spent in maintenance. It does however give a good appreciation of the comparative ongoing costs of the various bicycle choices. Table 4 is used in Section 7.2.

Table 4 Life-Cycle Cost Analysis of Bicycles

		Mountain Bicycle	Hybrid Bicycle	Specialized Bicycles
Acquisition	Up front cost	$1400	$1550	$2450
Maintenance	Hours Equivalent maintenance	$368/ year	$492/year	$300/year
Refinement	Professional maintenance/ Parts	$100/year	$100/year	$200/year
	Total:	$1400 + $486/year	$1550 + $592/year	$2450 + 500/year

7.2 Pay-Back Period

Pay-back period is simply the period of time in which a device may pay for itself over its lifespan. Taking the aforementioned models we can determine the payback period for different choices based on an individual’s average salary.

Using the values calculated in Section 7.1 one can construct a typical pay-off period analysis for each type of bicycle by taking the up-front cost, maintenance cost per year by time and professional maintenance cost. A graph of this is found in ANNEX D.

This analysis indicated that the pay of period between a hybrid and specialized bicycles occurs after 10 years. It is unlikely that one would own the same bicycles for greater than 20 years. This model does not take into account the possibly increasing maintenance cost over many years as a bicycle ages discussed in Section 9.2, nor does it take into account the “pay-back” factor from the time which is saved by use of different bicycle designs as outlined in Section 8.

8.0 Analytical Model

8.1 Model Boundaries and Concepts

An analytical model was built in order to take into account the factors discussed in Sections 1-7. This model is written in python and is found in ANNEX D. The basic philosophy is that one can equate the hours saved over a year to the equivalent in paid full-time work. Using the values calculated in Section 8.1, we could determine that for a mountain bike to “pay off” its own maintenance costs, it must save an individual 11.7 hours of work per year, or, using 250 working days, 2.8 minutes per day. One factor which could not be customised to the user was the speed of commute, which was assumed to be as calculated in Section 4.2 because of both the difficulties of solving a cubic, and the low likelihood that an individual would know their average power output. The model asks the user "How far do you live from work (in km)?", “How much do you earn per hour (assuming full time work)?" (to calculate a “time is money” pay back), “How many days would you ride to work per year? ", "How long (in hours) are you happy to commute via bicycle (assuming a one way trip)?" (to establish which bicycle type the user may realistically use) , “would you perform your own maintainence? 1/0" (to establish costs) and “What is your overall budget to spend on bicycles?" (assuming one would spend their entire budget on 2 bicycles, 50% on a mountain bike and 75% on a hybrid. The model outputs the time taken in years to pay back their environmental impact, the time in years when a bicycle choice becomes economically favorable over a mountain bike, the time in years when a bicycle choice is paid off entirely, the time saved per day for each type and finally the bicycle types which suit the commute distance and time.

Unfortunately, the queue theory analysis discussed in Section 4.1 had too many variables to be effectively analysed, as it would over-complicate the model. Overall, the boundaries of the model are in accordance to the various assumptions made in this portfolio, particularly Sections 1, 2, 4.2, 4.3, 5.2, 6 and 7.

The pay-back period in terms of carbon output is also included in the model. This simple calculation attempts to determine how long it would take an individual to negate the embodied carbon dioxide from the production of their bicycle. This value is calculated similarly to table 3 to be 85.6kg per bicycle (the complete table is found in ANNEX C). The estimate of car carbon dioxide output is based upon the U.S. Environmental Protection Agency estimate of 258g/km (Office of Transportation and Air Quality, 2008).

8.2 Reference Modes and Data Fitting

The survey results provide a good metric from which to measure the accuracy of the model. It can be noted from performing several iterations of the model, that travelling distances less than 5km are unlikely to result in the need for a second bicycle. Distances of greater than this represent a higher requirement, as seen in the survey results. Generally, for greater distances, road bicycles routinely pay themselves off before hybrids, although hybrids sometimes become economically favourable before road cycles. There appear to be very few cases, or at least a small window of cases, in which the client does require a bicycle which is better suited to commuting than the mountain bike (hybrid or road) and hybrid pays itself off before the road cycle. To the author’s knowledge, this is not an error in the code, and it remains possible for the hybrid bicycle to be favourable on some specific occasions.

As much as this allows for a model which applies to individuals on a personal level, savings of several minutes per day may not translate directly into monetary value, as a result of the Jevron’s paradox, which dictates that when has more, one tends to use more. Furthermore, the model may overestimate the value of one’s time spend in maintenance, thereby overestimating the ongoing costs of owning a bicycle, as maintenance time is realistically far less than the analysis indicates, as discussed in Section 9. 2. This model does not take into account the data trend that was noticed, which is that respondents generally chose to use commuting bicycles which were much cheaper than their existing mountain bikes. This allows for the various assumptions about aerodynamics, and higher efficiency of road bicycle to be taken into account.

The model indicates that the carbon footprint factor becomes negligible within very short periods, even with short commute distances. This indicates that the survey results which showed environmental consciousness as a major contributor to riding to work is a justified opinion, and that not buying a second bicycle out of environmental consciousness is not a significant argument against buying a second bicycle.

9.0 Optimization and Reliability

This Section focuses on factors which could not be integrated into the analytical model due to their complexity. In the aims of keeping the model simple, the following are factors which should be considered qualitatively (alongside anthropometric factors discussed in Section 2) when considering the client's choices.

9.1 Pareto Analysis

Pareto analysis dictates that in many circumstances, 80% of problems can be sourced to 20% of possible causes. This analysis can be applied to many circumstances and datasets. It can be observed that 80% of energy expenditure in riding is dedicated to air resistance, from Section 6.2. Air resistance can be correlated to rider position in the most part (Lukes et al., 2005), which is affected by few components overall being the handlebars and saddle position, that is approximately 20% of the components listed in table 3.

This allows us to generalise that having a "road cycling" stance when buying a hybrid bicycle may be the best solution to reduce energy use and increase riding speeds. If a hybrid bicycle had the capacity for both a "mountain biking" riding position and a "road cycling" position as seen in Figure 1, then the overall outcomes would be greatly improved. This could be achieved by use of modified dropped handlebars. However, due to the different diameters of road cycling handlebars and mountain biking handle bars, custom parts may be required, increasing environmental impact. These factors are too complex to be incorporated into the model and require precise knowledge of the bicycle of interest. However, some (generally more expensive (Giant, 2014)) hybrid bicycles do have dropped handlebars. This indicates that an expensive hybrid may in fact be a viable option.

9.2 The Bathtub Curve

The bathtub curve is commonly used in reliability engineering to establish the likelihood of failure over the course of the lifespan of a device. This can be used to enhance the time of maintenance analysis completed in Section 5.3. We can propose that as the likelihood of failures increases in a bicycle, the time period spent in maintenance increases. Hence, we can use the bathtub curve as an indicator of the time spent in maintenance over the course of the lifespan of a bicycle. Assuming the values determined in Section 5.3 to be the maximum maintenance values, a bathtub curve can be established for each bicycle type. The minimum period of time spent in maintenance is likely involves steps A, C, I, L and M, a total of 23 minutes for all bicycle types. This could be integrated into the model to establish a better estimation of both time spent in maintenance and maintenance costs. Alternatively, this graph could be used in conjunction with the PERT chart in Figure 3 to provide recommendations to the client, so that they can best use their time in maintenance, can improve their bicycle lifespan, and can make good decisions about when in the lifespan of the bicycle it is worthwhile to invest in replacement parts of professional services. Overall, this would severely reduce the estimates made in Sections 4.3 and 7.1. The hierarchy of total maintenance time between the three bicycles choices established in Section 4.3 would likely remain the same if taken over the entire lifespan of the bicycle.

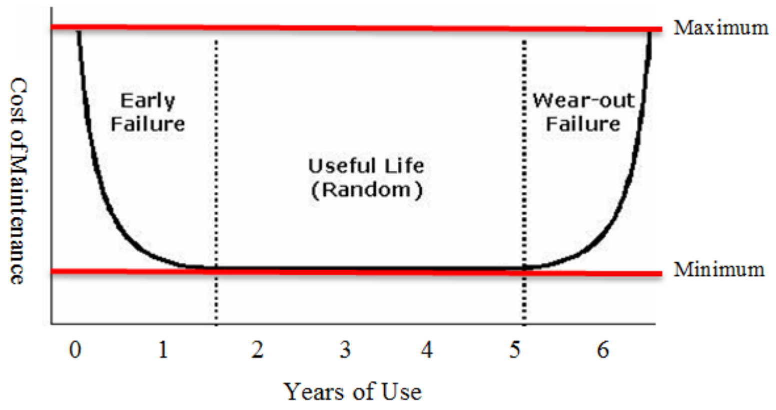

Figure 5 Bathtub curve indicating a relationship with Maintenance time/costs over a lifespan (adapted from (Unknown, 2008))

This application provides some reasonable information to improve the analytical model but would require some refinement. Specifically, the curve would likely favour the wear-out region, with the early failure (burn in) region being short and perhaps less steep. Analysis of a bicycle's maintenance requirements over its lifespan could provide an accurate graph, but this may require many years of continuous attention. It is also likely that the curve would look different for different users, and different bicycle types.

9.3 Optimization of Gear Ratios

A factor to be considered in using a bicycle for commuting and mountain biking is the factor of bicycle gears. Buying two bicycles allows each bicycle to have more specialized gear ratios for the given circumstance. Typically, mountain bicycles do not require gears which offer high ratios, as these ratios are only usable on smooth terrains which are encountered in road riding. Gear ratios come in three forms being the possible, usable and distinct gear ratios. Possible is the numerical value of gear combinations that exist between the front sprocket and the back cassette. Usable gears are those which do not involve extreme wear on the components, as a result of the chain sitting on an angle. Finally, distinct gears are those which have a ratio significantly different to other gears available.

One could relate this to the speed at which the individual may commute and the reliability of the bicycle (more gears requires more maintenance). This analysis may also support the assumptions made in Section 4.3 regarding the duration and frequency of maintenance of multiple bicycles, as multiple bicycles working within their reliable gear ranges would require less maintenance than bicycles ridden outside of the "usable" range of gears. Furthermore, fewer, specialised gears would require a shorter and less frequent maintenance cycle than a larger gear range. Generally we can say that this factor leans towards specialized bicycles.

Conclusions

This portfolio has outlined the analysis of the question of "Do mountain bikers require a specialized bicycle for commuting?" The analysis has taken into account anthropometric and comfort factors, responses of cyclists from the Canberra region, quantitative analysis of riding speeds and time and energy factors. Factors influencing the maintenance of bicycles, time in commute, user safety and comfort and environmental impacts were considered. Overall, an analytical model was built to amalgamate the analysis to establish the pay-back period of a bicycle. Optimisation and improvement of this model is briefly discussed, alongside qualitative matters to consider. Generally, the analysis seems to favour investment into a second road bicycle, with pay back periods being quite short (environmental and economic), and potential user comfort, time, bicycle reliability and safety outcomes being improved by use of specialised bicycles.

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Appendices

ANNEX A- Survey Questions

1. Age

- 10-20
- 20-30
- 30-40
- 40-50
- 50-60
- >60

* 2. Gender

- Male
- Female
- Unspecified

* 3. Do you mountain bike recreationally? If so, how often.

- Yes, (almost) every day
- Yes, more than once per week
- Yes, once per week
- Yes, once every few weeks
- Yes, once per month
- Yes, very irregularly
- No

* 4. Do you commute to work on a bicycle?

- Yes, most days of the week
- Yes, once or twice per week
- No

* 5. How far is the commute to your place of work/ study?

- <1km
- 1-5km
- 5-10km
- 10-20km
- 20-40km
- >50km

* 6. If you do commute to work on a bicycle, do you have a dedicated bike for this purpose?

- Yes
- No

7. If you do not commute on a bicycle to work, why? Check all those that apply.

- Too far
- Takes too long
- Not inclined to do so
- Don't have a dedicated commuting bicycle
- Not fit enough
- Other (please specify)

8. If you commute to work by bicycle, why? Check all that apply

- Fast
- Economic reasons
- Fitness
- Environmental sustainability
- Other (please specify)

* 9. Regardless, imagine that you mountain bike and commute to work on a bicycle. Would you buy a second bike for commuting, use a hybrid or commute on your mountain bike? Please provide a reason or reasons for your choice in the other field

- Have two bicycles, one for each purpose
- Have a hybrid
- Use a mountain bike to commute
- Other (please specify)

10. Estimate the net worth of your bicycle(s). Please provide the number and type of bicycle(s).

ANNEX B- Embodied Energy Graph

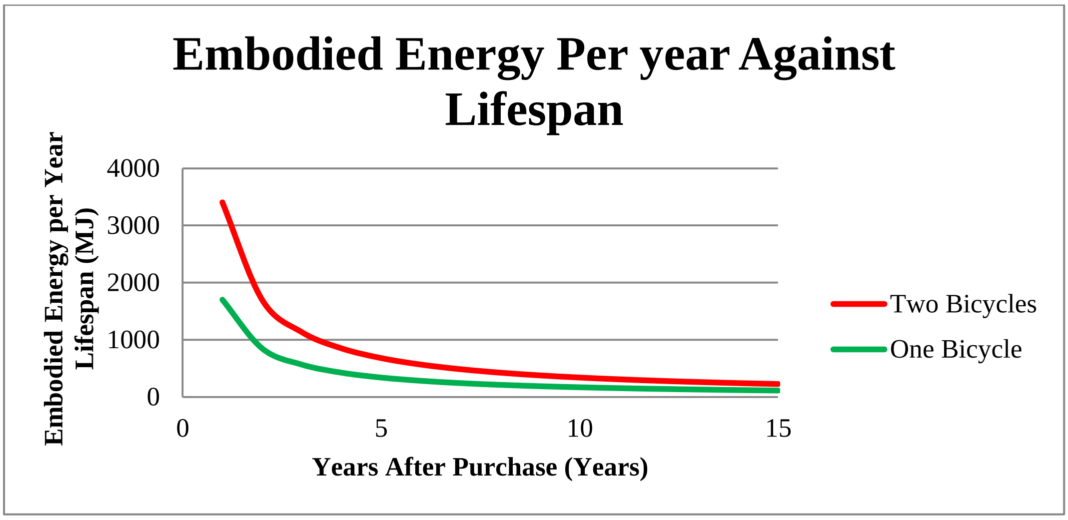


Figure 6 Graph showing the embodied energy impact as the lifespan of a bicycle increases. The graph indicates that as the lifespan of a bicycle increases, the embodied energy represented for each year reduces in a rectangular hyperbolic relationship

ANNEX C- Complete Materials Analysis Table

Component	Material	Estimated Total Mass (kg)	Specific Embodied Energy (MJ/kg)	Embodied Energy (MJ)	Specific Carbon Output (kg CO2/ kg)	Carbon output (kgCO2)	End of life Destination
Chain	Steel Alloy	0.1	20.1	2.0	1.37	0.1	
Crank Set	Aluminium	0.5	155	78.8	8.2561	4.2	Recycled
Fork	Aluminium	1.8	155	279.0	8.2561	14.9	Recycled
Frame	Aluminium	1.5	155	232.5	8.2561	12.4	Recycled
Handlebar	Aluminium	1.7	155	262.8	8.2561	14.0	Recycled
Pedals	Polycarbonate	0.5	112.9	54.2	6.03	2.9	Landfill
Wheel Rim	Aluminium	1.9	155	293.0	8.2561	15.6	Recycled
Saddle	Nylon	2.6	120.5	311.8	5.47	14.2	Reused
Spokes	Aluminium	0.2	155	33.1	8.2561	1.8	Recycled
Tires	Rigid Rubber	1.2	91	109.2	2.66	3.2	Reused
Casette	Aluminium	0.3	155	46.0	8.2561	2.4	Recycled
		12.3		1702.4		85.6	

Component	Material	Estimated Total Mass (kg)	Specific Embodied Energy (MJ/kg)	Embodied Energy (MJ)	Specific Carbon Output (kg CO2/ kg)	Carbon output (kgCO2)	End of life Destination
Chain	Steel Alloy	0.1	20.1	2.0	1.37	0.1	
Crank Set	Carbon fiber	0.3	315	95.0	1.2	0.4	Recycled
Fork	Carbon Fiber	1.1	315	340.2	1.2	1.3	Recycled
Frame	Carbon Fiber	0.9	315	283.5	1.2	1.1	Recycled
Handlebar	Carbon Fiber	1.0	315	315.0	1.2	1.2	Recycled

Pedals	Polycarbonate	0.5	112.9	54.2	6.03	2.9	Landfill
Wheel Rim	Carbon Fiber	1.1	315	352.8	1.2	1.3	Recycled
Saddle	Nylon	2.6	120.5	311.8	5.47	14.2	Reused
Spokes	Carbon Fiber	0.1	315	39.9	1.2	0.2	Recycled
Tires	Rigid Rubber	1.2	91	109.2	2.66	3.2	Reused
Casette	Carbon Fiber	0.2	315	55.4	1.2	0.2	Recycled
		9.1		1958.9		26.0	

ANNEX D- Analytical Model

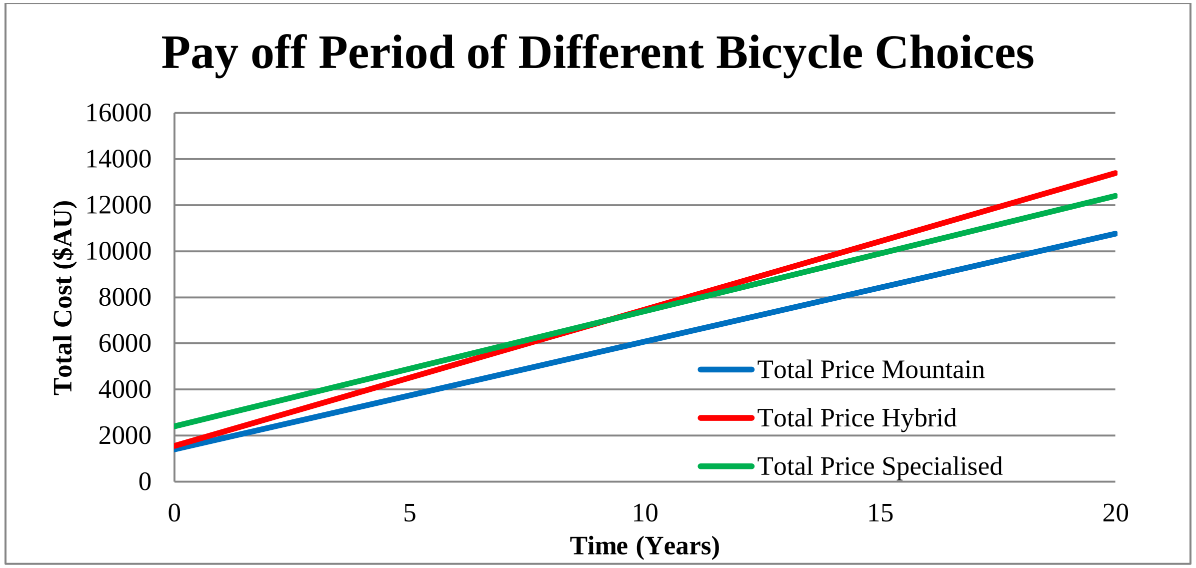
```
def xfrange(start, stop, step):

    while start < stop:

        yield start

        start += step


print("You are a mountain biker who wants to commute via bicycle. Should you buy a second bicycle? Should you buy a hybrid? ")

distance = float(input("How far do you live from work (in km)?"))

payperhour = float(input("How much do you earn per hour (assuming full time work)?"))

daysworked = int(input("How many days would you ride to work per year? "))

timecommute = float(input("How long (in hours) are you happy to commute via bicycle (assuming a one way trip)?"))

time_transit_mtb = distance/18.1 # standard times incorportated due to the need to solve a quadratic for a given power input.
```

```
time_transit_hybrid = distance/19.7

time_transit_road = distance/21.35

maintenance_pref = input("would you perform your own maintainence? 1/0")

if maintenance_pref == 1:

    fixcost_mtb = 1.53*6*payperhour + 100 #maintenance time with refinement costs, for a year

    fixcost_hybrid = 1.53*8*payperhour + 100

    fixcost_road = 2.5*3*payperhour + 200

else: #assumes the need for two services per year, services cost more for more bikes and for hybrids

    fixcost_mtb = 200

    fixcost_hybrid = 300

    fixcost_road = 400


costbicycle = int(input("What is your overall budget to spend on bicycles?")) #Maximum, assuming 2 bikes
bought


time_saved_payoff_mtb = 0 #setting this as the baseline

time_saved_payoff_hybrid = (time_transit_mtb-time_transit_hybrid)*payperhour*2 # *2 for to and from work,
values for one day

time_saved_payoff_road = (time_transit_mtb-time_transit_road)*payperhour*2


#this is the Section of code that determines how long it takes to pay off the bicycle
```

```
carbonprint1 = False

carbonprint2 = False

printed1 = False

printed2 = False

printed3 = False

printed4 = False

for n in xfrange(0,20,0.01): #iterating over years of ownership, 20 as upper limit

#note that the model assumes that 2 bicycles reaches the maximum of the budget, a mountain bike is exactly half, and that the hybrid is 75% of the budget.

    cost_mtb = costbicycle/2+fixcost_mtb*n - time_saved_payoff_mtb*n*daysworked

    cost_hybrid = costbicycle*0.75+fixcost_hybrid*n - time_saved_payoff_hybrid*n*daysworked

    cost_road = costbicycle + fixcost_road*n - time_saved_payoff_road*n*daysworked

    co2_bike = 85.6

    #for environmental impact

    co2_offset_bike = co2_bike - 0.258*distance*2*daysworked*n

    co2_offset_2bikes = 2*co2_bike - 0.258*distance*2*daysworked*n

    if co2_offset_bike < 0 and carbonprint1 == False:

        print("You can offset the carbon output of a bike by riding to work for {} years".format(n))

        carbonprint1 = True

    if co2_offset_2bikes < 0 and carbonprint2 == False:
```

```
        print("You can offset your carbon output of buying a two bikes by riding to work in {} years".format(n))
        carbonprint2 = True
    #print(cost_mtb, cost_hybrid, cost_road, co2_offset_bike, co2_offset_2bikes) #for checking
    #for economic aspects
    if cost_mtb > cost_hybrid and printed1 == False:
        print("Buying a hybrid would become economically favorable after {} years".format(n))
        printed1 = True
    if cost_mtb > cost_road and printed2 == False:
        print("Buying a second (road) bicycle would become economically favorable after {} years".format(n))
        printed2 = True
    if cost_hybrid < 0 and printed3 == False:
        print("A hybrid would pay itself off after {} years".format(n))
        printed3 = True
    if cost_road < 0 and printed4 == False:
        print("A second (road) bicycle would pay itself off after {} years".format(n))
        printed4 = True
if printed1 == False and printed2 == False and printed3 == False and printed4 == False:
    print("A hybrid or a road bicycle are not economical for you, stick to your mountain bike")
```

```python
print("In terms of commute time...")
if time_transit_mtb > timecommute:
    print("It is unlikely that you would be happy to commute via mountain bike")
if time_transit_hybrid > timecommute:
    print("It is unlikely that you would be happy to commute via hybrid bike")
if time_transit_road > timecommute:
    print("It is unlikely that you would be happy to commute via road bike")
else:
    print("Enjoy your ride!")
```


Pay off Period of Different Bicycle Choices
Total Cost ($AU)
16000
14000
12000
10000
8000
6000
4000
2000
0
0
5
10
15
20
Time (Years)
Total Price Mountain
Total Price Hybrid
Total Price Specialised

ANNEX E – Energy Mass Balance Diagram