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Campus Mobility for the Future: The Electric Bicycle

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ABSTRACT

Sustainable and practical personal mobility solutions for campus environments have traditionally revolved around the use of bicycles, or provision of pedestrian facilities. However many campus environments also experience traffic congestion, parking difficulties and pollution from fossil-fuelled vehicles. It appears that pedal power alone has not been sufficient to supplant the use of petrol and diesel vehicles to date, and therefore it is opportune to investigate both the reasons behind the continual use of environmentally unfriendly transport, and consider potential solutions. This paper presents the results from a year-long study into electric bicycle effectiveness for a large tropical campus, identifying barriers to bicycle use that can be overcome through the availability of public use electric bicycles.

Keywords: Electric Bicycle; E-Bike; Campus Transport; Personal Mobility

1. Introduction

The campus environment, especially that of the more established universities, has entered the public consciousness as being a haven for bicycle use [1]: not necessarily for reasons of their environmental credentials, but because their low cost suits the student budget. However many university campuses are notorious for parking problems [2], and it may also be asserted that the fossil-fuelled vehicles affordable to students are likely to be among the most polluting of their kind. Much research worldwide has been conducted on electro-mobility solutions, especially during recent years of increased awareness of CO_2 emissions and the environmental consequences of profligate consumption of fossil fuels. However, the common term "electric vehicles" has become almost synonymous with "electric cars," apart from some prominent niche examples which will be explored. In fact, cars are only one example of practical electric transportation.

Unfortunately electric cars tend to be expensive, mainly due to the cost of the battery assembly. A four seater electric car being used to transport a single person is also wasteful of energy, although perhaps less so than with a petrol engined vehicle. Electric cars require parking spaces just like existing vehicles, and thus will not solve campus parking problems. These vehicles are also costly in terms of insurance (especially for younger drivers), require road tax payments (or equivalent in different countries), and usually require drivers to posses a valid license. By contrast, bicycles do not require insurance, attract no road tax and typically do not require a license to ride in most countries. Furthermore, they are efficient, environmentally friendly, and far more dense, when parked and driven, than the equivalent rows of cars.

From experience, we know that at current oil prices, fossil fuelled vehicles are more attractive than bicycles for most users, but that bicycles are significantly cheaper. Thus barriers must exist to the use of bicycles for many potential riders. The premise of this paper is that many of these barriers can be overcome by technological means, at minimal cost, to create a usable form of transport for campus use. It should be noted that the emphasis here is on short journeys taken around a campus area, and perhaps short commutes from home to campus. Longer distance travel presents a different problem: petrol and diesel vehicles tend to become more efficient and less polluting per kilometre as distance increases [3], and a different set of alternative transport solutions should be considered. Short journeys by petrol-engined cars are especially polluting (particularly until the catalytic converter reaches full operating temperature), and are a good target for replacement by bicycle.

Apart from usage barriers, Section 2 presents other studies related to campus bicycle use and electrical-power assist bicycles. Section 3 analyses the specifics of the typical campus environment, as this relates to transportation options, while Section 4 surveys international transport legislation and proposes an electric bicycle solution for campus use. Since the authors have been operating such vehicles in a restricted-public lending scheme for more than a year, Section 5 reveals an analysis of system effectiveness and identifies particular usage challenges, before Section 6 concludes the paper.

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2. Literature Survey

2.1. Vehicles

The bicycle, in its present upright form, called a "safety bicycle" and introduced by the Rover model in 1885, is a relatively cheap method of extending the range, increasing the speed, and improving the energy efficiency of human powered transport. It can coast down hills, roll easily along the flat, and make use of gearing to tackle steep hills. Many bicycle alternatives exist, ranging from recumbent models to chunky off-road machines, however the "safety bicycle" shape remains most common.

Electric bicycles, with more than a century of commercial history (the first patents for electric bicycles were granted in the 1890s), have long been available, and found adopted in small numbers in many countries. Their relative lack of popularity until recently may be attributed to technological or economic factors (explored from Section 2.2 onwards), however the fact of their existence means that they are already covered by legislation in most countries (see Section 4).

In terms of personal electro-mobility alternatives, there are a plethora of amazing inventions ranging from the Segway, the Yike Bike, Ryno, various electric scooters, skateboards, power skates, electric quad bikes and so on. Ignoring the fossil-fuelled variants, recent alternatives have been released which are powered by compressed air [4], flywheel [5], fuel cell [6] and probably other unusual power sources. However the vast majority of experimental machines use a combination of electrical motor and battery. Battery solutions tend to be limited to the robust but weighty lead-acid cells in cheaper or older systems, through surprisingly few NiMH variants, to Lithium Ion (predominantly $LiFePO_4$ or $LiMn_2O_4$ based cells) in more modern and expensive variants [7].

The Segway is one of the most imaginative and innovative personal mobility solutions to have been developed in recent years, with a loyal following of users, and several niche application areas. However the Segway has not attracted widespread adoption on campus to date. General Motors have used the Segway as the foundation for their P.U.M.A. (Personal Urban Mobility & Accessibility) project which effectively adds car-like features to the Segway; a seat, roof and steering wheel. Whilst this is exciting and extremely attractive from a technological point of view, it leads to a very expensive transport solution, requires significant thoroughfare space, and may require licensing for use in certain locations (for example, even the basic Segway is not currently legal for use in public areas within Singapore). Electric quad bikes are likewise expensive, bulky to park and have few advantages over an electric bicycle.

In fact, all of the devices mentioned are expensive, certainly significantly more so than a standard bicycle, and most work on the premise of simply adding a motive power source to a bicycle-type system (or scooter/skateboard/skates). However it is by no means certain that lack of such power assistance is the main reason why bicycles may not have been more widely adopted in many campus environments. Thus, adding motive power alone may not lead to the more widespread adoption of electric bicycle-type transport.

2.2. Barriers

Obviously, many potential campus users of personal electric mobility vehicles (PEMV) have no effective choice apart from fossil-fuelled vehicles at present [8], usually due to commuting distance or traffic conditions. However it is possible to envisage a park-and-ride type scheme where a large car park on the periphery of a campus allows commuters to park, pick up a PEMV and use this for inter-campus transport. Campus occupants who need to attend a meeting elsewhere on a large campus, may consider using some type of PEMV, if it were available. In fact, studies (conducted for traditional bicycle use), show that a very positive correlation exists between provision of cycling facilities, and the public acceptance of their use, in terms of adoption by potential users [9].

Unfortunately, even when excellent cycling facilities exist, a number of potential users prefer to drive or employ other means of transport. These barriers to the adoption of cycling have been investigated by a number of authors over the years. Perhaps the definitive survey of these barriers is that compiled by Cleland [10], in which results from several earlier surveys are collated and presented. For convenience, the most useful of these surveys have been analysed here in **Table 1** along with some more recent survey data [11-13]. Various reasons are listed along with the identified proportion of respondents who give those reasons. The methodology for each survey differed, so the bottom row of the table indicates whether respondents were able to select only their primary reasons, were allowed to list multiple reasons or where given a free choice of answers. Less popular answers are were not captured in the table.

Since there is little correspondence between survey questions, and in some cases wide variations in the proportion of respondents citing a given reason, some interpretation is necessary. In his study, Cleland matched the top three reasons [10]. However in **Table 1**, it is reasonably clear without further ranking that some factors are more prominent than others as barriers to cycling:

- Lack of cycling facilities (including cycle paths, access to showers at work, and storage areas);
- Perceived danger (especially from other road-going traffic);
- The weather (particularly rain);
- Distance/time issues;

Table 1. Reasons given for *not* cycling, compiled from a number of different surveys (with different objectives, methodologies and question emphases). The reader is strongly advised to refer to the original published studies before comparing quantitative values across columns. An empty cell indicates a question that was not included in any particular survey.

	Salzburg	NHTSA	Davies	Snelson	AA	Cincinnati	Sydney	Jackson	Auckland	Wellington
Reference	[11]	[10,12]	[10,14]	[10,15]	[10,16]	[13]	[10,17]	[10,18]	[10]	[10,19]
Lack of cycle-ways/ facilities	22.6%					55% (lanes) 27% (showers) 22% (storage)	36%	41%	18% (lanes) 13% (storage) 10% (showers)	
Perceived danger	26.2%	3.4%	Y	11% - 17%	11%	40%	32%		23%	12%
Weather	13.0%	8.2%	Y			52%			10% (rain)	6%
Too far	10.7%					22%		Y		3%
Time issues/ too busy	5.1%	16.9%				31%		22%		7%
Too much exertion/ effort	2.8%		Y (hills)	17% (age) 8% - 16% (effort)	8%	19% (hills)	0%	17%		6% (hills) 5% (age)
Limited carrying capacity	8.8%					26% (items) 13% (passengers)				2%
Don't enjoy it/comfort	3.2%	2.6%								41%
No bicycle		26%			13%					
Theft/ vandalism			Y				10%		28%	
Pollution/ traffic			Y	7% - 16%	7%					
Out of	% for each reason (1 allowed)	% for each reason (1 allowed)	Y/N to given reasons	Unclear	Percentage for each reason (1 allowed)	Percentage for each reason (multiple allowed)	Percentage for each reason (1 allowed)	Percentage for each reason (multiple allowed)	Unclear	Percentage for each reason (1 allowed)

- The effort required (particularly relating to hill climbing).

Much research has been conducted on some of these points, including the health benefits and risks associated with bicycle riding [20]; with most studies concluding that the health benefits of regular cycling exercise outweigh the dangers of sensible bicycle use for short-distance transportation. City planners have also long considered the provision of cycling facilities, and the impact of this on usage patterns [8,21].

It is evident that many city and campus planners have, in recent years, emphasised facilities for bicycle use. Cycling is generally promoted worldwide as a sensible and sustainable transport choice for campus and city commuting. As fuel prices continue to increase, and with greater public awareness of environmental sustainability, rates of bicycle use should rise.

3. Analysis of Campus Environment

University populations (where students may live on or near campus) tend to involve less commuting than is the norm [2] in other communities, and thus in many cases already tend to have a higher proportion of bicycle use than general society [1]. Flat campuses in dry areas tend to be the most cycling-friendly and cycle paths and racks (especially racks with security or in locked and fenced areas) encourage cyclists [1]. In addition, the image of cycling being healthy and "green" and of course the fact that it is relatively inexpensive, have traditionally contributed to large-scale use of bicycles on campus. These are all positive reasons for using bicycles.

There are also negative reasons that count against driving (and thus implicitly encourage cycling), such as parking difficulties and costs (Salzburg reported more than double the number of cyclists a week after introducing parking charges [10]), the expense of purchasing, road taxing, maintaining and fuelling a car. It may also be that students are more environmentally conscious than the general population, and thus more likely to reject polluting and energy-inefficient means of transport.

Campus environments also exhibit strongly correlated transport flows. In Nanyang Technological University (NTU), Singapore, for example, lectures begin half past the hour from 8.30am until 6.30pm, and end at twenty minutes past the hour. There is thus a ten minute window of large-scale movement as a significant proportion of the 33,000 students and more than 5000 staff move between lecture, laboratory and tutorial locations, or travel to one of the 18 canteens on the main 200 hectare (almost

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500 acre) campus. Public transport entering the campus is overwhelmed, especially at peak times from 8am to perhaps 9.45am: car park entrances have queues of cars, and parking spaces become scarce.

The consequence of the correlated people movement is that campus transport facilities must cater for a peak of activity that is many times greater than average activity: naturally reducing transport efficiency. It also means that there will be concentrations of people, cars and bicycles near to food and beverage facilities at those times, and particular concentrations in the vicinity of teaching facilities.

Finally, the nature of a campus is that one authority exercises control over planning, building, transport and parking provision. Unlike a city or a suburban neighbourhood, cohesive planning and action are generally much more easily possible.

4. An Electric Bicycle Solution

Up to this point, we have carefully analysed the use of bicycles on campus, presenting and analysing survey results that attempt to explain barriers to greater adoption of the bicycle. If this data is then matched up with some of the characteristics of the campus environment, it is possible to propose technical, planning and procedural solutions that together should encourage the greater adoption of bicycle transport. This is the focus of the remainder of the paper.

4.1. Legal Framework

Firstly, however, it is necessary to work within the bounds of legislation. Most countries differentiate between bicycles and motor vehicles, with the latter requiring road tax, insurance and possibly an up-front purchase tax. Bicycles may be fitted with electric motors, and still be classified as bicycles, provided certain provisions are made, primarily in terms of the maximum motor power. Fitting a motor of greater power would result in a reclassification of the machine as a motor vehicle. **Table 2** surveys the maximum legal power allowed for bicycles in various territories. Notably China [22]—the manufacturer of almost all electric bicycle components, and probably the largest user of such vehicles—does not appear to have clearly defined national rules in this regard, and Hong Kong is absent from the list since such vehicles are totally prohibited in Hong Kong territory.

Most countries stipulate a maximum speed above which motor power must cease, ranging from 24 km/h in Japan up to 32 km/h in Canada and the USA [23]. Most countries also require the machines to resemble normal bicycles and be fitted with pedals. Some countries allow three-wheeled (or even four-wheeled) electric bicycles, a few such as Singapore, specify two-wheeled use only.

Table 2. Maximum power for electric motor assisted bicycles in various countries (constructed primarily using data from [23]).

Country	Motor power output
Australia	200 W (currently tabling legislation to move to 250 W)
Canada	500 W
Europe	250 W
India	250 W
Japan	250 W
New Zealand	300 W
Singapore	200 W (note potential shift to 250 W in the near future)
United Kingdom	200 W in UK law overridden by 250 W in European legislation
United States of America	750 W

The issue of pedelec is interesting: European and Singaporean law in particular require a pedelec: when powered, the motor must turn on within a certain time after the pedals are operated (such as one revolution of the pedals), and must turn off within a certain time after the pedals have been released (such as the equivalent of a quarter of a revolution at the original speed). This gives rise to the electric assist bicycle, the type of machine that requires a rider to contribute some effort to the motion, but allows the motor to assist to a certain extent.

4.2. Motor Type and Placement

Most modern electric bicycles employ brushless DC motors, usually flat hub mounted assemblies consisting of permanent magnet rotor and fixed armature coils energised sequentially by a motor controller. This arrangement means that brushes and commutator are not required, leading to potentially higher motor reliability. **Table 3**, listing typical technology choices for electric bicycles, also notes that brushed DC motors are sometimes used (they may be of lower cost).

Hub mounted motors may be placed on either front wheel or rear wheel hub, as shown in **Figures 1 (a)** and **(b)**. Direct drive systems will power the bicycle directly, and must cope with a wide range of speeds and conditions, whereas geared motors (usually employing planetary gearing) may allow greater torque at low speeds, and are better able to be adapted to use with different bicycle wheel diameters. Front wheel direct drive allows power to be applied to front wheel (through motor) as well as rear wheel (through pedals), providing a very stable power transfer arrangement.

Although hub-mounted direct drive BLDC systems are most common, several chain drive variants exist, either using the existing bicycle chain in-line with the pedal chain ring (the motor normally mounted behind the pedals), or utilising a separate chain attached to the pedal

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Table 3. Typical technology choices for adding electric power assist to a standard bicycle frame.

Motor Placement	Battery	Control	Motor type
Front wheel (hub)	Lead-acid	Pedelec (magnetic)	Brushless DC (BLDC)
Above front wheel	(NiCd)/NiMH	Pedelec (torque sensor)	Brushed DC
In front of pedals	$LiFePO_4$	Throttle	Other (incl. AC)
Above pedals	$LiMn_2O_4$	Simple on/off	**Gearing**
Behind/below pedals	Fuel cell	**Sensors**	Through bike gears
Rear wheel (hub)	Super-capacitor	Speed (wheel rotation)	Direct hub drive (front)
Above/in front of rear wheel	**Wheel size**	Cadence (pedal rotation)	Direct hub drive (rear)
Controller	small (14", 16")	Battery voltage	Planetary geared
Regenerative	medium (18", 20")	Torque (at crank)	Separate chain drive
Non-regenerative	large (26", 27" and 700C)	Torque (at hub)	Friction drive to tyres

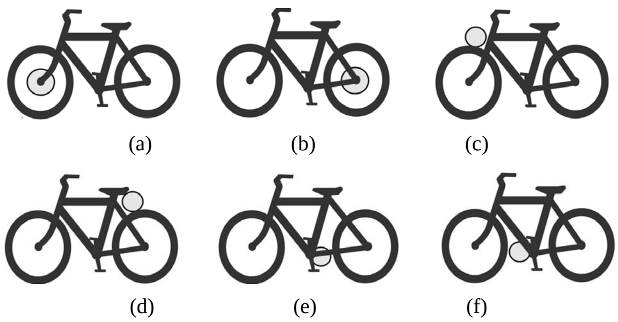

Figure 1. Typical electric bicycle motor mounting points (a) front and (b) rear hub; (c) front and (d) rear friction drive; (e) chain drive in-line with derailleur; (f) chain drive to separate chain-ring.

chain ring. In both cases, a free-wheel mechanism must be provided to prevent the motor from spinning the pedals—something which could result in injury to the rider. The normal solution is to provide a free-wheel between the pedals and the pedal chain ring, thus the pedal chain ring can rotate and be driven freely by electric motor, yet the pedals remain stationary.

Apart from hub mounting and chain-drive systems, friction drive has, historically at least, been a common drive system for powered bicycles. This involves a motor mounted above either the front or rear bicycle wheels powering a drive wheel in contact with the tyre. Several decades ago, small internal combustion engines would sit in the same location. These could often be flipped upwards to take them out of contact with the bicycle tyres when not in use. Each of these drive systems is shown in **Figure 1**.

In general, geared motors allow the flexibility of changing the torque/speed relationship (either fixed, as in a planetary geared system, or adjustable through the bicycle's own gearing), but suffer from greater wear and reduced transmission efficiency. Brushless motors are most powerful (weight-for-weight), but more difficult to control than brushed motors, thus leading to more expensive control systems.

4.3. Frame Issues and Wheel Size

Standard bicycle frames need to be able to accommodate the extra mass of electric bicycle components (especially battery), but also must have space for mounting the motor, controller and battery. Common locations for batteries are on some kind of rack above the rear wheel, between the rear wheel and seat post, below a crossbar, or above the front wheel. At least one electric bicycle conversion kit locates batteries as panniers carried either side of the rear wheel. Various options are shown in **Figure 2**, and this issue will be discussed more fully below in Section 4.5.

Chain-drive motors tend to be large enough that the bicycle pedals have to be moved further apart than is usual to avoid the motor from obstructing normal pedalling motion. In these systems, the need for an extra chain (in some cases-as different arrangements do exist), and a chain-ring freewheel, also tend to increase the distance between pedals.

Hub motors require a certain hub clearance of typically 110 mm: that is the distance between the forks to accommodate the motor (and maybe more if disc brakes are to be fitted). 110 mm is fairly standard, except on smaller frames where the front fork clearance may be as low as 65 mm or 70 mm. It should also be noted that, due to the large shaft torque, hub motors above about 200 W should not be used on aluminium forks. For this reason, some hub motor manufacturers recommend that a torque arm be fitted to hub motors.

Bicycle wheel size, for pedal powered bicycles, is often conceived primarily as an issue of comfort and rider

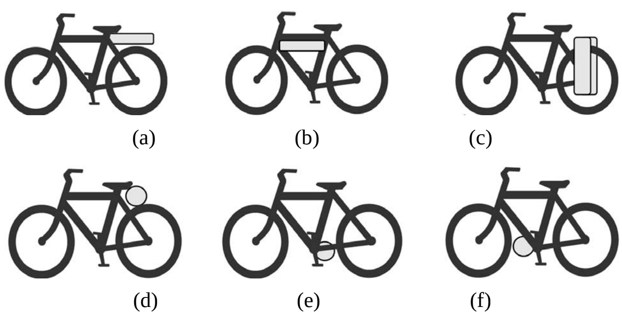

Figure 2. Typical electric bicycle battery mounting points, (a) above the rear wheel; (b) below the crossbar; (c) as rear panniers; (d) behind the seat post; (e) above the front wheel or as front panniers; (f) built into the frsame or wheel.

acceptance, however for an un-geared direct drive hub motor, a smaller wheel gives greater torque: 40% more for an 18" wheel over and above a 26" wheel. This is important for hill-climbing ability, but conversely a smaller wheel driven in the same way (in terms of revolutions per minute) will achieve a lower maximum speed. However, since maximum speed is restricted by legislation in many countries, this may not be a significant limitation in practice.

4.4. Controller Types

Although there are many research and technology issues related to motor controllers, to the end-user they can be classified as either allowing regenerative braking or not (see **Table 3**). A regenerative braking system, detecting the rider applying brake pressure, will operate the motor as a dynamo, converting mechanical rotation into power [24], reducing the kinetic energy of the vehicle. A controller that supports regenerative braking is likely to be slightly more costly than one that does not. Anecdotally, the regenerative controllers also tend to be slightly less efficient in terms of maximum motor power output.

One particular problem with regenerative systems is imposed by the charging regime for whatever battery technology is in use: for example the maximum rate at which the battery can be recharged. This is a particular issue for the popular Lithium Ion batteries, which have stringent charging requirements, and results in a constant retardation force being applied during regenerative braking. Support for variable retardation is an active research topic [25].

4.5. Battery Type and Placement

As listed in **Table 3**, several battery technologies are available for powering electric bicycle motors. Of the choices given, Lithium Ion cells offer the best power-to-weight ratio, although they suffer from regenerative braking issues (as mentioned in Section 4.4), and may potentially be dangerous in the event of an accident. Supercapacitors are an interesting research area that may well be usable for future systems.

Whatever battery technology is used, the power source may well be the heaviest single component of an electric bicycle. The potential placement locations were briefly surveyed in Section 4.3, however it should be noted here that battery location can significantly influence the centre-of-gravity of the machine, and contribute to the feelings of stability, or otherwise.

Finally, the batteries listed in **Table 3** must be rechargeable in some way: either being removed from the machine and attached to a charger, or the entire bicycle connected to a charging attachment. Complete removal allows the possibility of swapping a discharged battery for a fully charged one. Some machines, often home-made ones, have solar panels mounted on them, or solar panels attached to a trailer for recharging (which may also house a battery).

4.6. Safety and Security

In terms of rider safety, of course wearing a helmet is the most obvious and effective safety precaution [26]. The relationship between motor power and safety is a complex one, primarily related to increase in speed, but also in increased weight. This area has been well studied by the New South Wales Centre for Road Safety [27]—the conclusion is that, at least for smaller motor powers (250 W and below), there is little correlation between safety and motor power.

The larger mass of electric bicycles due to motors (which weigh around 5 kg for a 250 W hub BLDC), battery (again around 5 kg for an 8 Ah 24 V Lithium Ion) and other components, will require better brakes than a standard bicycle to maintain a similar stopping distance. Rim brakes are still sufficient, and at least one comercial electric bicycle has a rear strap brake: disc brakes are not necessary in most cases. In fact, in regenerative systems, the motor will also contribute to braking—although this should not be relied upon since it depends upon correct motor, battery and controller operation, and can be temporarily inactivated when the battery is fully charged, or controller temperature becomes elevated.

It is also important that motor power is de-asserted during braking, and to this end most electric bicycles are fitted with brake switches, which allow the controller to detect brake application and turn the motor off accordingly.

Finally, the issue of theft should be mentioned. An electric power assisted bicycle is likely to be more expensive than a standard bicycle, and thus a more attractive target of theft. It thus requires a good quality lock, and deserves consideration of technological anti-theft measures. Several authors have studied such systems, generally by incorporating an electromagnetic deadlock within the motor assembly. An alternative approach has been taken by the Copenhagen Wheel project [28] which determines the presence or absence of the owner whenever the vehicle moves and reacts appropriately.

5. Reflections from Singapore

The Singapore electric bicycle initiative ("ebi") is a research-intensive drive to determine the optimum parameters of a street-legal electric bicycle for the NTU campus, and similar locations. Almost one hundred design combinations of features from **Table 3** have been tested across this campus by student volunteers for more than a year (and some designs for over two years). A

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large amount of survey feedback information has been analysed to form a set of reflections relating to electric bicycles on (this) campus.

5.1. Environmental Factors

Apart from the issues mentioned previously that are generic to many campus environments worldwide, the NTU campus is relatively hilly, suffers from widely separated facilities and exists in a tropical climate where daytime temperature lies between 28˚C and 30˚C year round and rainfall is characterized by sudden torrential downpours which result in significant water run-off into storm drains, but which dry up within a few tens of minutes. In this environment, it is unpleasant to be cycling in the rain. The ambient temperature and high levels of humidity in Singapore mean that almost any physical exertion more strenuous than a stroll will result in severe perspiration for most people [29]. Riding downhill feels pleasant due to the cooling airflow, and slow flat riding is tolerable most of the time, but uphill riding soon leads to perspiration.

In the tropical context, the authors have found that this has become a barrier to the use of bicycles. One of the most important features of the electric bicycle is its ability to assist the rider in hill-climbing. Indeed, on a small-wheeled bicycle with sufficient pedal gearing, it is quite possible to surmount relatively steep 10% hills without undue perspiration. In fact, the use of an electric motor to assist riders on the flat, and to provide most of the motive effort uphill, on the ebi, provides an excellent solution. The motor assistance allows riders to comfortably cover distances and terrains that would otherwise result in severe perspiration, and has proven to be a major positive factor in the public acceptance of this solution for the campus.

NTU has many kilometres of covered walkways, built to protect pedestrians from the heavy rain. Although it may not be entirely legal to use them, the walkways have proven to be an excellent resource for cyclists during rainstorms. In fact, the latest campus plan outlines a dual-path covered walkway concept—one side is reserved for pedestrians, while the other side is available for the use of cyclists (electric or otherwise). Although it is possible to fit a roof or rain shield to any bicycle, the riding characteristics differ as a result, especially in the presence of crosswinds. Covered walkways or cyclepaths are probably the best method of encouraging riders and overcoming some of the main barriers noted in Section 2.2 by protecting riders from rain or excessive sunlight.

5.2. Social Issues

Students, as a group, may tend to be more environmentally conscious than the population as a whole. There is thus mileage to be gained by promoting the environmentally sustainable characteristic of an electric bicycle that is charged by being plugged into a solar energy grid. In this area, success breeds success, with one of the biggest factors in popularity appearing to be linked to those who see the electric bicycles in action.

However there has been some concern regarding the style of electric bicycles in general. Small wheeled machines, while more useful for hill-climbing, appear to be less attractive than machines with larger wheels. The placement of controller and battery also impacts the look and feel of the machines. Many of the cheap bicycles manufactured in China are considered by the student population to be particularly ugly. This has been a surprisingly significant consideration for wide scale adoption: it is thus extremely important to have a solution that is attractive, easy to ride, and evokes positive feelings in both riders and other campus users.

Tied in with the look and feel of the bicycle is the fact that a public-use scheme must cater to both male and female students. Obviously there are several differences between the typical anatomy of these two groups, and this is reflected in general bicycle solutions for both groups: the presence of a crossbar and the saddle shape are the two main differentiating factors. Saddle and handlebar height are two other considerations that need to vary quite widely between taller and shorter riders, but these can be accommodated quite easy with adjustable stem and seat post.

The male/female shaped bicycle issue has been found to be important. Many male students would not feel happy riding a girl's bicycle, irrespective of how comfortable it is (and it is often *not* particularly comfortable).

5.3. Mechanical Issues

With experience of various electric bicycles and components in different arrangements, some useful insight has been developed pertaining to use in public hire schemes. **Table 4** notes the various mechanical points noted during the trials.

The final issue is security-an electric bicycle is a bigger investment and more attractive target of theft. Although Singapore is an extremely safe place, and no bicycles or components were lost during the trials, users had to be careful to keep the machines locked when unattended.

5.4. Computational Technology

There is an increasing trend for greater and greater computational complexity in consumer and transportation devices. For example, modern motor cars may contain 40 or more embedded processors, driven by numerous factors which include the efficiency in terms of power and cost that can be gained from the use of the devices, im-

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Table 4. Mechanical issues identified during the trials.

Motor cogging is a problem, especially with larger direct drive BLDC motors, causing a noisy drive that is jerky at low speed.	The centre of gravity of bicycles, especially with high battery placement, can lead to instability. Falls when mounting/dismounting are common.
Front wheel drive motors tend to cause over-steer during acceleration.	Heavy bicycles with high-mounted batteries, when parked, are dangerous if knocked over.
Hub motors should not be used with alloy forks, due to danger of fracture (although 200 W and below may be acceptable).	The changed centre-of-gravity usually prevents a actory-fitted kickstand from operating correctly.
Torque arms are mandated for larger hub motors, where torque can be sufficient to rotate the fixed axle, undo the wheel-nuts and break the drive cable.	Some of the geared hub motors available on the market are asymmetrical (rear motors *should* be, to accommodate the gear block, but front motors are often the same). This leads to difficulties with rim brakes.
Chain-drive systems experience enhanced chain, gear and derailleur wear.	

provements in operational effectiveness, additional features and so on. The advantages in having a perceived high-technology solution for advanced vehicles should also not be under-estimated as a selling point. Bicycles, similarly to motor cars, have also been equipped with computers for many years-cycling computers can track speed, distance, cadence and other attributes of a users travel.

For electric bicycles, the use of modern BLDC motors necessitates relatively complex control algorithms, usually provided by a simple microcontroller. These bicycles thus already incorporate a simple computer, which can conceivably also be used to provide standard bicycle computer functions, perhaps augmented by the BLDC controller access to additional sensing information.

Moving upward in technology (and requiring substantially more computing power), GPS-assisted mapping and navigation systems are as useful for bicycles as they are for cars, moderated mainly by the reduced range of most cycle riders compared to cars (*i.e.* they are more likely to confine their journeys to areas that they are already familiar with). Electric vehicles of all types can benefit from energy-aware route guidance—for example how best to navigate from point A to point B given the amount of energy available, knowledge of battery characteristics and the usage patterns of the current rider (which can be tracked or possibly inferred as a journey progresses).

For the NTU electric bicycle scheme, Android touch-screen computers have been provided for every machine.

A custom navigation solution for the university campus, which encodes campus points of interest, pedestrian

Figure 3. Screen shots of the Android eBike application showing navigation endpoint (top) and current location with destination search bar (bottom).

areas, high traffic areas and safety blackspots, has been written, called the eBike app (see **Figure 3**). This is based upon an OpenStreetMaps dataset and a community fork of the AndNav2 application. The NTU eBike app is open source, freely available for download and modification. In addition to navigation capabilities, IEEE802.11 communications and a campus server allow each bicycle to periodically announce their locations, receive messages, and access location-aware services. These include social networking-based applications which enable riders to know where their friends are currently riding, participate in campus discovery tours, operate a distance-based charging scheme and so on.

Although the energy-saving features of the current campus bicycle computers are not particularly significant, the usability aspects are important. These can be classified into social or technical spheres. Apart from the social aspects already mentioned, the authors have continually attempted to improve the attractiveness of these bicycles for campus users (who are predominantly the undergraduate student population), in many ways including choice of frame, colour scheme, styling, accessories and so on. The use of an Android-based touch-screen system, one of the most desirable and advanced computing solutions currently available, increases the desirability of the bikes for many users. Technical benefits of the system

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revolve around the ability to track the usage and location of bicycles at all times: knowledge of routes, likely arrival times, predicting battery discharge rates and so on.

One significant improvement that the ebi computers provide is the ability to advise riders which charging station to aim towards. In cases where charging stations can become periodically full (for example the charging stations at popular canteens during the lunch hours), there exists a usability issue when riders head over to the canteen only to find no parking/charging stations free. Other public hire systems, such as the Barclays public cycle scheme in London, provide a touchscreen controller at each charging location that can advise users of the status of other nearby charging stations, including the number of bays free. In the NTU scheme, the ability for the bicycle and central server to communicate, allows the relevant information to be advised to the cycles as they are heading towards a particular charging station if that charging station is full (or even likely to be full-remember, the location and destination of *other* riders is similarly predictable in many cases). The destination can be inferred based upon day and time, user, or programmed destination: particularly on the basis that users are more likely to program unfamiliar destinations into the navigation stations than familiar ones. Riders travelling to a familiar destination-where they do not require navigation information-would probably have made the journey before and thus have a relatively more predictable endpoint. For the small pilot scheme run so far with very limited charging locations, and few bicycles being equipped with the computers, this feature of the system was not exercised, but is expected to be an important usability improvement in larger scale schemes.

Regardless of the operational benefits provided through the use of capable and connected bicycle computers, these are attractive to students and have been seen to encourage users to value the cycles more. Increased adoption rates are the eventual aim, and sometimes look-and-feel is a more important human motivator than the actual technical features that are provided.

5.5. Changing Attitudes

Retrospective to the initial campus trials of the ebi system, users and potential users (80 people in total) were surveyed to determine changes in attitudes to cycling caused by the proposed solution, minus the Android bicycle computer. An initial free-form survey was used to derive a set of likely questions, formulated with reference to **Table 1**. Some respondents had not ridden the eBikes personally, but all were made aware of the scheme. **Table 5** presents the riding experience evaluation among those who had ridden the eBikes.

Table 5. eBike riders evaluation of the riding experience.

	Very good	*Good*	*Poor*	*Very poor*
Comfort	44%	**50%**	6%	0%
Convenience	**50%**	43%	6%	0%
Power	**47%**	**47%**	0%	6%
Stability	**47%**	35%	18%	0%

Clearly, the scheme is considered to be convenient by most users, relatively comfortable despite the smaller bicycle frames used, and sufficiently powerful (apart from two respondents (6%) who, from their associated written comments, appear to be motorcycle riders).

For all participants, it was important to validate the international studies of Section 2.2 in the tropical campus environment. Thus a number of questions were posed to determine the perceived barriers to bicycle use. Respondents who do not cycle regularly were asked to indicate their main reasons, with 134 “excuses” being given across 14 classes, as plotted using the black coloured histogram bars in **Figure 4**. The same questions were then repeated for the situation where a full scale ebi scheme is in use as proposed in this paper, plotted in the grey coloured histogram bars. The results very much validate Section 2.2 with the four primary international reasons (lack of facilities, inclement weather, distance/time issues and degree of effort/hill climbing) featuring strongly in the list. For the hilly NTU campus, hills are cited as a significant barrier, related also to the complaint of becoming sweaty. Tropical rain and lack of facilities are also significant barriers. The road danger is an unusual response given that the campus roads have a maximum vehicular speed limit of 40 km/h. Comments by respondents clarify that the concern is mainly due to narrow roads and lack of cycling-friendly or cyclist-aware drivers in Singapore.

Interestingly, the adoption of electric bicycles can be seen to solve the hill-climbing and sweatiness issue for the majority of respondents (a stated aim of the system), but acts to exacerbate the feeling of danger, concern over lack of facilities (apart from showers which would no longer be necessary), and highlights one factor we cannot control easily; tropical rain.

Within the subset of respondents who have used an ebi regularly (20), the issue of hills and sweatiness is very much seen as solved (75% and 87.5% respectively). The problems of rain and lack of facilities such as cycling lanes or parking spaces, are not affected by the solution. Only the issue of perceived danger is increased by the use of ebis, perhaps due to the greater power available and increased mass/momentum leading to a raised risk of damage.

Since the questions above are primarily negative, we also attempted to gauge the positive aspects of electric bicycle use on campus through the questions shown in **Table 6**.

Evidently, electric bicycle use is seen as more environmentally friendly than the alternative modes of transport,

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Table 6. Positive aspects of eBike use on campus.

	Very true	*Partially true*	*Partly untrue*	*Definitely untrue*
Environmentally friendly	**80%**	16%	5%	0%
It is convenient	48%	**52%**	0%	0%
It is safe	9%	42%	**44%**	5%
It is fun	**71%**	27%	2%	0%
It is quicker than walking (on campus)	**86%**	14%	2%	0%
It is quicker than driving on campus	33%	**37%**	33%	0%
It looks "cool"	29%	**37%**	27%	10%
It is a cheap form of transport	**58%**	26%	16%	2%
It makes me feel good	**49%**	39%	10%	2%

is relatively convenient, fun, quicker than walking, cheap and feels good. However it is not perceived as being safe (perhaps linked to the same issues that arose in **Figure 4**), is not particularly "cool" (remember that the Android computer was not used on these bicycles). Respondents were split on whether eBike use is quicker than driving. This may be because of the very low proportion of respondents who own a car. Starting from the laboratory where the main charging station is located, it is actually quicker to select an eBike, wheel outside cycle to any location on campus and park at the building entrance, than it is to head to the car park, unlock, enter and start the car, manoeuvre out of the parking space, pay the parking fee on exit, negotiate the speed bumps, exit the car park junction, drive to the destination, enter a car park, find a parking space, exit and lock the car and then walk to the destination office.

Finally, and most positively, 63% of surveyed campus users are "very interested" in joining the eBike scheme, 35% are "interested" and only 3% are "not interested". Among other things, this shows that the solution is acceptable to a wide cross-section of potential participants, male and female alike. From **Table 6** we also noted that 71% of all respondents considered the solution to be fun. These figures bode very well for user adoption of the ebi when it is expanded in scale to cover all campus locations and users.

6. Conclusions

Bicycle use is known to be healthy, efficient, environmentally friendly and in some localities is even faster than driving (either due to traffic conditions, or the distance of available parking spaces from origin and destination respectively). Unfortunately, bicycle adoption rates are not high in many places, due to various barriers and perceived barriers to more widespread use.

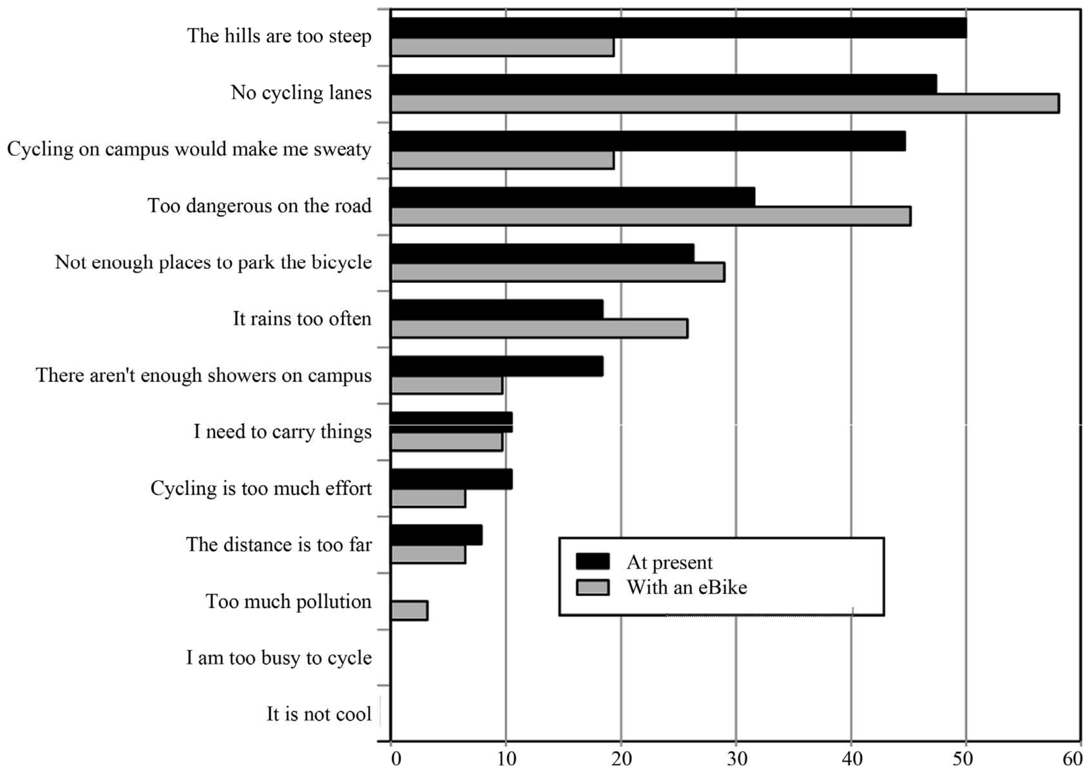

Figure 4. Respondents attitudes are surveyed concerning barriers to use for standard bicycles and the proposed eBike solution.

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This paper first explored the barriers to bicycle adoption, in particular for a tropical university campus environment, and hence propose technological means to overcome these barriers by defining and testing a range of electric bicycle alternatives to converge on a suitable solution. The electric bicycles in question use a pedelec sensor to control 200 to 250 W electric motors in a rider-assist configuration (chosen to be in compliance with Singaporean or European laws). The rider must pedal, causing the motor to contribute to the motion. The main aim in this environment being to ensure that whether the rider is going up hill, down, or riding on the flat, their rate of energy expenditure can be maintained low enough to prevent excessive perspiration.

These electric bicycles, of many types, have been evaluated in practice in a semi-public hire scheme on the Nanyang Technological University campus in Singapore. The results of the study, including insights into the scheme and various findings are presented here in this paper.

The scheme has many more aspiring riders than can be accommodated. It is a popular and useful service, with some models of electric bicycle being very well-used. Riders consider the majority of the electric bicycles to be both comfortable and fun to use, and extremely convenient for campus travel. Students and the public alike view the scheme positively, and we have seen a reduction in the number of miles driven by car within the campus for the majority of users who are also drivers.

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