DESIGN OF NOVEL HYBRID ELECTRIC BICYCLE

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Abstract
Active transportation; involving cycling and walking, is inversely related to obesity. In North America, Australia, and Canada, active transportation is much less common than in Europe. Along with the known health benefits, cycling is also more environmentally friendly and cost effective when used as a form of transport.

There are numerous factors limiting the use of bicycles as transport. The ultimate aim of this project is to develop a personal transport vehicle which encourages active transportation. To do this, the vehicle needs to solve all the problems that are inherent in bicycles whilst retaining the benefits. It must be practical and safe enough to be the preferred choice where a larger vehicle is not necessary. We present in this paper our solution to the first of these problems – range and power.

Our approach to this problem was to design a hybrid-electric bicycle that allows the rider to exert less effort and maintain a higher speed, making it much more viable and appealing for transport. To achieve this, the bicycle senses the rider’s torque and supplies assistance via two electric hub motors. The rider can choose from four modes of operation, each with user adjustable values. There are five modes of operation, including a proportional assistance mode, a peak-effort mode, a target speed mode, cadence assistance, and a high-regeneration mode. These four modes will enable the rider to commute at a greater speed than on conventional bicycles while requiring less effort. This however will not eliminate the health benefits to riding as the rider is always expected to exert a degree of effort for the bicycle to remain operational. The increase in speed coupled with the reduction in effort increase the effective range of the rider, making this design a much more viable and appealing option to commuting in a car.

Keywords: Hybrid, Bicycle, Human-Electric, Urban mobility, Alternative energy

1 Introduction
Cycling provides both the individual as well as the wider community with numerous benefits that make it an ideal mode of transport. These benefits include improvements to both personal and civic health, reducing traffic congestion, air pollution and greenhouse gas emissions, as well as the economic benefits associated with those improvements.

There are however several problems that have hindered the success of bicycles as a mode of transport in developed countries. This paper presents a prototype that alleviates three identified problems. Those three problems are: slow speed,
high level of effort required, and unsuitability to long range trips.
The designs presented aim to reduce the effort required to maintain a higher average speed and as a result achieve a much greater effective range. The proposed solution uses electric motors to provide the required assistance.

2 The Problem
In many Western nations, participation in physical activity has declined in recent years. This is partly due to fewer manual jobs, fewer journeys are taken by bike or on foot as well as the physical elements of housework, shopping and other activities, having significantly diminished.

More than 50 per cent of Americans [1] and 69 per cent of adults in the United Kingdom [2] are not meeting the recommended 30 minutes of moderate physical activity on most days of the week. This substantially increases their risk of contracting up to twenty chronic diseases or conditions [3] while putting strain on the economy. In 2002 the cost of physical inactivity on the UK economy was estimated to be £8.2 billion [2].

A lack of physical activity also creates an imbalance between the body’s energy intake and expenditure, leading to weight gain and consequently causing the current obesity epidemic. Obesity is a chronic condition that affects a person’s quality of life and may require lifelong treatment. Obesity and overweight causes many preventable diseases such as heart disease and diabetes, resulting in approximately 300,000 deaths per year in America [1] as well as accounting for 18 million sick days and 30,000 premature deaths in the United Kingdom [3]. In 2003, high body mass was responsible for 7.2 per cent of total deaths in Australia [4].

Decades of transportation strategies and infrastructure investments focusing on cars have resulted in chronic traffic congestion, high fuel prices, and inefficient transport systems around the world. The average American drives 15,000 miles per year, and the total miles driven has increased three times faster than the population growth rate [1]. The resulting increase in traffic congestion and greenhouse gas emissions are of great concern. Traffic congestion causes several problems including the waste of time and fuel, pollution, and health issues. The estimated cost to the United Kingdom’s economy due to congestion is £20 billion annually [2], while in the United States, the average American spends the equivalent of an entire work week every year stuck in traffic [1]. Between the years of 1990 and 2007, European greenhouse gas emissions as a result of transport increased by 36 per cent, while greenhouse gas emissions from other sectors decreased by 15 per cent [5]. It has also been estimated that annually 24,000 people in the United Kingdom die prematurely due to exposure to air pollution from particulates, ozone, and sulphur dioxide, most of which is related to road traffic [3].

3 Cycling Benefits
Regular bicycle usage provides both the cyclist as well as the wider community with numerous benefits that make it an ideal solution to the aforementioned problems. These benefits include improvements to both personal and civic health, reducing traffic congestion, reducing air pollution and greenhouse gas emissions, and the economic benefits associated with those improvements.

3.1 Health
Cycling regularly provides improvements in physiological well-being and musculoskeletal health. Health benefits include a reduction in the risk of developing up to 20 life threatening diseases including cardiovascular disease (including coronary heart disease and stroke), type 2 diabetes, hypertension, osteoporosis, arthritis, and various cancers. Studies show that the relationship between physical activity and the risk of developing such conditions is an inverse dose-response. This means that the more a patient is physically active, the less likely they are to develop these conditions and can reduce the risk of these diseases by up to 50 per cent, as well as a 20 to 30 per cent reduction in the risk of premature death [2]. This reduction in risk can be achieved through low levels of physical activity such as incorporating cycling into ones daily commute. European countries that rely heavily on active transport have much lower rates of obesity than countries like Australia, the United States of America, and Canada which are heavily reliant on the car [6].
In the United States for example, cars are used for 55 per cent of trips of about 500 metres, and 85 per cent for trips around 1 kilometre [7]. The recent obesity epidemic is due to an imbalance of energy intake and energy expenditure which results in weight gain. Obesity may require lifelong treatment and can lead to an increased risk of developing hypertension, coronary heart disease, type-2 diabetes, and osteoporosis. Cycling is particularly beneficial for those who are overweight or obese as 70 per cent of their weight is distributed through the bicycle’s saddle, handle bar and pedals [3]. This significantly reduces the dynamic forces acting on the body when compared to activities such as running, potentially preventing serious injury.

As well as the physical health benefits, cycling also promotes improved mental health and well-being irrespective of socio-economic or health status. Cycling has positive effects on the cyclist’s self-confidence, wellbeing, stress tolerance, sleeping difficulties, and reduced tiredness among other medical symptoms [8].

### 3.2 Traffic Congestion

One of the problems that cycling can alleviate is traffic congestion; which results in loss of time, increases in greenhouse gas emissions, and reduced vehicle efficiency. Traffic congestion costs the average American the equivalent of an entire working week in wasted time over the course of one year [1]. An increase in regular cycling as a mode of transport would result in a significant reduction in traffic congestion in modern, population dense cities.

One of the reasons that cycling has an impact on traffic congestion is that due to the size and increased mobility of the bicycle, in urban environments bicycles can move at least 5 times more people than a car [1].

Cycling also has the potential to dramatically increase the catchment area of public transport services, making them more accessible and convenient to the populace. This results in close to a 15 fold increase in the catchment area [9]. Cycling has a twofold impact on traffic congestion as the use of public transport takes potential drivers off the road while also reducing the amount of car trips taken to public transport stations, especially during peak travel times.

Of the carbon dioxide emissions relating to transport in Australia, cars are responsible for about 50 per cent [10]. In the United Kingdom road transport accounts for around 70 per cent of the air pollution of cities as well as 22 per cent of greenhouse gas emissions [2]. Substituting a bicycle for a car on short trips is an effective way of reducing carbon dioxide emissions; as a result every kilometre cycled results in great benefits to the community in terms of pollution and greenhouse gas emissions. Reductions in carbon dioxide emissions of at least 21 million tons per year [1] in the United States of America, as well as a conservative estimate of 11 million tonnes per year in Europe [5] can be achieved with a modest increase in cycling. It is predicted that by 2020 if the European cycling modal share were to increase to levels seen in Denmark in 2000, the total distance travelled by cyclists would reach 481 billion kilometres and between 55 and 120 million tonnes of CO2 emissions would be saved annually. This would account for 5 to 11 per cent of the European Union’s greenhouse gas emissions targets [5].

As well as all the benefits mentioned above, there are associated savings to either individuals or to the economy. In Australia it was estimated that for each kilometre travelled per person on a bicycle, the economy benefited by $1.43 [10]. In the United States a modest increase in the cycling transport
mode share would result in fuel savings, greenhouse gas reductions, and health care savings of more than $10 billion annually [1]. In the United Kingdom it is estimated that the reduction in health risk factors due to an increase in cycling would save £11.16 per person per year for those under 45 years of age and £99.53 per person per year for those between the ages of 45 and 64 [2].

All these factors contribute to the lack of utilisation of cycling as a mode of transport. The convenience of driving to work in comfort, protected from the elements, while exerting very little effort is something that most of us will find very difficult to abandon. The limitations above are inherent with conventional bicycles and prevent a vast majority from using the bicycle as a means of transport.

4 Cycling Problems
There are several limitations with riding conventional bicycles that have had a significant impact on their usage in developed countries. The first of these limitations is the perception that cycling for commuting purposes involves a higher investment and sacrifice from the rider compared to driving. This is not an economic investment; it is one of time and effort. With conventional bicycles people believe that due to the limited speed of bicycles, that they will need to allocate more time in their already busy schedules to accommodate the added time require for the commute.

Along the same lines of the previous point, many potential cyclists are deterred by the distances that they would need to cover to commute. Cycling is a great form of transport for short distances; however in many countries the average commute is quite long.

Another limiting factor is that cycling is form of active transport. Whilst this is a good thing, for most this would result in arriving at work as if they had just finished an intense gym session and remaining in such a state is neither practical nor hygienic. This of course can be resolved with a little preparation and having a shower and change of clothing once at work. This however this brings us back to the first point of allocating more for the commute.

Safety is one of the paramount concerns for those who cycle regularly. Sharing roads with other transport vehicles that are faster and have significantly greater mass is a frightening prospect. Whilst wearing a helmet does offer some protection, it has done little to change the perception that cycling is a risky form of transport.

As well as offering its occupants better protection in case of an accident, a car also protects its passengers from extreme and harsh weather conditions. This is a significant factor when commuters decide what form of transport to utilise.

5 Solution
The key objective of this project is to design and produce a hybrid electric bicycle that will alleviate or eliminate some of the limitations of the conventional bicycle mentioned above. The design and prototype outlined in this paper aim to make cycling a much more appealing and viable option to the car for commuting purposes.

Without major alterations to their basic design or extensive infrastructure developments, there are few options available to make bicycles safer or better to ride in bad weather conditions. The proposed solution is to design and construct a prototype hybrid electric bicycle that gives the cyclist an assistance provided by electric motors. The cyclist will have several modes to select from to better suit their requirements. These modes will allow for user-adjustable assistance levels to cater for people of differing builds, strengths, and endurance levels. The cyclist’s interaction with the bicycle remains familiar and unchanged.

Although the distances for the commute remain the same, the cyclist will not be required to pedal as vigorously to maintain an acceptable pace, due to the assistance of the motors. This allows the rider a greater degree of flexibility in the commute, inasmuch as the rider may choose to pedal vigorously anyway, increasing the velocity of travel and arriving sooner. Alternatively, less vigorous pedalling will result in the same travel time as an unassisted rider, but without as much exertion and associated sweating or showering. In all cases, the rider will experience an increased effective range beyond that which is possible when unassisted.

6 Design and Prototype
In order to successfully fulfil the requirements of the aforementioned solution, several integral aspects of the prototype needed to be researched and designed, these are outlined below.
6.1 Bicycle Frame
The type of bicycle frame selected will greatly affect the performance of the prototype. The frame selected for use in the prototype is a road bicycle frame. The frame from the Cell Bikes SS300 road bike was chosen for several reasons. These include:
- Lightweight construction
- Rigid structure
- Low friction co-efficient
- Designed for speed
These factors will provide the prototype with the most efficient operational performance.

6.2 Motors
Two 48v motors are used to provide the required assistance. The motors selected are the 400W Smart Pie 3 motors produced by Golden Motor. These motors are direct drive, brushless DC hub motors that are mounted at the front and rear forks of the bike frame. This means that for each motor there is only one moving part; the casing housing the magnets. These motors were selected due to their:
- Lightweight construction
- Built in motor controller
- High efficiency
- Small size
- Power and torque characteristics
Two motors are utilised in this design for two reasons, to remedy an imbalance that would be created if only one motor was used, and to reduce the load on each motor. The later point has the potential to increase service life of the motors as well as improve the prototypes efficiency, especially under heavy load where these motors become inefficient. By effectively halving the load on each motor, the motors will be able to operate in regions offering much higher efficiencies.

6.3 Power
The power source selected is a 48v, 20Ah Lithium Iron Phosphate (LiFePO₄) battery. The 48v supply and motor voltage was chosen to improve efficiency and the range of the prototype. Since electrical power is the product of the current and the voltage flowing; the higher the voltage, the lower the current for the same power output and efficiency. This results in a battery pack that will be able to provide the motors with power for much longer.

The characteristics of the LiFePO₄ battery pack are ideal for such a project. These include the near constant supply voltage from full charge till exhaustion, fast charge time, light weight construction, high safety, and good specific power.

6.4 Control System
The control system for this project must achieve several targets. These targets include providing the cyclist with assistance when required, displaying relevant information, providing an easy to use and intuitive user interface, and finally operating in a failsafe and reliable manner.

The controller comprises of 5 user assistance modes that the user can switch between to change the characteristics of the bike. These modes are:
- Proportional assistance – Provides motor assistance proportional to the cyclist’s effort (torque).
- Peak-effort – Provides assistance once the user selected maximum effort has been reached or exceeded. This is controlled using a PD (Proportional, Derivative) controller
- Target speed – Provides assistance to maintain a user selected speed. This is controlled using a PD (Proportional, Derivative) controller
- Cadence assistance – Provides assistance proportional to the cyclist’s cadence.
- High-regeneration – increases the load on the cyclist while regenerating energy using the motors.

The bike may also be used without assistance. In order to gain assistance the cyclist must be pedalling. To the user the only difference between operating this prototype and a conventional bicycle is selection of assistance mode and assistance level.

The controller was developed using the open source Arduino Mega 2560 microcontroller board, and a custom control and display unit, as well as a custom designed circuit board to interface the controller to the motors, sensors, and user interface.

6.5 Sensors
The control system relies heavily upon three sets of sensor data to determine the required level of assistance. These are for speed, cadence, and torque.

The speed sensing is achieved using a reed switch and two magnets placed on the rear wheel spokes.
180 degrees apart. This provides the controller with a speed reading every half revolution. The cadence and torque sensing is obtained using a Thun X-Cell RT sensor. This is a device that fits in the bike frame’s bottom bracket. To sense torque it uses Hall Effect sensors to pick up changes in the magnetic properties due to strain, according to the Villari effect.

7 Testing and Results

The controller was developed with testing in mind, as a result all relevant data such as speed, torque, cadence, distance, motor outputs, brake application, and motor currents are serially output by the controller five times per second. A small tablet pc with a serial monitor application was used to record the data transmission. The primary aim of testing was to determine how well the prototype is able to assist the cyclist, and how the different cycling modes affect the cyclist. A suitable course with inclines, bends, and straight asphalted roads was selected. The main test was an attempt to maintain a speed of 20km/h around the course using the various assistance modes as well as without assistance. Several data sets were collected for each cycling mode to ensure that the data collected is indicative of the prototypes actual performance and minimise the effects of uncontrollable variables such as wind speed and direction.

The averaged results clearly show a significant reduction in the effort required to maintain the 20km/h speed on the same course. This reduction is in the magnitude of between 53 per cent and 77 per cent of the power required to complete this course. It is also apparent that these cycling assistance modes do not simply reduce the force required to turn the pedals, but they also have the potential to significantly reduce the required rate of pedalling (cadence).

As mentioned above, there are many variables that can cause discrepancies in the results, and as a result these values are merely indicative of the potential gains achieved by this prototype. A more controlled environment is needed for testing purposes.

8 Conclusion

The prototype has been extremely encouraging and has achieved all the design objectives that were identified. However as with all projects several improvements and optimisations to the prototype can be made to further improve it, mainly the optimisation of the control algorithms for the different cycling modes. This prototype is part of an on-going project to develop a personal transport vehicle which encourages active transportation. The benefits of cycling have been extensively documented, yet a small percentage cycle regularly, this prototype has the potential to change that; it maintains the benefits of cycling while reducing the problems that have hindered the bicycles success in many developed countries. As a result this prototype has the potential to help create a much healthier, cleaner, and more sustainable future for our cities.

Table 1: Averages for results from prototype testing

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cadence (RPM)</th>
<th>Torque (N.m)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Assistance</td>
<td>56.0</td>
<td>28.0</td>
<td>171.6</td>
</tr>
<tr>
<td>Proportional</td>
<td>49.9</td>
<td>13.6</td>
<td>79.1</td>
</tr>
<tr>
<td>Assistance</td>
<td>47.2</td>
<td>9.8</td>
<td>56.0</td>
</tr>
<tr>
<td>Peak-Effort</td>
<td>43.5</td>
<td>16.2</td>
<td>85.0</td>
</tr>
<tr>
<td>Target speed</td>
<td>27.6</td>
<td>9.9</td>
<td>39.1</td>
</tr>
</tbody>
</table>

References


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