The Copenhagen Wheel: An innovative electric bicycle system that harnesses the power of real-time information and crowd sourcing

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Abstract: This paper presents the ongoing research and development of ‘The Copenhagen Wheel’ – an innovative electric bicycle system developed by MIT’s SENSEable City Lab for the City of Copenhagen, with support from the Italian Ministry for the Environment and Ducati Energia s.p.a. The aim of this paper is to show that the Copenhagen Wheel not only represents a leap-frog technical solution for the electric bike market – that includes the development of a regenerative braking system and innovative motor control – but also uses real-time sensing and the powers of crowd sourcing to improve the cycling experience; get more people riding bikes; and to aid in the design and development of cities. The initial prototype of The Copenhagen Wheel was presented at the Mayor’s Summit at the COP15 United Nations Climate Change Conference in Copenhagen, December 2009. It is currently in its final prototyping phase and will go commercial in 12 months time.

Keywords: Electric Bicycles, Innovation, Transportation, Sustainability, Real-time Information, City Governance, Crowd Sourcing

1. Introduction

This paper presents the ongoing research and development of The Copenhagen Wheel – the wheel that turns ordinary bikes, quickly and easily into electric hybrids with regeneration and real-time environmental sensing capabilities.

It shows how SENSEable City Lab has avoided incremental technical improvements in favour of a leap-frog solution, that is technically advantageous, improves the cycling experience and has the potential to foster the culture of cycling in cities.

To demonstrate the above, this paper begins by outlining the rise of the electric bike (e-bike) market and some of the challenges that will threaten its 25-year growth trend. It will then briefly identify where the e-bike market could innovate – both on a technical and cultural level.
The Copenhagen Wheel is presented as a response to these opportunities for innovation. Approaches that aid the cultural acceptance of e-bikes, technical advances and key performance indicators are provided. This includes an overview of the ability for the wheel to harvest the energy a cyclist inputs while braking and cycling as well as information about gearing, battery life, motor control through torque sensing, locking, theft deterrents, the innovative spoking method, environmental sensing and iPhone integration for motor and gear control.

Lastly, the paper outlines how, with the aid of a few small sensors, the Copenhagen Wheel becomes more than a vehicle that gets you from a to b. Rather, it is a smart, networked device that can transmit information about the environment, personal fitness and location to a rider’s phone and the web in real-time. The advantages of this are discussed; as is the potential for this type of feedback loop to radically transform the cycling experience, aid in transport related policy decisions and finally, get more people buying e-bikes and cycling further and more frequently.

2. The Rise and Rise of Electric Bikes?

It can no longer be disputed: across the globe, electric bicycle numbers are on the rise. Nowhere has the rise of e-bikes been more prevalent than in China where units-sold have risen from the tens of thousands in the late 1990’s to over ten million in 2005 [1]. In the US also, electric bikes are becoming popular for short trips to the grocery store or leisurely rides [2]. Meanwhile, in India, the young-and-moneyed call center workers lean heavily toward scooter-like e-bikes as their vehicle of choice [3].

The reasons for this increase are many, and vary from nation to nation. In China, a country renowned for its push-bike culture, the shift to e-bikes has been influenced by the following: changes in urban form that have rendered trip distances too long for ordinary bicycles and too slow by other means of transport; national and local government policies targeting pollution; rising income levels with an increased proportion of income spent on transport; and the improvement of e-bike battery and motor technologies [4]. Meanwhile, in countries like the US and Australia, rising oil prices, the adoption of a green lifestyle ethic and the fact that e-bikes are suitable for elderly or physically impaired riders has seen numbers increase significantly over the last two decades.

However, the e-bike market is not without its problems. Concerns over safety (particularly that you can not hear the bikes approaching) have already seen e-bikes banned in more than three Chinese cities [4]. In addition many e-bikes use lead-acid batteries and environmental lifecycle assessments have been less than favorable [1]. Perhaps one of the biggest problems facing the adoption of e-bikes, however is the potential saturation of the market. We have already seen this occur with push-bikes, where, even in a country like Denmark, with its progressive bicycle policies and excellent cycling infrastructure, the number of people who cycle to work has remained virtually constant over the last 10 years [5].

As such, although we see a steady increase in the number of e-bikes being sold, there are still a number of problems to tackle if we want this growth to be a continuing trend. The Copenhagen Wheel team at MIT’s SENSEable City Lab, have chosen to address this challenge not through incremental improvements to e-bike technology, but through attempting to ‘reinvent the wheel’ and innovate on both a technical and cultural level.

3. Innovate to generate

Innovation in any market is more than an improved technical solution. As Jens Martin Skibsted, the Danish designer and owner of the bicycle company Biomega points out: “The winner will seldom be the one that’s the most functional, but rather the one that can become an inherent part of our culture” [6].

There is plenty of room to innovate in the e-bike market of today - both on a technical as well as a cultural-acceptance level. Currently and particularly with ‘pedalec’ bicycles (bikes where riders must pedal a certain percentage of the time), designs are clunky and unwieldy, with battery packs that are bulky external things that must be hard-wired to motors (and often use environmentally unfriendly lead-acid batteries). In addition, e-bikes are heavy and there is often no way of integrating gearing or of doing the obvious: capturing the energy expended through the act of pedalling (fig. 1).
Culturally, many improvements can also be made. At present, consumers of e-bikes must either buy a brand new bike or must deal with integrating and wiring components into their existing bike – a time consuming task. Product theft is also an issue, with riders who live or work in dense urban areas having to lock their expensive equipment outside. Couple this with perceived and actual safety issues and a general lack of cycling infrastructure and it becomes obvious why only a segment of the market might adopt this technology.

The approach taken by SENSEable City Lab when faced with these challenges was to look at the issues holistically. Consisting of architects and urban planners, a mechanical and an electrical engineer, computer scientists, interaction designers and a physicist, the team was active in exploring and borrowing ideas from several fields including formula one racing, gaming, urban planning and design, social networking, sensor systems and real-time data collection and web development.

What resulted was a brief for Cycling 2.0 – aimed at providing technically robust, leap-frog solutions that improve the cycling experience and support the implementation of cycling infrastructure and cycling as a culture.

4. The Copenhagen Wheel

The Copenhagen Wheel (fig. 2) is a bicycle wheel that can be easily retrofitted into any ordinary bike. It’s sleek red hub not only contains a motor, batteries and an internal gear system, but also includes environmental and location sensors which are powered by the batteries in the wheel and provide data for cycling-related mobile applications.

Figure 1: Typical electric bike found on the market - with external battery pack.

The brief that was generated by the SENSEable City Lab team was as follows:

**Goal:** To make the cycling experience more pleasurable:
- The bicycle should be controlled only through pedalling (no throttle) with one remote for choosing one of three modes:
  - Off
  - Motor Assist
  - Pedal Assist (Regeneration/exercise mode)
- All components, including the motor, batteries, gears, locking mechanism, locationing technology and environmental sensors should be integrated into a hub in the back wheel.
- The wheel must be easily retrofittable into any standard bicycle.
- The weight should be no more than a ‘heavy bike’ when fitted into a regular bike.
- The wheel must harvest energy through braking and pedalling.
- Health monitoring (calories burnt, effort expended etc) should occur through measuring the torque applied by the cyclist.
- Environmental/location monitoring should occur through placing small sensors in the hub – to be powered by the wheel’s batteries.
- Applications should be developed that harness the data gathered through the locationing device, torque and environmental sensors.

Figure 2: With all components packed into one hub and no external wiring, the Copenhagen Wheel represents a departure from other electric bikes on the market.
5. Technological innovations and performance

A key factor in the success of the Copenhagen Wheel is that all components are packed into a single hub that sits in the rear wheel. With no external wires or battery packs, the wheel becomes a plug-and-play device that transforms any ordinary bike, quickly and easily into a smart electric hybrid. This ease of use is important in capturing the segment of the market that are not bike experts or who do not want to buy a whole new bike in order to go electric. Meanwhile, a range of spoke lengths allows the hub to be retrofitted onto both road-bike and mountain bike wheels.

Figure 3 shows the components of the Copenhagen Wheel. As the wheel is in final prototyping phase, specific component details will not be printed. However, principles and some key performance indicators can be found below.

Figure 3: The components of the Copenhagen Wheel

A. Braking

In order to maximize the regeneration ability of the Copenhagen Wheel, a coaster brake mechanism is integrated with the other components in the hub. Its operation is as follows: when the rider begins to pedal backwards, the wheel initially brakes electronically. As the rider applies more pressure when braking, mechanical braking begins.

B. Regeneration

The Copenhagen Wheel uses a technology similar to the KERS (Kinetic Energy Recovery System), which has revolutionized Formula One racing over the past couple of years. When you brake, your kinetic energy is recuperated by the electric motor and then stored by batteries within the wheel.

Regeneration occurs during the electronic phase of braking. It also occurs in exercise mode - where riders are working against the motor, thus giving themselves a workout and in turn recharging the batteries in the hub.

C. Gears

At present, an internal 3-speed hub gear is used. The gears are changed electronically from the controller on the handlebars.

D. Batteries

The battery pack is easily removable from the hub, enabling cyclists to charge it indoors without having to transport the entire bike to a charging point. Currently, 16 x 3.7V Lithium Polymer batteries are arranged in a donut shape around the motor. Performance calculations and tests suggest that battery life is around 4 hours given a typical daily commute of 2km by a 70kg person with a gentle upslope of 0.01.

E. Motor Control through Torque Sensing

When cycling, the rider can choose one of three motor assist modes: low, medium and high. Each mode represents how much the motor is supplementing the cyclist’s inputted effort (eg: effort x1, x2, x3).

A sleeve-style mechanical torque sensor was developed that measures the amount of effort that the rider is exerting as well as the speed and direction that the pressure is being applied. The readings from the torque sensor tell the motor how much to supplement the rider, based on the motor assist mode the rider has chosen.

Similarly, when the rider wants a workout or to recharge their batteries, they may choose a low, medium or high ‘exercise’ mode. Here, the rider is working against motor eg: effort x (-1), effort x (-2), effort x (-3).

F. Locking and Anti-theft mechanism

The Copenhagen Wheel includes an intelligent locking and anti-theft mechanism.

It operates as follows:
If {bike moves} {check if owner’s mobile is nearby}
If {owner’s mobile not detected} {alarm!} else {unlock bike}

Additionally, as an anti-theft deterrent, the hub uses onboard accelerometers to detect undesired movement and upon detection sound an audible alarm as well as restrict wheel movement to prevent effective pedaling. The hub also reports its position through the GPRS connection when in the alarm state to alert the owner that their bike is on the move.
G. Spokes
In order to distinguish the Copenhagen Wheel from other bikes on the market and to increase the overall elegance of the wheel, the SENSEable City Lab developed an innovative spoking method. (fig. 4) One end of the spoke connects at the rim via a standard thread and nipple. The spoke then comes down toward the hub, loops through a curve that is carved out of the face of the casing and continues back up to connect to the rim. Lastly, different size spokes can be easily made for different size bike wheels.

Figure 4: The innovative spokes on the Copenhagen Wheel (shown here with inner electronics revealed).

H. Environmental Sensors and Location Awareness
A suite of environmental sensors, including CO, NOx, temperature, noise (dB) and humidity are located inside the hub. They collect information at 2-second intervals and transfer it to the hub controller. The integrated communication and locationing device then sends the data to the handlebar controller (a smart-phone) where it is processed and used to power applications that relate to a cyclists health, community or the environment.

I. iPhone control
The Copenhagen Wheel is controlled through the rider’s smart-phone and thus becomes a natural extension of their everyday life. In our case, this capability was developed on an iPhone, however, any Smart Phone with Bluetooth capability could be used. The rider places their phone in the cradle on the handlebar and the bike unlocks because the phone and the wheel sync via Bluetooth. The cyclist can then use their phone and the dedicated Copenhagen Wheel application to control the bike as well as view and share the data that is collected from the sensors in the wheel.

6. Ride, Analyze, Share - the power of real-time information and control
With the benefits of cheap electronics and a few small sensors, The Copenhagen Wheel is more than a vehicle to get you from a to b. It is in fact, a smart, networked device that has the power to encourage people to ride further and more frequently. The key to this is that the wheel can collect and transmit information to the rider’s iPhone on the handlebars and also to the web - in real-time. In turn, the iPhone and web application compiles the information so that the rider can easily access it, either during their commute, pre or post-ride. Harnessing the real-time feedback loop of information is crucial to promoting a continued culture of cycling. Equally important is the design of the interface through which the information is viewed. The data must be easy to navigate, not be distracting to the rider and relevant to a cyclists need and concerns. Fig. 5 shows the ‘splash-screen’ for the iPhone interface. It is broken into three function categories: ride, analyze and share.

Figure 5: Ride, Analyze and Share – the three components of the iPhone interface.

A. Ride
The Ride screen (fig 6.) allows the cyclist to control the bike while riding. This includes the amount of motor assist desired and gear changing. It is also where ‘critical’ real-time information is shown. For instance, if the rider has been exposed to a harmful level of pollutants for an extended period of time, the screen will flash a warning that allows the rider to divert from their present route. Similarly, if a friend from Facebook or another social networking site/service has a Copenhagen Wheel and is nearby, the rider will receive a
friend proximity notice. This service, named *I crossed your path* aims to make some of the virtual connections we have, physical. Finally, the rider gets real-time weather, upcoming road condition and noise warnings.

![Figure 6: Cyclists control the amount of motor assist they require, change gears and get real-time updates through the ‘Ride’ screen.](image)

### B. Analyze

The Analyze screen (Fig. 7) is predominantly accessed pre or post ride. Through it, cyclists can locate their bike and analyze data from recent trips. This data falls into one of three categories: personal health (calories burnt, effort expended, exercise targets met etc.), the environment (noise and environmental pollution exposure, temperature, road conditions etc.) and community (number of friends that crossed paths etc.).

In health terms, the analyze screen is where the Copenhagen Wheel becomes like a personal trainer. It can tell the rider whether they are reaching their personal best or how much of their recommended daily exercise they have completed – encouraging them to ride more if they haven’t reached their goals. In environmental terms, we envision schemes like *Green Miles* – a bit like a frequent flyer program, only good for the environment. Here cyclists keep track of the number of ‘green’ miles they are riding rather than the un-environmentally friendly miles that they would have collected if they were traveling by car or other transport mode. These miles could be traded and provide an incentive to ride a bike more frequently. Lastly, allowing cyclists to analyze where and when they cross paths with known friends helps to build a community of connected riders and builds social capital in cities.

![Figure 7: Cyclists can analyze health, environmental and community data that their wheel is collecting through the ‘Analyze’ screen.](image)

### C. Share

Both the Ride and Analyze screens are useful in that they further promote cycling to the cyclist themselves. However, it is through the Share screen (Fig. 8) that the real power of networked data collection is unleashed. The Share screen allows cyclists to share their data with their friends, but also, if they wish, with their city. Sharing data between friends gives the cyclist access to a larger pool of information from which they can make more intelligent cycling decisions. For instance, a friend’s previous routes will have recorded road conditions and pollution levels over time – helpful when a rider is planning a journey in a new part of town. (Fig. 9).

Meanwhile, when many cyclists donate the information their wheel is collecting to their municipality, the city gains access to a new scale of fine-grained environmental information. Through this, cities can: cross-analyze different types of environmental data on a scale that has never before been achieved before; build a more detailed understanding of the impact of transportation, on a city’s infrastructure or study dynamic phenomena like urban heat islands. Ultimately, this type of crowd sourcing can influence how the city allocates its resources, how it responds to environmental conditions in real-time or how it structures and implements environmental and transportation policies. In particular, schemes like *Green Miles* could be expanded so that all citizens can participate in plans to reduce emissions, perhaps paving the way for cities to enter carbon-trading schemes.
Figure 8: The ‘Share’ screen allows cyclists to share the data their wheel is collecting with friends, or with their city.

Figure 9: NOx data collected while cycling in Copenhagen during December 2009.

7. Conclusions

The Copenhagen Wheel project began by asking the question: how can we improve the cycling experience in order to encourage more people to ride bikes. What was discovered was that a relatively small amount of technology could be used to augment the bicycle – for great effect. By approaching the design of The Copenhagen Wheel holistically, and not settling for an incremental improvement, we were able to create solutions that not only innovatively answered our technical brief, but also tapped into the potential that the digital networking of people, objects and cities through real-time information loops brings.

The Copenhagen Wheel can be seen as part of the general trend of inserting intelligence into our everyday objects to create a smart, supporting infrastructure around ourselves. In this way, it is much more than a bicycle or a clean mode of transport. Instead we hope that it is opening the doors for citizens to improve their quality of life, participate in governance and the maintenance of public resources and become actuators of change in their own cities.

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References


Figures

Figure 1:
Figure 2:  
Photo taken by Max Tomasinelli

Figures 3:  
Author’s own

Figure 4:  
Photo taken by Max Tomasinelli

Figures 5-8:  
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