

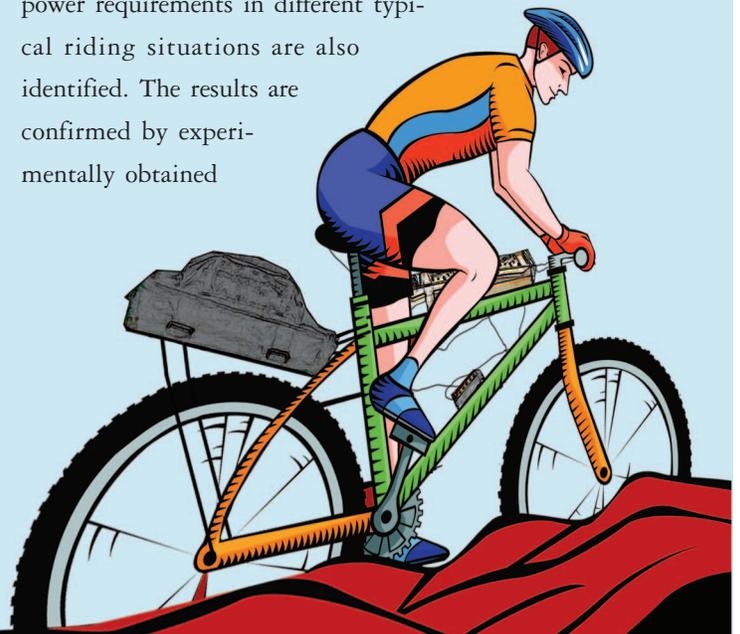
ELECTRIC BICYCLES

A performance evaluation

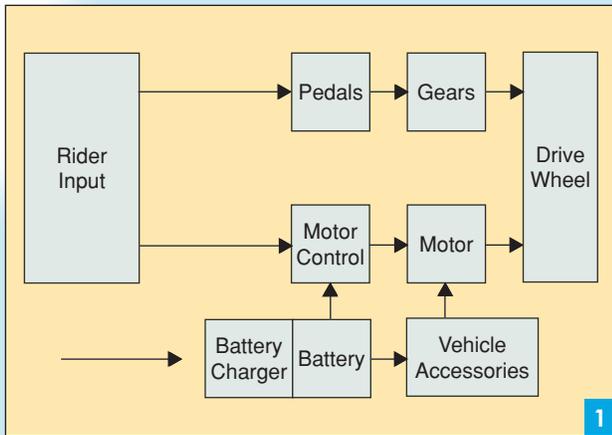
BY ANNETTE MUETZE & YING C. TAN

ELECTRIC-MOTOR-POWERED BICYCLES have been making their way into the U.S. market for about two decades. In the United States, such bicycles can be fully powered by a motor. In other countries such as Japan, electric-motor-powered bicycles are required to operate with 50% human pedal power for up to 12 mi/h, and an even higher percentage of human power is required above that speed. Such bicycles are commonly known as “pedelecs” (pedal electric cycle). In this article, the term “electric bicycle” is used to describe “electric-motor-powered bicycles,” including both fully and partially motor-powered bicycles. Electric bicycles can be used for a variety of purposes, for instance, as a vehicle for police or law enforcement in cities where parking and traffic are a problem, as a guide bicycle during bicycle races, as a park ranger vehicle, or for leisurely rides and commuting purposes. In the United States, electric bicycles are currently used most commonly for short trips to grocery stores or for leisurely rides.

First, this article provides a systematic, comprehensive classification of electric bicycles that includes an overview of the state of the art of today’s commercially available electric bicycles (e.g., [1]–[12]). The overview includes less commonly considered topics, such as regulatory issues in various countries, and different performance requirements of electric bicycles. Using knowledge from the field of professional bicycling as a starting point, the findings are supported and theoretically expanded. The power requirements in different typical riding situations are also identified. The results are confirmed by experimentally obtained



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Parallel hybrid schematic diagram [9].

data that have been collected in the context of real-life applications. From the results, the key parameters, needs, and challenges involved in improving the performance of electric bicycles are identified. The article then gives a summary of the different results that can serve as a roadmap for such improvements. This summary includes both market trends and regulations and technical-science-related aspects. Different paths of further research to build on the presented work are outlined in the conclusion.

Evaluation of the State of the Art

Basic Configuration of an Electric Bicycle System

The basic configuration of an electric bicycle drive consists of a controller that controls the power flow from the battery to the electric motor. This power flow acts in parallel with the power delivered by the rider via the pedal of the bike (Figure 1).

The rider of an E-bike can choose to

- rely on the motor completely
- pedal and use the motor at the same time
- pedal only (use as a conventional bicycle).

Overview of Electric Bicycles Worldwide

Electric bicycles have been gaining increasing attention worldwide, especially in China, Europe, Japan, Taiwan, and the United States. In the following, the most distinguishing aspects of electric bicycles in these countries are summarized, based on the authors' own studies and Frank Jamerson's *Electric Bikes Worldwide 2002* [1].

Today, China is the largest manufacturer of electric bicycles, exporting the majority of the electric bicycles while also meeting a strong local demand. According to China's Electric Bike General Technical Qualification GB17761-1999 [9], Chinese electric bicycles may not exceed 20 km/h and may not be heavier than 40 kg.

In Europe, most electric bicycles are manufactured in Germany and the Netherlands, and pedelec-type electric bicycles are more common.

In Japan, most electric bicycles are produced by the automotive industry, and electric bicycles are required by

TABLE 1. ASPECTS FAVORING THE USE OF ELECTRIC BICYCLES.

Energy Costs	Averaging, costs* are <ul style="list-style-type: none"> • US\$7.1/100 mi = US\$4.4/100 km for going by car, but only • US\$0.12/100 mi = US\$0.7/100 km for going by electric bicycle.
Other Costs	Generally, no insurance, license, registration, and parking are needed.
Traffic Flow	Most states allow electric bicycles on bicycle paths; avoidance of traffic jams.
Environmental Friendliness	Zero-emission vehicle
Health Benefit	Incorporation of exercise and longer-distance commuting

*Sample cost calculation for a 100-mi trip on a 2002 Mitsubishi Lancer:

- Gas tank capacity: 28 mi/gal [13]
- Approximate gas rate as of November 2004: US\$2/gal
- Costs for 100 mi: US\$2/gal/(28 mi/gal)·100 mi = US\$7.1

Sample cost calculation for a 100-mi trip on an electric bicycle:

- Power to travel at 10 mi/h: 120 W (experimentally obtained, see Figure 4)
- Duration: 100 mi/10 mi/h = 10 h
- Energy usage: 1.2 kWh
- Madison Gas & Electric rate as of November 2004: US\$0.1/kWh
- Costs for 100 mi: 1.2 kWh · 0.1 \$/kWh = US\$0.12

law to be pedelec-type bicycles. Electric bicycles produced in Taiwan are mostly exported to Europe.

In regard to the United States, electric bicycles are not as popular as in the other countries mentioned and most electric bicycles are imported. In some states, the federal law and the state law for electric bicycles differ.

Aspects Favoring the Use of Electric Bicycles

A number of aspects favor the use of electric bicycles in different situations. These include lower energy cost per distance traveled (1–2% of going by car when going by electric bicycle) for a single rider; savings in other costs such as insurance, licenses, registration, parking, improvement of the traffic flow; environmental friendliness; and the health benefit for the rider (Table 1).

Performance Range of Commercially Available Electric Bicycles

Table 2 gives a comparative overview of the performance ranges of today's commercially available electric bicycles according to the authors' market research. It illustrates how widely the specifications of electric bicycles vary according to the bicycle design and the riding conditions for which the electric bicycle is designed. The influence of several factors and parameters on the different criteria and performance requirements are discussed in the "Investigation of Technical Performance Requirements" section.

Criteria for Classification of Electric Bicycles

Criteria for classification of electric bicycles have been determined such that they are independent of the country and the purpose of use. These are the bicycle

kit type, motor type, motor assembly, assist type, throttle type, motor placement, and battery type (Table 3). The assets and drawbacks of these criteria are shown for each subcategory in Tables 4–10 (bicycle

kit, motor, motor assembly, assist, throttle, motor placement, and battery types). In these tables, several aspects should be pointed out: In general, both brushed and brushless dc motors are used by manufacturers of electric bicycles, but, as far as the authors know, synchronous motors and induction motors are not being used. Even though technical aspects do exist, both the assist and the throttle types depend largely on the rider's personal preference. The design of the assist type can be significantly influenced by the country's regulation. Unless close attention is paid, both full- and half-assist types can look the same at first glance.



Electric bicycle test set-up used for the experimental investigation.

TABLE 2. PERFORMANCE RANGE OF COMMERCIALY AVAILABLE ELECTRIC BICYCLES.

TABLE 2. PERFORMANCE RANGE OF COMMERCIALY AVAILABLE ELECTRIC BICYCLES.		
<i>Speed</i>		
Average speed	12 mi/h	19 km/h
Maximum speed**	20 mi/h	32 km/h
Travel range (Full charge)	10–50 mi	16–80 km
<i>Batteries</i>		
Charging time	2–6 h	
Cycles of charge/discharge	Up to 400	
<i>Power</i>		
Power consumption (Each full charge)	100–500 Wh	
On-board power supply	12–36 V	
<i>Torque</i>		
Hill climbing ability	up to 6% slope	
<i>Weight</i>		
Electric bicycle kit excluding original bicycle weight	10–50 lbs	4.6–22.8 kg
<i>Price range</i>		
Electric bicycle kit only	US\$250–US\$800	
Electric bicycle kit and bicycle (Custom built electric bicycles)	US\$800–US\$2600	

**Sec. 2085 of the federal law [14] defines a “low-speed electric bicycle” as “a two- or three-wheeled vehicle with fully operable pedals and an electric motor of less than 750 W, whose maximum speed on a paved level surface, when powered solely by such a motor while ridden by an operator who weighs 170 pounds, is less than 20 mi/h.”

TABLE 3. CRITERIA FOR CLASSIFICATION OF ELECTRIC BICYCLES.

Criteria	Options	Table Reference
Bicycle Kit Type	• Custom built • Add on	Table 4
Motor Type***	• Brushed dc machine • Brushless dc machine	Table 5
Motor Assembly	• Gear • Hub • Friction	Table 6
Assist Type	• Full-assist • Half-assist	Table 7
Throttle Type	• Thumb throttle • Twist throttle • Push button	Table 8
Motor Placement	• Front wheel • Rear wheel	Table 9
Battery Type	• Lead acid • NiMH • Others	Table 10

***At large, both brushed and brushless dc motors are used by most electric bicycle or electric bicycle kit manufacturers. To the authors' knowledge, induction motors and synchronous motors are rarely used in commercially available electric bicycles and, thus, they are not discussed here.

TABLE 4. ASSETS AND DRAWBACKS OF DIFFERENT BICYCLE KIT TYPES.

Bicycle Kit Type	
Custom Built	Add On
Assets:	Assets:
• High-end bicycles	• Comparatively inexpensive
• Good appearance	• Mounting flexibility
• Safety features	• Suitable for different bicycle types
• Little/no installation required	• Bicycle can be reconverted to a conventional bicycle
Drawback:	Drawbacks:
• <i>Comparatively high costs</i>	• <i>Installation needed</i>
	• <i>Connections may not be robust</i>

Performance Evaluation of Electric Bicycles

Criteria have been defined to evaluate the performance of electric bicycles. These are technical performance, practicability, design, environmental friendliness, and cost and economics (Table 11). The subcategories of all criteria, with the exception of the technical performance and cost and economics, are commented upon individually in Tables 12–14 (practicability, design, and environmental criteria). The technical performance characteristics such as power, torque, and speed have been investigated both theoretically and experimentally and are discussed in the “Investigation of Technical Performance Requirements” section. Cost and economics are discussed in Table 1.

Even though the technical maturity of electric bicycles has been, and is still, improving, still more work needs to be done to make electric bicycles competitive with other vehicles. This includes more research on the durability and lifetime of such bicycles, the long charging time of batteries, and the sparse availability of charging stations.

Investigation of Technical Performance Requirements

Theoretical Background

The total power P_{total} required to drive the bicycle is given by the sum of the power to overcome the air drag

TABLE 5. ASSETS AND DRAWBACKS OF DIFFERENT MOTOR TYPES.	
Motor Type	
Brushed dc Motor	Brushless dc Motor
Asset: <ul style="list-style-type: none"> Simple controller 	Assets: <ul style="list-style-type: none"> Higher efficiency and brushed motor Reduced size when compared with brushed motor
Drawbacks: <ul style="list-style-type: none"> Lower efficiency than brushless motor Brushes increase the motor size and can increase the difficulty of mounting the motor into the fork of the bicycle 	Drawback: <ul style="list-style-type: none"> More complex controller than brushed dc motor

TABLE 7. ASSETS AND DRAWBACKS OF DIFFERENT ASSIST TYPES.	
Assist Type	
Full-Assist	Half-Assist
Choices of modes of operation: <ul style="list-style-type: none"> Pedaling only Motor operation only Pedaling and motor operation in parallel 	Choices of modes of operation: <ul style="list-style-type: none"> Motor assistance is only available when the user is pedaling Level of assistance is determined by the user input
Asset: <ul style="list-style-type: none"> Increased number of choices of modes of operation 	Asset: <ul style="list-style-type: none"> Meets the law requirements in more countries than the full-assist type
Drawback: <ul style="list-style-type: none"> Not legally allowed in all countries 	Drawback: <ul style="list-style-type: none"> Rider always has to pedal

TABLE 6. ASSETS AND DRAWBACKS OF DIFFERENT MOTOR ASSEMBLY TYPES.		
Motor Assembly Type		
Gear	Hub	Friction
Assets: <ul style="list-style-type: none"> Provides desired gear reduction ratio Enables easier torque sensing/adjustment/assists 	Assets: <ul style="list-style-type: none"> Motor integrated in the wheel Easy mounting Minimal maintenance 	Asset: <ul style="list-style-type: none"> Light weight
Drawbacks: <ul style="list-style-type: none"> Chain/belt may get entangled Chain/belt may need maintenance: lubrication/tension 	Drawbacks: <ul style="list-style-type: none"> Can be heavy Significant shift of the center of gravity 	Drawbacks: <ul style="list-style-type: none"> Less efficient due to friction loss Tires wear out easily



Power Tap hub [15] used for the experimental investigation.

P_{drag} , the power to overcome the slope P_{hill} , and the power to overcome the friction P_{friction} . Equations (1)–(4) show the relationships as discussed in [6] and [8], where the symbols for the parameters, their units, and some remarks are summarized in Table 15.

$$P_{\text{total}} = P_{\text{drag}} + P_{\text{hill}} + P_{\text{friction}}, \quad (1)$$

$$P_{\text{drag}} = \frac{C_d \cdot D \cdot A}{2} \cdot (v_g + v_w)^2 \cdot v_g, \quad (2)$$

$$P_{\text{hill}} = 9.81 \cdot G \cdot v_g \cdot m, \quad (3)$$

$$P_{\text{friction}} = 9.81 \cdot m \cdot R_c \cdot v_g. \quad (4)$$

The three cases that can be distinguished according to Wilson's *Bicycle Science* [8] correspond to the following riding conditions:

■ Case 1

At speeds greater than 3 m/s (≈ 6 mi/h), the majority of the power is used to overcome the air drag

→ Flat ground, high speed:

→ $P_{\text{drag}} \uparrow\uparrow, P_{\text{hill}} = 0, P_{\text{drag}} > P_{\text{friction}}$.

■ Case 2

At speeds less than 3 m/s (≈ 6 mi/h) and at level surfaces, the majority of the power is used to overcome the rolling resistance

→ Flat ground, low speed:

→ $P_{\text{friction}} \uparrow\uparrow, P_{\text{hill}} = 0, P_{\text{friction}} > P_{\text{drag}}$.

■ Case 3

On steep hills, the power required for overcoming air drag and rolling resistance is small when compared with the power required to overcome the slope

→ Hilly ground, low speed:

→ $P_{\text{hill}} \uparrow\uparrow, P_{\text{hill}} > P_{\text{drag}}, P_{\text{hill}} > P_{\text{friction}}$.

Experimental Evaluation of the Technical Performance of Electric Bicycles

Two types of measurements were designed to experimentally evaluate electric bicycle performance during real-life applications:

- 1) The requirements in terms of power P versus ground speed v_g with respect to the influence of the load m , slope grade G , and head wind speed v_w are experimentally determined.
- 2) The riding profiles in terms of power P , torque T , and ground speed v_g are measured during riding intervals of different riders, where the bicycle is used for a short leisurely ride, grocery shopping, or commuting.

Test Vehicle Description and Instrumentation

For the experimental investigation, an electric bicycle with a brushed dc motor installed in the front hub, a

TABLE 8. ASSETS AND DRAWBACKS OF DIFFERENT THROTTLE TYPES.

Throttle Type		
Thumb Throttle	Twist Throttle	Push Button
Asset:	Asset:	Asset:
<ul style="list-style-type: none"> • Reduced risk of accidental acceleration 	<ul style="list-style-type: none"> • Feels like moped/motorcycle 	<ul style="list-style-type: none"> • Inexpensive
Drawback:	Drawback:	Drawback:
<ul style="list-style-type: none"> • May be less comfortable than other types (personal preference) 	<ul style="list-style-type: none"> • Throttle can be turned accidentally 	<ul style="list-style-type: none"> • Need to push button repetitively for more precise control

TABLE 9. ASSETS AND DRAWBACKS OF DIFFERENT MOTOR PLACEMENT TYPES.

Motor Placement Type	
Front	Rear
Assets:	Assets:
<ul style="list-style-type: none"> • Comparatively easy installation • Good weight distribution • Suitable for lowland and hilly regions with good roads 	<ul style="list-style-type: none"> • Best for lightweight vehicles in general, including bicycles • Better traction for hill climbing • Suitable for mountainous regions and poor ground conditions
Drawback:	Drawback:
<ul style="list-style-type: none"> • Front wheel slides are more dangerous than rear wheel slides 	<ul style="list-style-type: none"> • Comparatively complex installation

TABLE 10. ASSETS AND DRAWBACKS OF DIFFERENT BATTERY TYPES.

Battery Type			
Lead-Acid	NiMH	Others	Regenerative Braking
Asset:	Assets:	Assets and drawbacks depend on type	
<ul style="list-style-type: none"> • Inexpensive 	<ul style="list-style-type: none"> • Light • Good performance 	Assets:	
Drawback:	Drawback:	Drawback:	
<ul style="list-style-type: none"> • Heavy 	<ul style="list-style-type: none"> • Cost 	<ul style="list-style-type: none"> • Recovered energy increases the bicycle performance 	
		<ul style="list-style-type: none"> • More complex controller than nonregenerative type 	

controller, thumb throttle, and battery pack are used (Figure 2). This bicycle is a commercially available bicycle that has been available in the laboratory. All experiments were carried out using this test vehicle. The electric hub motor in the front wheel is not used during the measurements, yet, using this bicycle, the actual set-up of an electric bicycle is represented. For all measurements, the tire pressure was kept at 50–60 psi, which is typical for bicycles that are used for leisure and commuting and that are commonly not reinflated before each ride. The torque and speed are directly measured in the hub of the rear wheel of the test bicycle, using a power tap hub (Figure 3) [15]. The measurement information is transmitted to the Power Tap central processing unit (CPU) through the receiver. Furthermore, the relative head-wind speed as seen while riding is measured by means of an anemometer. The head-wind speed is then obtained from the difference of anemometer and power tap speed.

Experimental Investigation of Power Requirement as a Function of Load, Speed, and Head Wind

For these experiments, four different riders rode the test bicycle without using the hub motor under different riding conditions. The experiments were conducted for speeds up to 12 mi/h (19 km/h), which is typical for city rides. The air density is approximated to be constant. Furthermore, based on the theoretical results, rolling and drag coefficients are assumed to be almost constant and are not investigated in detail. For each measurement point, five to ten measurements were conducted and the average value was taken. Usually, the deviation of the individual measurements for one point was in the order of less than 20%. Three series of measurements were carried out:

- 1) total power P_{total} versus ground speed v_g as a function of load m (Figure 4)
- 2) total power P_{total} versus ground speed v_g as a function of slope grade G (Figure 5)

- 3) total power P_{total} versus ground speed v_g as a function of wind speed v_w (Figure 6).

In the following, the measurement results are discussed.

The series of measurements for total power P_{total} versus ground speed v_g as a function of load m (Figure 4) illustrates (3) and (4). For a given ground speed v_g , small variations in load result in small variations in power

TABLE 11. CRITERIA FOR PERFORMANCE EVALUATION OF ELECTRIC BICYCLES.		
Technical Performance	<ul style="list-style-type: none"> • Power • Torque • Speed • Efficiency • Distance/charge 	Text
Practicability	<ul style="list-style-type: none"> • Technical maturity • Battery charging • Operating condition • Service/maintenance 	Table 7
Design	<ul style="list-style-type: none"> • Ergonomics • Safety • Battery 	Table 13
Environment	<ul style="list-style-type: none"> • Pollution • Noise 	Table 14
Cost and Economics	<ul style="list-style-type: none"> • Unit price • Other costs 	Table 1

TABLE 12. ASPECTS OF THE DIFFERENT PRACTICABILITY CRITERIA.	
Practicability Criteria	
Technical Maturity	<ul style="list-style-type: none"> • Technical performance is improving, yet more work is needed to be competitive with other vehicles. • More research is needed on the durability/lifetime of electric bicycles.
Battery Charging	<ul style="list-style-type: none"> • Long charging time; typically four hours compared with four minutes for a gasoline-fueled vehicle. • Sparse availability of charging stations; recharging can often only be done at home.
Operating Condition	<p>Assets:</p> <ul style="list-style-type: none"> • no age limit • generally no license required • easy to operate <p>Drawbacks:</p> <ul style="list-style-type: none"> • weather dependence • not winter/wet weather/rain friendly
Service/Maintenance	<p>Asset: Conventional bicycle parts can be serviced by a conventional bicycle shop.</p> <p>Drawback: After-sales service and maintenance are not well established today.</p>

TABLE 13. ASPECTS OF THE DIFFERENT DESIGN CRITERIA.	
Design Criteria	
Ergonomic	<ul style="list-style-type: none"> • Bicycle size is small. Parking is easy compared with other bicycles. • Honks, headlights, and disk breaks can be added for safety purposes.
Safety	<p>Asset: not as explosive as fuel vehicles (accidents)</p> <p>Drawback: More tests on general road safety and crash tests on electric bicycles traveling at high speed are required.</p>
Battery	<ul style="list-style-type: none"> • Significant component to increase the electric bicycle performance significantly. • Lighter-weight, higher-energy-density batteries are needed.

requirement (20 W difference of required power for 15-kg load variation). For doubled load, twice the power is required, as is illustrated by comparing the curves for (64 + 20) kg and (154 + 20) kg load. Generally, a heavier rider also has a larger effective area A which increases the power needed to overcome the air drag (2) and accounts for the nonlinear increase from the curves obtained for (64 + 20) kg and (154 + 20) kg load.

An addition of 10 kg to the bicycle systems requires additional power of approximately 10–15 W. Thus, there is not a significantly larger amount of energy needed to propel the bike if the load difference is less than a few kilograms.

The series of measurements, total power P_{total} versus ground speed v_g as a function of the slope grade G (Figure 5), visualizes the correlation of (3). (Note that sim-

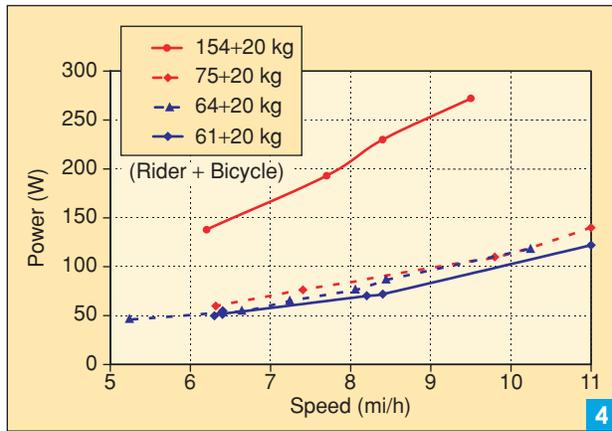
ELECTRIC-MOTOR-POWERED BICYCLES HAVE BEEN MAKING THEIR WAY INTO THE U.S. MARKET FOR ABOUT TWO DECADES.

ilar results have also been obtained with other riders than the one of Figure 5, but the results of Figure 5 have been selected as they are the most complete set of measurements illustrating this analysis.) For a given ground speed v_g , P_{friction} is constant, but P_{hill} is directly proportional to the slope grade G . Thus, neglecting the P_{drag} , P_{total} increases linearly with the slope grade G . For approximately an 80-kg weight of rider and bicycle, 320 W (47 Nm torque) are required to climb up a reasonable slope of 4% at 10 mi/h.

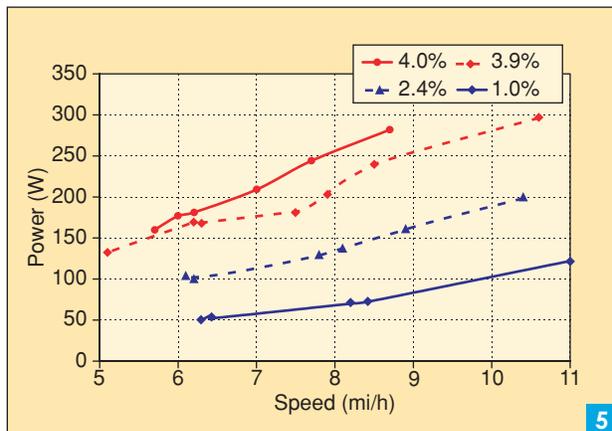
With electric bicycles rated at the maximum power allowed by federal law of 750 W, the maximum torque capability at 10 mi/h is 110 Nm. As a result, the steepest slope electric bicycles can climb at 10 mi/h ground

speed is 8%. It is important to note that unless riding on hilly terrain, city rides usually need high torques only for a short period of time. Therefore, motors designed for city rides can have rated power below the federal law provisions.

The measurement results for total power P_{total} versus ground speed v_g as a function of head wind v_w (Figure 6) are in line with (2). (Note that similar results have also been obtained with riders other than the one of Figure 6, but the results of Figure 6 have been selected as they are

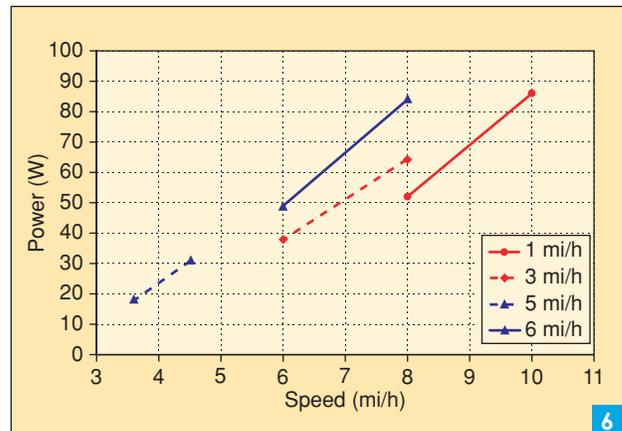


Influence of the weight of the rider and bicycle influence on the power versus speed curve; no wind, constant slope $G \approx 1\%$.



Influence of the slope of the path on the power versus speed curve; no wind, weight of rider and bicycle $m = 81$ kg, all slopes taken as average.

Environmental Criteria	
Pollution	• No gas emission
Noise	• 55–60 dB compared with fuel/gas vehicle levels of 65–70 dB



Influence of the head wind on the power versus speed curve; no wind, weight of rider and bicycle $m = 81$ kg, all head wind speeds taken as average.

the most complete set of measurements illustrating this analysis.) With increasing v_w , the power requirement increases. However, due to the very stochastic nature of wind, this experiment only provides a rough idea of the trend. Furthermore, crouching or an upright position affects the frontal area A . Yet, at relatively low ground speed this significantly affects the power requirement, notably with flat ground. Future work to obtain accurate results can be done by using wind tunnels.

It is important to note that head wind does not seem to be a major criterion for city-ride electric bicycles, given the usual profiles of city rides.

Experimental Riding Interval Analysis

For the second group of measurements, four different riders rode the test bicycle around the city of Madison,

TABLE 15. SYMBOL AND PARAMETER DEFINITION.

Symbol	Parameter	Unit	Remarks
C_d	Drag coefficient	–	The drag coefficient is small for aerodynamic bodies. Typical values are: Passenger car: $C_d = 0.3$, recumbent bicyclist: $C_d = 0.77$, upright cyclist: $C_d = 1$ [6], and $C_d = 0.5$ for a cyclist [3].
D	Density of air	kg/m^3	
A	Frontal area	m^2	The frontal area is the area of the mass encountered by the air. Typical values are $A = 0.5 \text{ m}^2$ [3] and $A = 0.4 \text{ m}^2$ [6].
v_g	Ground speed	m/s	
v_w	Head wind speed	m/s	
G	Slope grade	–	The slope grade is rise/run. For steep grades, G should be expressed by $\arctan(\text{rise/run})$.
m	Weight****	kg	
R_c	Rolling coefficient	–	The rolling coefficient depends on friction effects. For example, compacted gravel and smooth asphalt paths have different rolling coefficient of 0.004 [3] and 0.014 [6], respectively.
9.81	Gravity acceleration	m/s^2	

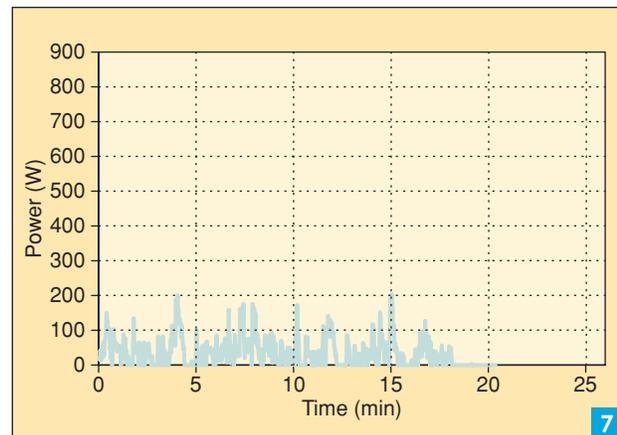
**** Rider and bicycle, including accessories

Wisconsin, for 16–26 min. The average and maximum total power requirements $P_{\text{ave}}/P_{\text{max}}$, torques $T_{\text{ave}}/T_{\text{max}}$, and ground speeds $v_{\text{ave}}/v_{\text{max}}$ are summarized in Table 16. For illustration, Figures 7 and 8 show the power versus

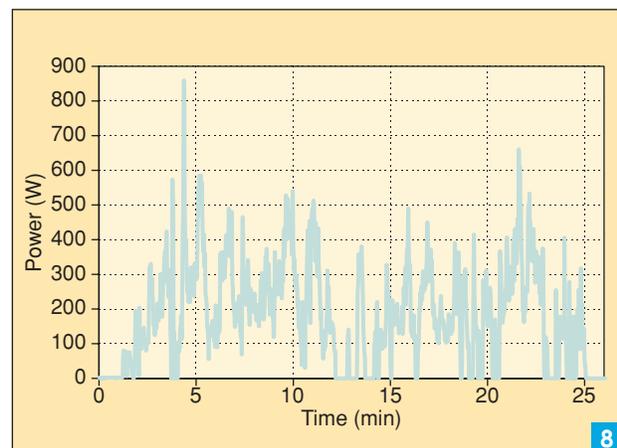
TABLE 16. RESULTS OF INTERVAL RIDING ANALYSIS.

	Rider 1	Rider 2	Rider 3	Rider 4
Rider weight [kg]	50	75	85	95
P_{ave} [W]	35.6	133.9	66.3	179.0
P_{max} [W]	204.0	389.1	368.6	857.0
T_{ave} [Nm]	4.7	8.2	5.9	9.9
T_{max} [Nm]	27.9	40.8	26.4	50.2
$v_{g,\text{av}}$ [mi/h]	5.4	12.7	7.6	13.0
$v_{g,\text{max}}$ [mi/h]	9.2	20.9	18.3	24.2 ^Δ
$v_{g,\text{av}}$ [km/h]	8.7	20.4	12.2	20.9
$v_{g,\text{max}}$ [km/h]	14.8	33.6	29.4	39.0
Interval time [min]	18	16	22	25
Energy [Wh]	11.9	35.7	24.31	77.6

^Δ Above the speed limit for low-speed electric bicycles according to U.S. federal law (Table 2).



Power versus time profile of Rider 1 (same scales as Figure 8 by intention).



Power versus time profile of Rider 4.

time profiles of the two rides of Riders 1 and 4. These two rides represent the two extremes in terms of power requirements that are covered (same scales on both figures by intention). It should be noted that the maximum speed of the ride of Rider 4 exceeds the speed limit for low-speed electric bicycles according to U.S. law of 20 mi/h (Table 2).

The four riding profiles cover a broad spectrum of P_{ave} , P_{max} , T_{ave} , T_{max} , v_{ave} , and v_{max} . Neglecting the athletic figure of Rider 4, a maximum torque of 30 Nm, along with a maximum power of somewhat less than 400 W, an average torque of 6–8 Nm, and an average power in the order of 100 W, reflects the requirements of an average ride. It is noticeable that the ride of Rider 1 is shorter than the ride of Rider 3 and about as long as the ride of Rider 2, but consumes less than 50% of the energy because of the lower weight of the rider. Even with assuming an efficiency of the drive of 50%, the energy requirement of the rides of Riders 1–3 could be met by a laptop-size battery. Such an energy source could be easily put on and taken off the bicycle and the bicycle can be recharged in a similar way as is today common with cell phones.

Summary of Performance Requirements

Drawing from the previous discussions, the electric bicycle performance evaluation is summarized in terms of different key parameters. These include market trends and regulations, opportunities for improvement by special-purpose-design to attract customers, identification of possibly oversized components and reduction of oversizing, and identification of areas where further research is needed (Table 5). In a similar way as before, the subcategories of the different areas (market trends, regulations, special-purpose design, comments on oversized components and on research and development) are compared and commented upon individually in Tables 17–22. Summarizing, more publicity is still needed to

TABLE 17. SUMMARY: ELECTRIC BICYCLE PERFORMANCE EVALUATION.

Market Trend		
Market Trend	• Demand	Table 18
	• Publicity	
Regulations	• On-road law	Table 19
	• Bicycle assembly	
Special-Purpose Bicycles	• City bicycle	Table 20
	• Hill bicycle	
	• Distance bicycle	
	• Speedy bicycle	
Reduction of Possible Oversizing	• Motor	Table 21
	• Battery	
Research and Development	• Battery	Table 22
	• Technical	
	• Regenerative braking	

introduce the public to electric bicycles. Also, more attention needs to be paid to releasing electric bicycles from licensing. A uniform standard/guideline for designers/manufacturers of electric bicycles would favor an increase in popularity and avoid the quality of electric bicycles being compromised. Custom-designed bicycles that are most efficient over a given operating cycle, such as city, hill, and distance, and “speedy bicycles” would help to re-duce the additional cost and weight of oversized components. In this context, the electric bicycle market would benefit from further research both on the battery and on the drive technology and their use with electric bicycles.

Conclusions

The issues associated with electric bicycles may be addressed by custom-designed drives that are most efficient over a given operating cycle. These include city bicycles, hill bicycles, distance bicycles, and speedy bicycles.

The results of the studies listed here can serve as a platform to improve electric bicycle performance if new drive systems are designed around key parameters that will result in improvement of the system performance. Furthermore, they can be used for comparison of existing drives in a systematical, comprehensive, and technical way.

TABLE 18. COMMENTS ON MARKET TRENDS.

Market Trend
Demand
The market demand for electric bicycles might increase if nongreen vehicles are banned. For example, in Beijing, Tianjin, Guangzhou municipals banned the sale and operation of fuel-assisted vehicles.
As a result, in the first half of 2000, sales of electric bicycles sales in Shanghai increased 99.14%, compared with the same period in the previous years.
Publicity
More publicity is needed to introduce the public to electric bicycles.

TABLE 19. COMMENTS ON REGULATIONS.

Regulations
On-Road Law
U.S. states have different laws for electric bicycles, particularly regarding the licensing aspect. Releasing electric bicycles from licensing would favor an increase in popularity.
Bicycle Assembly
A uniform standard/guideline for designers/manufacturers of electric bicycles would avoid the quality of electric bicycles being compromised.

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TABLE 20. SPECIAL-PURPOSE DESIGN OF ELECTRIC BICYCLES.	
Special-Purpose Bicycles	
City Bicycle	<ul style="list-style-type: none"> Fast acceleration, frequent stops Average power 150 W Average speed 17.6 km/h (11 mi/h)
Hill Bicycle	<ul style="list-style-type: none"> High torque capability Maximum power 300 W at 12.8 km/h (8 mi/h) for a short time corresponding to a (4% slope grade)
Distance Bicycle	<ul style="list-style-type: none"> Designed for traveling at constant and comparatively low speed, but for a longer distance For example average speed 16 km/h (10 mi/h) at average power 100 W
Speedy Bicycle	<ul style="list-style-type: none"> Fast acceleration capability High-speed capability 29km/h (18mi/h) Average power 200 W For example: guide bicycle in cycling competitions, vehicle for law enforcers

TABLE 21. COMMENTS OF OVERSIZING RISK.	
Possibly Oversized Components	
Motor	<ul style="list-style-type: none"> Maximum power according to federal law: 750 W at 20 mi/h speed This is much more power than is normally required with electric bicycles. Electric bikes in the current market generally do not exceed 400 W. Drawing from Figures 4 and 5, this value is a good guideline for general design.
Battery	<ul style="list-style-type: none"> In a similar way as with the motor, careful selection of the battery could reduce the heavy battery weight. For example, drawing from Table 16, a laptop-size battery that could be easily put on and taken off the bicycle would be sufficient for short rides up to 30 min. Then, the bicycle recharging would be handled in a similar way as is today common with cell phones.

TABLE 22. COMMENTS ON RESEARCH AND DEVELOPMENT.	
Areas of Further Research and Development	
Battery	<ul style="list-style-type: none"> Further investigation is needed to examine how improved battery technology could improve the performance of electric bicycles. Further investigation on the importance and influence of battery density and charging time on electric bicycles is needed.
Drive	<ul style="list-style-type: none"> The motor should be designed to be most efficient over the operating cycle. Further investigation is needed on the assets and drawbacks of different motor types and controllers.
Regenerative Braking	<ul style="list-style-type: none"> Regenerative braking will be more useful in hilly areas or when braking is used often, as in city rides. Future work needs to identify the percentage recoverable energy, the impact on efficiency, cost, and the reduction of dependence on battery technology.