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A Comparative Study of 12 Electrically Assisted Bicycles

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Abstract

A sample of 12 electric bicycles offered on the Belgian and Italian markets was the subject of a comparative quality and performance study. This sample contains electric bicycles of different price categories and with different drive technologies. This paper describes the test program that was used for the study and reveals the differences that were observed between the test samples. The electric bicycles were tested on the road in the Brussels region. An appreciation of the electric traction offered by the bicycle in different situations was given: electrical assistance at start, on a flat road, when riding uphill and when decelerating or braking with the bicycle. The vehicle's driving range under real driving conditions, was determined for the different electric bicycles. Also the electricity consumption when recharging the traction battery was measured and allowed to make an analysis of the cost for driving an electric bicycle. An environmental analysis (well-to-wheel) was made of the electric bicycles and put against the environmental impact of a thermal moped and an electric scooter.

Keywords: light electric vehicle, bicycle; energy consumption, vehicle performance, environment

1 Introduction

Light Electric Vehicles (LEV) form a group of promising alternative vehicles for both personal mobility and goods delivery. In particular, electric bicycles are becoming more and more popular in Western Europe. In the 1990s, when electric bicycles were introduced in Europe, the target group of these bicycles was mainly elderly people. More recently also younger people are attracted to this product: parents who are transporting their children on their bicycle or in a trailer or more and more bicycle commuters are appreciating the electrical assistance on a bike. It is clear that the products available on the European market present different performances. To evaluate this statement, experimental and scientific evidence is needed. Therefore a sample of 12 electric bicycles available on the Belgian and Italian markets was the subject of a comparative quality and performance study. This sample contains electric bicycles of different price categories and with different drive technologies. This paper describes the test program that was used for this analysis and reveals the most important differences that were observed between the test samples. The electric bicycles were tested in the laboratory and on the road in the Brussels region. An appreciation of the electric traction offered by the bicycle in different situations was given based on the on-road tests: electrical assistance at start, on a flat road, when riding uphill and when decelerating or braking the bicycle. The vehicle's driving range under real driving conditions, was determined for the whole collection of electric bicycles. Also the electricity consumption when recharging the traction battery was measured and allowed to make an analysis of

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the cost per kilometre for driving the different electric bicycles.

2 Test Program

The test program that was used to make the comparative assessment of the electrically assisted bicycles consisted of different aspects. In this paragraph a brief overview of the test program is provided.

2.1 General assessment

A general assessment of the electrically assisted bicycles was made and resulted in a suggestion for the evaluation of:

- stability of the bicycle when driving
- driving comfort of the bicycle
- driving comfort of the bicycle without the electrical assistance
- sensitivity of the electrical drive train to rain
- ease of use, in particular the human machine interface of the electrical drive train

For the above-mentioned aspects, dedicated on-road tests with the 12 test samples were organized and the subjective feedback of the test persons was collected. These tests also permitted determining the driving range of the bicycles with electrical assistance.
The general assessment also included an evaluation or valuation of the following aspects: exchangeability of the battery pack, the weight of the battery pack, the quality of the user's manual, recharging the battery (complexity of the procedure, indication of charging, charging time) and the presence of (electronic) theft protection.
If available, the following information was collected: availability of spare parts, delivery time, information about the life time of the battery pack, purchase cost of the complete bicycle and cost of a battery pack replacement. In Figure 1 the purchase price of the electric bicycle and of a spare battery pack are shown for the 12 test samples. Significant differences in purchase price can be observed: ranging from 738 € up to 2219 € for the complete bicycle and ranging from 198 € up to 630 € for a spare battery pack.

2.2 Assessment of the electrical assistance

The electric bicycles were tested on three different test tracks. Three different test persons drove with all bicycles, each following a certain route. The main characteristics of these test tracks can be found in Table 1:

Table 1: detailed overview of the test tracks of the on-road tests

	Length	Cumulated climbing	Maximal slope
Parcours 1			
outward	14,8km	155m	12%
return	14,8km	113m	7%
Parcours 2 (closed)	10,2km	129m	8%
Parcours 3			
outward	14km	140m	10%
return	14km	134m	7%

In total the different test persons have cycled over 4000km with these test samples. These on road tests allowed making a general assessment about the driving behavior of the different test samples (see list of different criteria in paragraph 2.1)
The importance of these different criteria depends on the type of usage. When the bicycle is used in an urban environment with a large number of start and stops (crossroads, traffic lights...), the assistance at start becomes an important criterion. If the bicycle is used in a hilly environment the behavior of the assistance when driving uphill, is very important for the users' comfort and appreciation.
Based on the findings during the test trips an assessment of the electrical assistance was given in four different situations: assistance at start, assistance on a flat road, when driving uphill and when decelerating or breaking. An overview can be found in Table 2.

2.3 Integration of the electrical motorization

The way the electrical assistance system is integrated in the bicycle frame differs from model to model. The ergonomics of the different subsystems and the interaction with the bicycle is very important. Special attention was paid to the exchangeability of the battery pack, accessibility of the connector to charge the battery pack, the matching of the gear system with the electric motor system and the integration of the lights in the electrical system. Also the weight of the complete bicycle (including the battery pack) and the weight of the battery pack as such were determined and are shown in Figure 2.

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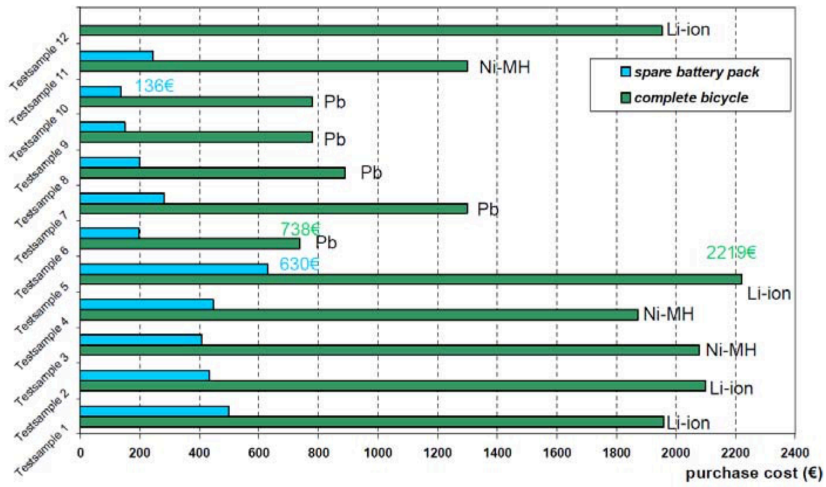

Figure 1: Average purchase cost of the complete bicycle and of a spare battery pack

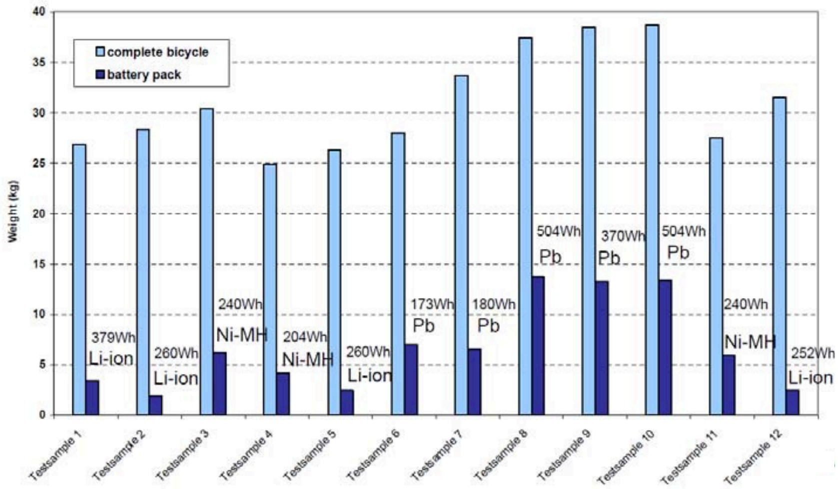

Figure 2: Weight information of the different test samples

3 Legislative framework

In order to be able to consider an electric bicycle as a "normal" bike from a legal point of view, it needs to fulfil certain conditions. However, if one of the conditions is not fulfilled (e.g. the maximal vehicle speed with electrical assistance is higher than 25km/h), insurance compensations might be denied to the victim in case of an accident. In the Belgian road legislation for instance, (see also http://www.wegcode.be) several definitions have been incorporated, among which the following: (Article 2.15.1.) "Non motorised vehicle": each vehicle with two or more wheels, which is propelled by means of pedals or handgrips, by one or more of the users and which is not equipped with an engine, such as a bicycle, a tricycle or quadricycle. The presence of an electrical assistance motor with a nominal rated power of up to 0,25 kW, of which the traction force is gradually reduced and finally interrupted when the vehicle reaches a speed of 25 km/h, or sooner, if the cyclist stops pedalling, brings no modification in classification as a 'non motorized vehicle'. The above definition contains the

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description of a bicycle with electrical assistance motor in conformity with the definition according to the European directive 2002/24/EC. Most of the electric bicycles offered on the European market comply with this restriction, however not all of them do. With some electric bicycles the electrical assistance motor continues to provide traction force at speeds higher than 25km/h. However, in these cases the motor power generally remains below 0,25kW. The typical maximum speeds obtained with this type of electric bicycles are around 38 to 40 km/h. An example is the Flyer F-series of the manufacturer Biketec™ that was available on the Swiss market. In Switzerland, an appropriate category of vehicle has been defined (‘light motorcycle’), which allows the user to contract a limited insurance coverage and to carry a bicycle helmet. In Belgium however, this category doesn’t exist (yet) and so the latter kind of electric bicycle is defined as a motorcycle of category B. Consequently, a full (moped) insurance is required and also wearing a fall helmet (instead of a bicycle helmet) becomes mandatory.
Another example of non-compliance with the Belgian road legislation is the group of electric bicycles, which provide electric traction without requiring the driver to turn the pedals. In these circumstances, the electric bicycles are functioning as electric scooters. However, the maximal speed of the vehicle, upon functioning as an `electric scooter', varies. Some electric bicycles can only be operated fully electrically to a very limited speed (typically 6km/h), whereupon turning the pedals becomes necessary to activate the electrical assistance at higher speeds. In Germany the category of 'electrically assisted bicycles', which is thus considered as an 'ordinary bicycle', is extended to this type of electric bicycles where pedalling at low vehicle speed is not necessary. This consideration is valid for vehicle speeds up to 6km/h. As from a speed higher than 6km/h, turning the pedals is again necessary to keep the electrical assistance active.

4 Classification

A first important distinction, which can be made between different models of electric bicycles, is their compliance to the European directive 2002/24/EC. This was discussed in detail in paragraph 3. Electric bicycles that satisfy to the above-mentioned restrictions can consequently be considered as `regular' bicycles. This directive has been meanwhile incorporated into the legislation and traffic regulations of many European member states and is thus effective on public roads. However some `electric bicycles' do not comply or at least not completely, with these restrictions and thus don’t fit in this category. This means that these `vehicles' can no longer be considered as an ordinary bicycle from a legal point of view. Moreover, a type approval becomes compulsory and the vehicle could be classified in the category of mopeds or motorcycles (situation differs from country to country).
From a technical point of view, one can divide the broad group of electric bicycles into more specific groups. A first important difference is the location of its electric motor. Mainly two possibilities are used: electric bicycles equipped with a hub motor and electric bicycles with a motor at the level of the bottom bracket. Moreover, electric bicycles equipped with a hub motor can be distinguished on the basis of the hub motor being mounted in the front wheel or in the rear wheel. In exceptional cases, another location for the motor is used (e.g. behind the saddle, on top of the front wheel…). Also different solutions for mechanical transmission of the motor power can be identified.

Figure 3: example of a hub motor (left) and of a motor near the bottom bracket (right)

Among the set of electric bicycles that were evaluated, the different above-mentioned types were represented: with a rear or front wheel mounted hub motor and with the motor near the bottom bracket of the bicycle. The investigated electrical assistance systems with the motor mounted near the pedal axis are contributing to the propulsion of the bicycle via the chain wheel and gear system of the bicycle. This arrangement allows employing the motor power with the bike’s gear system in a favourable way to ride uphill or to have a best assistance at start. Because the complete traction force of the bicycle is now transferred trough the chain transmission, the wear of these parts will be increased. Practical experience pointed out that the chain and chain wheels need to be replaced each 8000km. With all tested bicycles that have the motor at the level of the pedal axis, the mass is concentrated in the

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middle of the bicycle. This is positive for the comfort and the stability of the bicycle.
If the motor is placed in the front wheel, this allows using a traditional rear wheel traction system (chain, gear system). On slopes or on slippery roads slipping of the motorized front wheel can occur. Putting more weight on the front wheel can reduce this. If a hub motor is used (both front- or rear-wheel mounted), it should be able to handle the complete range of operation (in terms of speed and torque) without a gear system. The motor should be able to bring the bicycle to its maximum speed within the legal framework. It should deliver sufficient traction force at low speeds for starting or for riding uphill. This was not the case for all the models of electrically assisted bicycles that were tested. Consequently, they are not appropriate for demanding or challenging uphill cycling.

Another important difference is the type of control of the electrical assistance. One distinguishes electric bicycles with or without measurement of the effort of the cyclist (force applied on the pedals). In the first case the contribution to the traction force of vehicle by the electric motor can be made proportional to the contribution of the cyclist. For instance, the assistance motor could be assigned to double the effort made by the cyclist. Which distribution is chosen between the motor power and the human power can further be controlled in function of the other driving parameters (speed, different assistance modes selected by the user…). It concerns a technically quite complex system, which can be found on the more expensive bicycle models. These systems offer a great ease of use, in particular when starting from standstill. The latter is conceived as comfortable for the user. In the case that no sensor is used for measuring the cyclists effort is used, the electric motor power will be modulated manually by the cyclist, for instance by means of a twist grip or with a push button. Again different systems are available, each resulting in a different level of ergonomics and comfort. The assistance motor now only contributes when the pedals are turning, possibly without the cyclist needing to push them hard.

Figure 4: Selection of different assistance modes (left) and modulation of electrical assistance with a thumb switch (right)

When one evaluates the batteries used with the different electric bicycles, three types of batteries can be identified: nickel metal hydride (NiMH) batteries, lithium batteries and lead batteries The lead batteries have the disadvantage to be heavy, but are very cheap. NiMH batteries are significantly more expensive, but are used more frequently as they have a higher energy density than lead batteries. Lithium batteries have the highest energy density and consequently are much lighter than the other types of batteries, for the same quantity of useful energy. Also the price of this type of batteries is much higher than for lead batteries, but become more and more competitive with NiMH batteries. Many of the recent models of electric bicycles are equipped with this kind of battery, which results in better handling of the battery pack and the complete bicycle.
The memory-effect, that was prominent with the nickel cadmium (NiCd) batteries, is not an issue with the above-mentioned battery technologies. Meanwhile, NiCd batteries are, no longer sold in Europe because of the environmental and health impact of Cadmium. The life span of a battery of an electric bicycle can be expressed in a number of complete discharge cycles. A real life span for lead batteries is approximately 200 cycles. The lifetime for NiMH batteries and for Li-ion batteries are in the range of 500 complete cycles. Next to the life span expressed in cycles, the battery also has a limited life in absolute time. Typically, the ageing of the battery becomes more and more noticeable after about five years because the useful energy capacity starts to drop significantly (below 80% of its rated capacity) and the self-discharge of the battery increases. The obtention of this information is important for the potential users in order to avoid any misunderstanding or disappointment and to enable them to calculate real operational cost, including battery replacement.

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5 Determining the driving range of the electric bicycle

Forecasting the driving range of an electric vehicle or of an electric bicycle in particular, is not easy. The results strongly depend on the way the bicycle is used. The most important parameters defining the range of the bicycle are the weight, the topography (steepness of the hills), the speed profile and the effort (or power) delivered by the driver (cyclist). The first parameter, the weight, plays an important role in the amount of energy that is required to complete a certain trip. The higher the weight, the more energy is required for the same trip. Here, the total weight is important: the weight of the bicycle, but also the weight of the cyclist as well as a possible cargo (e.g. a backpack). A second parameter is the topography of the route. It is clear that more energy is required to ride up a hill compared to drive the same distance on the flat. Finally, the speed profile is also important; in particular the number of start and stops is essential for the estimation of the required electrical energy. An itinerary on which can be cycled at a (more or less) constant speed and without any stop, will require less energy from the electrical traction chain compared to a route with the same length but where the cyclist needs to stop and start quit often (for example in urban traffic). The latter is even more applicable if the electric bicycle is to be used for distribution of mail, flyers or folders and needs to stop and start again at every doorstep along the delivery round.
The efficiency of the used electronic motor controller will also affect the electrical energy consumption at the battery side and thus the driving range of the electric vehicle.
It is not always easy to determine the exact available electrical energy of the battery pack installed on the bicycle. However, most of the times the nominal voltage and the rated capacity of the battery pack are mentioned in the user manual or on the battery pack. Often the current capacity is mentioned and expressed in Ah, but often without outlining at which discharge period this value is true. The frequently used and standard discharge period of 10h can be assumed as a consequence. However the battery pack of an electric bicycle is discharged much faster in normal usage (typically about 1 to 2 hours). Moreover, a battery will deliver less energy (ampere-hours) if more current is drawn than the rated value (Peukert's law). Also the battery temperature is affecting the useful energy capacity of the battery pack. Both temperature and discharge current will vary during the normal use of the electric bicycle. For example, a battery pack with a rated capacity of 10Ah (no further details available) and with a nominal voltage of 24V, results in an expected available energy content of 240Wh.
In general the battery pack of an electric bicycle is used until 50 to close to 100 percent of its useful capacity (deep cycles). To improve the lifetime performance of the battery pack, the maximal depth of discharge could be limited (by the manufacturer). Furthermore, for some battery types the capacity may increase the first few tens of cycles compared to the initial capacity. Taking the latter into account and due to Peukert's law, the actual useful capacity can deviate significantly from the expected value.

Important differences exist in the level of the power assistance provided by the electrical motor of the electric bicycles. Generally, one can state that the more power the electric motor provides to the traction chain, the larger the energy consumption at the side of the battery. When the cyclist is required to provide a large part of the required effort by himself, then the driving range can be significantly increased. How large this effort is, depends on the working principle of the electrical assistance that is used and differs from model to model and is in general well described in the user manual. Some types of electric bicycles let the cyclist modulate the level of electrical assistance by means of a twist grip for example. The driving range of these electric bicycles therefore depends on the way the electric assistance is used by the user. With other types of electric bicycles the degree of the power assistance is predetermined by the associated control system of the bicycle and the power of the electric motor is modulated in function of sensor input (typically the rotational speed of the pedals or the rotational speed of the motor and the torque on the pedals). In this way, the share of human power and electrical power can be managed by the motor system. Some manufactures offer different modes of electrical assistance (e.g. economic, normal, sportive…) that can be selected by the user or pre-programmed by the manufacturers and its dealers. This is done to find a best compromise between energy consumption (driving range) and the level of assistance.

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6 Test results

A first interesting point of comparison is the weight of the different electric bicycles. An important variation of the weight was observed: the lightest bicycle weighs 24,9kg and the heaviest one 38,7kg. This is a variation of 13,8kg. An overview of the weight of both the bicycle (with the battery) and of the battery can be found in paragraph 2.1, in Figure 2.

Also large differences can be observed in the weight of the battery packs of the different models. The lightest battery weighs only 1,9kg, while as the heaviest one weighs 13,7 kg.

Another parameter that has been analysed is the driving range of the different models. The different electrically assisted bicycles, with fully charged battery pack, were used on the test track until the battery was completely discharged and the electrical assistance of the bicycle shut down. The travelled distance was recorded and the results are shown in the figure below.

The lowest value of the result of each bicycle corresponds to the driving range obtained by the test person who was using the available assistance at maximum extent, thus minimizing his own effort while driving the different models. The highest setting of the electrical assistance was used for these tests.

The charging time for the different test samples and the energy consumption from the electricity grid can be found in Figure 6. Charging time is ranging from less than 2 hours up to 7 hours and 5 minutes. This is an important element to consider if one would decide to recharge his battery pack underway (in particular if the trip is larger than the driving range).

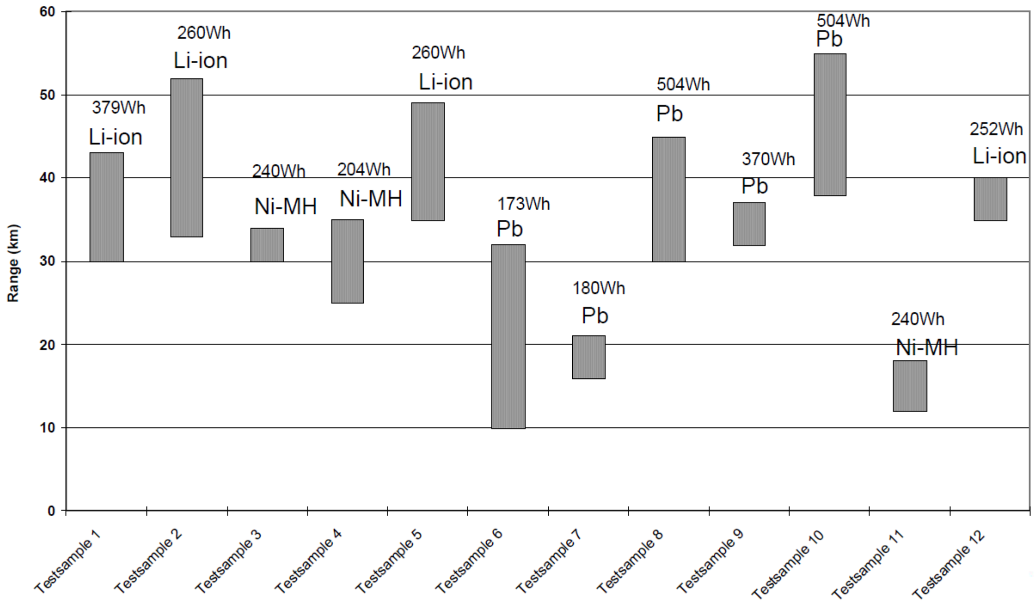

Figure 5: Spread of the driving ranges of the electric bicycles used in the highest assistance mode

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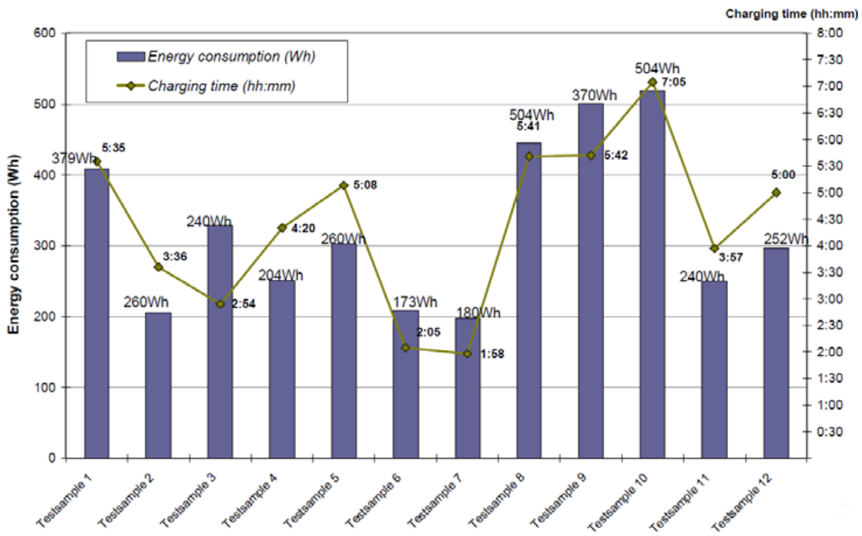
Figure 6: Energy consumption and charging time for a complete charge

Table 2: Overview of the subjective assessment of the electrical assistance

	Maximal speed	Assistance at start	Assistance on a flat road	Assistance on slopes
Test sample 1	25 km/h	none	good	good
Test sample 2	25 km/h	very good	very good	average
Test sample 3	25 km/h	average	average	average
Test sample 4	25 km/h	none	good	good
Test sample 5	28 km/h	very good	very good	very good
Test sample 6	20 km/h	none	average	insufficient
Test sample 7	20 km/h	none	good	insufficient
Test sample 8	28 km/h	none	good	average
Test sample 9	22 km/h	none	very good	good
Test sample 10	28 km/h	none	very good	very good
Test sample 11	30 km/h	none	good	average
Test sample 12	25 km/h	very good	very good	very good

7 Environmental analysis

An environmental assessment of electrically assisted bicycles, based on the Ecoscore methodology, was performed and put against the impact of a thermal moped. The Ecoscore methodology is a well-to-wheel methodology and thus allowing the comparison of the environmental impact of different vehicles using different kinds of fuels. The methodology will not be discussed in this paper but more details can be found in references [11] and [12]. The Ecoscore indicator is a number between 0 and 100. Zero means an infinitely polluting vehicle and 100 a perfect clean and non polluting vehicle.
The electricity consumption data (Wh per charge) from Figure 6 in combination with the driving range data from Figure 5 provides us with consumption data (Wh per kilometre) for set of electric bicycles. An overview of the consumption data is given in Table 3. This data is then used with the Ecoscore methodology, to assess the environmental impact. The Ecoscore methodology presents a single indicator that combines 4 different impacts: impact on global warming trough the emissions of greenhouse gasses, impact on human health and on ecosystems trough the

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emission of different pollutants (e.g. SO_2, PM_{10}, NO_X …) and finally the impact of noise.

It is clear that in the case of an electric bicycle there are no direct (tailpipe) emissions due to the electrical drive train. However, the production of the electricity required to recharge the battery will cause airborne emissions. Of course, different production methods for electricity are known, and are characterised by the emission of a combination of pollutants per produced kilowatt-hour of electrical energy. For this analysis the pollutants related to Belgian Electricity mix anno 2005 were considered. An extended database with the emission and consumption data of mopeds was used to assess the environmental impact of mopeds using thermal petrol engines. For this analysis also a full electric scooter (Vectrix) was added. Consumption data from the manufacturer were used.
An important gap can be observed between the Ecoscore of the thermal petrol mopeds and the Ecoscore of the electric scooter and of the 12 electric bicycles. This analysis confirms the low environmental impact of these vehicles.

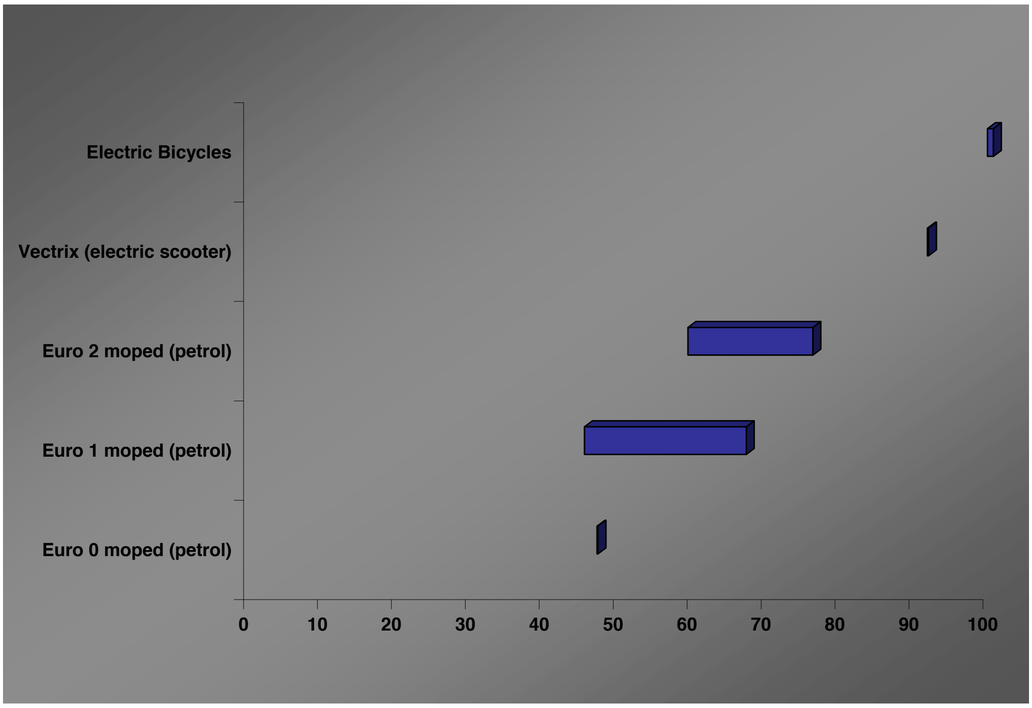

Figure 7: Ecoscore of electrically assisted bicycles compared with other motorized two-wheelers

Table 3: Consumption data of the electric bicycles and the electric scooter used for environmental assessment

Test sample	1	2	3	4	5	6	7	8	9	10	11	12	Vectrix
Average autonomy (km)	36,5	42,5	32	30	42	21	18,5	37,5	34,5	46,5	15	37,5	72,4
Electricity consumption (Wh/charge)	408	206	328	251	303	209	198	445	501	519	250	297	
Consumption (Wh/km)	11,2	4,8	10,3	8,4	7,2	10,0	10,7	11,9	14,5	11,2	16,7	7,9	107,2

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8 Conclusions

Determining the driving range of an electric vehicle or an electric bicycle in particular, is not an easy task. The reason is because it is related to the way the bicycle is used or driven. However, the most influencing parameters were identified: the total weight of the bicycle (including driver, possible luggage), the topography of the route, the speed profile and the effort of the cyclist. The first parameter, the total weight, plays a very important role in the amount of energy that is required to finish a certain trip. If the total weight is higher, a larger amount of energy is required. The second parameter is the topology of the route. It is clear that more energy is required to drive uphill as to drive the same distance on a flat road. The speed profile is important as well, in particular the number of start and stops. Driving at a constant speed without any stop will consume less energy compared to driving the same distance but stopping and accelerating multiple times (which is typical in an urban context). When considering the driving range of an electric bicycle, the energy content of the battery pack is one of the most important characteristics of the vehicle. Mostly, the energy content of the battery pack is expressed in Ah. The energy content is then obtained by multiplying this number with the nominal voltage level of the battery pack. Another important characteristic of the bicycle, influencing the driving range, is the way the electrical energy is used during use. Important differences exist in the level of electrical assistance or in the level of the power delivered by the electric motor. In general one can consider that if the motor delivers more power, more energy is consumed and extracted from the battery pack. When the cyclist is delivering an important share of the total traction power, this can influence strongly the driving range. The amount of power that is delivered by the electric motor can be influenced by the driver and differs from bicycle to bicycle. Some systems allow the user to modulate the electrical assistance, for instance with a throttle. With other systems, the level of electrical assistance is determined by a control system. This control system can then modulate the assistance in function of different parameters: vehicle speed, rotational speed of the pedals and the effort on the pedals.

The comparative study allowed determining both the driving ranges and the electricity consumption for battery recharging. Important differences in performance have been identified between the different models in terms of driving range and in terms of electrical assistance. The electrical assistance was evaluated on a flat road, on slopes, at start and when braking. The consumption information was used to make an environmental assessment of electrically assisted bicycles. The Ecoscore methodology was used to make this assessment and a clear advantage of electrically assisted bicycles compared to thermal mopeds was shown.

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Authors

Jean-Marc Timmermans graduated in 2003 as an Electromechanical Engineer at the Vrije Universiteit Brussel. His master thesis dealt with the development of a test bench for electric bicycles. As an academic assistant, he was involved in projects about the evaluation of the environmental impact of both conventional and alternative vehicles and was also involved in the development and evaluation of electric bikes for postal delivery use. Further research goes to the evaluation and optimization of hybrid electric drive trains for vehicles.

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