# Is Regenerative Braking Useful on an Electric Bicycle?

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The first or second question everyone asks about an electric bicycle is “Does it have regenerative braking?”. It seems that the idea has seeped deep into the popular consciousness and is now associated with all electric vehicles. Some bicycles do indeed have it, but the question this paper asks is, “is it worth the effort and expense to put regenerative braking on an electric bicycle?”.

Many people will say “of course, I want it all!”. But, in the real world, you never get it “all”. Your bicycle doesn't have a rocket engine on it, for instance, even though it's perfectly technically feasible to do that. What you “hopefully” get, is the list of items that get you the most for your dollar. In a perfect world, e-bike designers would go down that hypothetical list in order of “most bang for your buck” until they had put on all of the features that you can afford to pay for. So, how far up that list should regenerative braking be?

One way to approach this would be to arbitrarily decide on some range increase that would make regenerative braking a worthwhile investment. So, I will do that by saying that I don't believe a regenerative braking system is worth its transistors unless you get at least a 10% range boost from it. Now, 10% is pretty modest, so that's not too high a standard.

So, what does it take to get 10% more range? Well, it takes 10% more battery power. In other words your regenerative braking system has to be able to recover 10% of whatever the capacity of your battery is, over the time it normally takes you to discharge the battery completely.

I'll use our 16 Amp-hour, 37 Volt lithium polymer battery system as our example. It has a total usable energy of about 500 Watt-hours. A typical energy use for one our our EMD units on a bicycle is about 15 Wh per mile. So the range with 500 Watt-hours “in the tank” would be 33 miles. So, what would it take for a regen system to recover 10% of that, or 50 Watt-hours, thereby extending our range by 3.3 miles?

The obvious source for recovering energy would be stopping at stop signs or traffic lights. If we assume a total weight of bike plus rider of 220 lbs (100 kg), moving at about 16 mph (25 km/h), it's a simple physics 101 problem to calculate the energy available to be recovered by slowing the bike to zero mph. It works out to about 2400 Joules.

A Joule is a tiny unit. 3600 Joules make one Watt-hour. So 2400 Joules is .67 Watt-hours. So how many stops would it take from 16 mph to recover 50 Watt-hours at .67 Watt-hours per stop? The answer is 75.

Of course, we can't recover 100% of the kinetic energy because all real systems are less than 100% efficient. A reasonable efficiency would be more like 75%. If we factor that in, we can only recover .67 times .75, or .50 Watt-hours per stop. Now were talking 100 stops to recover 10% of the energy in the battery.

If we divide 100 stops into 33 miles, that's an average of 1742 feet between stops for the entire 33 miles. A typical city block is about 500 feet, so that corresponds to a full stop every 3 city blocks. In a congested urban area that might happen. More typically stops will be further apart. Also, under such conditions bicyclists often don't stop completely at intersections, but rather roll through at low speed. A third or more of the energy that would be returned to the battery is instead retained as momentum. This is more efficient than regenerative braking since retained momentum doesn't incur mechanical and electrical losses.

There's another factor here we haven't considered. If we have 1800 Joules (2400 Joules at 75% efficiency) that can be recovered, we have to put them somewhere. We put them in the battery, obviously.

Batteries are always designed to be charged at a certain maximum rate. Charge them above the designed rate, and they will suffer from a shortened service life. In the case of our 16Ah lithium ion polymer battery, we recommend charging at no more than 3 Amps to maximize life. Three Amps at 37 Volts, is 111 Joules per second. If we have 1800 Joules to put in the battery, it will take 1800 divided by 111 or 16.2 seconds to do so. Taking 16 seconds to stop from 16 miles per hour, is a very slow stop. A more typical, but still relaxed stop, would be 3 or 4 seconds. If we've got four seconds at 111 Joules per second charge rate, we can only put 444 Joules or .12 Watt-hours into the battery per stop.

Taking this new number into account, we would need 416 stops to get 50 Watt-hours back. That's 418 feet average between stops over 33 miles. More than 1 stop per city block. You might do that if you're a mail carrier.

At a more reasonable 2000 feet average between stops, we will stop 87 times in 33 miles and recover 10.5 Watt-hours of energy, or 2.1% of the battery's total energy. That corresponds to 7 tenths of a mile of added range.

The newest battery technology on the market, lithium iron phosphate, sometimes abbreviated as LiFePO4 has the ability to be rapid charged. A bicycle sized LiFePO4 battery can absorb 1800 Joules in 3 or 4 seconds. The trade-off is that you lose about 25% capacity compared to the same weight in lithium ion polymer batteries. Still, LiFePO4 has other advantages, such as extremely long life, so it is a reasonable alternative.

With LiFePO4, 87 stops will recover 44 watt-hours. That's still less than 10%, though it's not too bad at a bit less than 9 %.

What about hills? We go up hills burning up a lot of energy, surely we can recover some of that on the way down?

OK, lets do some more calculations. For this part, I'm going to rely on figures from John S. Lamancusa's Bicycle Power Calculator from Penn State University.

I'll start out by assuming that most riders, when they crest a hill, will simply coast down the other side at top speed, unless the hill is so steep that they reach unsafe speeds. For the sake of this paper, let's assume that 25 mph is the fastest any rider would want to coast down a hill. What's the steepest hill that the rider can coast down and not exceed 25 mph?Assuming the same 220 lb. bike plus rider weight, along with road tires and an upright seating position, the BPC calculates a 2.9% slope.

So, for any slope steeper than that, regenerative braking could recover useful energy. But remember, there's a limit to how fast batteries can be charged and still maintain a long service life. From the previous discussion, our 20Ah lithium ion polymer is limited to 111 Joules per second.

After allowing for the 75% efficiency factor, the BPC calculates that the slope where the charging rate would just equal 111 Joules per second and the regen braking could just barely hold the bike at 25 mph, is 4.1%. Anything steeper than that, and you would have to use friction braking and throw energy away or use LiFePO4 batteries.

Let's assume that we have some 4.1% grade on our route. How much of it do we need to recover 75 Watt-hours of energy? Well, we're charging at 111 Joules per second or .031 Watt-hours per second. In 1612 seconds, we will have recovered 50 Watt-hours of energy. 1612 seconds is 26 minutes and 53 seconds. At 25 mph, we will have covered 11.2 miles in that time. The slope is 4.1%, so we must have started 2400 feet higher than where we finished.

In other words, our 33 mile ride must have downhills that add up to 2400 feet of elevation loss, and they must all be grades of about 4%. If the grade is less than 4.1 % but steeper than 2.9%, the BPC reveals that the shallower the grade, the more elevation loss is needed to recover 10% of the battery energy.

At a 3.3% grade, you would need 5725 feet of loss and the slope would be 33 miles long. For grades steeper than 4.1%, we would need LiFePO4 batteries to recover all the energy. Assuming a 6% grade, the steepest allowed for interstate highways, we could recover 270 joules per second with LiFePO4. That corresponds to almost 1500 feet of elevation loss over about 5 miles to recover 10% of the battery energy.

There may be a few 11 mile, 4% grades out there. I-70 coming out of the Eisenhower tunnel through the Continental Divide as it descends into Denver comes to mind. But, this is the sort of elevation loss that you're just not going to encounter in 33 miles of typical urban riding. Also, the very steepest grades of 6% and over are rare because road designers try and avoid steep grades.

Typically, you'll have a numerous shallow slopes that you simply coast down at full speed, and a few short steep hills. Let's say that you have a mile of 4% downgrade on a typical 33 mile route. That's 4.3 Watt-hours or 0.9% potential energy recovery. Add that to our 2.1% from stops, and we've got a grand total of 3% energy recovery due to regenerative braking under these conditions. That's about a mile of added range.

LiFePO4 could do much better. Let's say we also have a mile of 6% grade on our hypothetical route. We could get 10.8 Watt-hours from using regen to slow our descent. Add to the 44 Watt-hours from braking and the 4.3 Watt-hours from lesser grades and we're at almost 60 Watt-hours or about 12%.

So, from this analysis regenerative braking using rapid charge batteries like LiFePO4 could be a winning proposition. Note however that we assumed over 500 feet of steep elevation loss. That's not typical of most riding. We also assumed a lot of pretty hard stops. Riders interested in conserving their energy don't stop this hard very often. The coast up to intersections slowly using the last of their momentum to overcome wind drag. The stop at the end, if there is one, is gentle.

There's one more factor though, that we haven't considered. The above calculations assume that there's no energy loss associated with adding regenerative braking. That's a valid assumption for a pure electric vehicle such as an electric car or scooter. The electric motors on such a vehicle are usually either driving or braking with very little coasting. A bicycle however is fundamentally different. It spends a lot of time either coasting or being pedaled with the motor shut down. Our typical energy use assumptions above reflect a ratio of motor on to motor off of about 1 to 1. In other words the motor is shut down 50% of the time.

The way regenerative braking is implemented is to have the motor continuously engaged. So, even when you're just pedaling or coasting, the motor is engaged. That means that there is a drag torque caused by parasitic losses in the motor. That drag sucks power from the rider.

It's a fair assumption to say that the rider is probably pedaling as much as he or she wants to. So any extra power that the rider has to put out to compensate for parasitic motor drag will ultimately be pulled out of the battery from extra use.

A typical hub motor might have a drag torque of 0.5 to 1 N-m. At 15 mph cruising speed, that's 10 to 20 watts of power to overcome motor drag. Over the course of a 33 mile ride with the motor off 50% of the time, that's 11 to 22 Watt-hours lost to parasitic motor drag. That has to be subtracted from any gains from regen braking. Using our best case number of 60 Watt-hours, we get instead 38 to 49 Watt-hours or 7.6% to 9.8% back. Using the more conservative Lithium ion polymer number of 14.8 Watt-hours recovered we get *negative* 7.2 to positive 3.8 Watt-hours.

In other words, under less than optimal conditions regenerative braking on a bicycle can actually end up costing you energy!

Well, you might say, just use a clutch on the motor and only engage it when you want braking. Yes, that would work, but it's interesting to note that no one has done it. And for a very good reason: cost.

With a continuously engaged hub motor system, regenerative braking can be almost free to implement. So, given the marketing advantages that accrue to anyone who can advertise regenerative braking, it can be worth the minimal effort involved . And indeed, the only systems that have regenerative braking are direct drive hub motors.

With a higher performance mid-drive system such as Ecospeed's or even an internally geared hub motor, the cost of regenerative braking would not be zero. So, the question becomes, “if I'm going to add x dollars to the cost, where's the best place to spend it?” Since there is no reasonable scenario that allows regenerative braking to contribute even modestly to the performance of an electric bicycle and there's a good chance of it actually hurting performance, the answer is clearly, “not on regen”.

In fact, if you look at where the energy that propels your electric bicycle is actually going, the answer is “spend the money of fairings and other aerodynamic aids”.  The BPC reveals that at 25 mph, over 80 percent of power is going just to overcome wind resistance. That's where the big gains are. But, that's another paper.