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DESIGN AND ANALYSIS OF ELECTRIC BIKES FOR LOCAL COMMUTES

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ABSTRACT

In today's society, those who do not take advantage of public transportation services typically drive personal vehicles to school, work, and other locations of interest. Due to the required amount of physical exertion, walking or riding a bike is often avoided. This is concerning given that a large percentage of carbon and hazardous emissions emanate from motor vehicles. This creates a need for an alternative means of travel for shorter commutes with electric bikes (e-bikes) one potential solution. They have zero tailpipe emissions and significantly lower overall emissions relative to motorized vehicles; however, their cost often prevents them from being readily marketable. In order to address this issue, two undergraduate capstone design teams have constructed e-bikes using recycled and donated parts over the past two years.

In the first year, the runner from a pickup truck was scavenged from a junkyard and employed as the frame to provide for the greatest environmental benefit. However, this resulted in an odd bicycle shape because of limited material availability. As a result, the second year's team decided to use a donated chrome moly tube as the frame while focusing on ergonomics and aesthetics. This second bike was designed so that a male rider of average height (5'10" – 1.78 m) could complete commutes of several miles in relative comfort. Both e-bikes employ a direct drive motor (first year – front wheel; second year – back wheel) to provide assistance when needed, leaving the rider less fatigued. To promote further development in electric bike design, each team has made a considerable effort to record the design process with highlights presented in this effort. Furthermore, e-bike testing results are presented including center of mass calculations, braking distances, turning radii, and overall efficiencies quantified by the miles traveled using the same battery pack. This information will be used to compare the bikes against each other in order to illustrate bike attributes that are desired when an electric motor is employed.

The result is an appealing, cost-effective, and efficient electrical bike that will greatly reduce traffic related emissions should it become widely implemented. Given the issues related to transportation at a university (e.g., available parking) including the reticence of students to traverse long distances across campus to attend classes, it is believed that this effort can serve as a model example to other universities who might see e-bikes as a potential solution to reducing congestion and improving student attendance.

INTRODUCTION

In an urban setting, passenger vehicles are the most common form of transportation, despite the average commute being less than a few miles [1]. There are other options that include walking, biking, or riding the bus; however, they all have drawbacks regarding their usage. For example, busses tend to be crowded and slow, and walking and biking is often avoided because they are physically demanding and take longer. As a result, the majority of people drive resulting in the emanation of a significant amount of emissions [1]. Electrical bikes, or e-bikes, are a potential solution to this problem. E-bikes utilize an electric motor that allows the riders to travel further, faster, with less physical effort. Hence, riders, sedentary in physique, found that commuting by e-bike was easier than expected and convenient to the operator during tests for typical commutes [2]. Moreover, because of their smaller size, e-bikes require less energy to make the same trips as a car or bus. Additionally, by being electrically powered, an e-bike does not directly emit pollution into its surroundings.

While e-bikes have no tailpipe emissions, there are still emissions generated during their fabrication and through re-charging of the battery pack [3]. One study in China compared the emission ratings between different vehicles used for transportation. It took into account the amount of people each option could carry. In addition, it accounted for the fact that the e-bike battery standard (lead-acid) tends to last only one to two years; whereas, heavier bus batteries (also lead-acid) typically last three years or more [4]. The study showed that, per kilometer, e-bikes produce significantly lower emissions relative to cars or buses in all categories besides lead emissions [4]. However, since lead-acid batteries are an outdated technology, utilizing lithium-ion batteries for an e-bike should result in lower emissions in all categories [5].

This reduction in emissions due to e-bikes is important because of the effect that air pollution has on respiratory health [6]. This is significant when in a city or on a college campus because motor vehicles are traveling in close proximity to bikers and students walking to class. This traffic-related air pollution is in direct contact with these bystanders, and has a greater influence than other emitters, such as power plants that are usually located on the outskirts of cities. Through the replacement of motor vehicles with a lower emitting method of travel (i.e., e-bikes), these traffic-related air pollution levels will be reduced and public health will be improved [7]. This potential emissions reduction has been observed in a study performed on the Low Emissions Zone of Amsterdam (LEZA); an area where only vehicles with emission ratings that do not exceed a certain limit are permitted to travel. The study compared pollution levels (i.e., NO_2, NO_x, PM_{10}, EC and absorbance) within the zone over two years prior to its implementation and found a "statistically significant decrease in their levels" [7].

As a result, this effort applies these findings to the University of Kansas (KU) for determining the possibility of a fleet of e-bikes used as the main means of transportation around campus. For this reason, the project's target audience is the student population attending KU. A large portion of the student body lives off campus, and the majority drive to class and for errands [8]. During a survey made of the University's student body, half of the students would be willing to use bikes as an alternate form of transport [8]. Moreover, the relatively small size of Lawrence allows e-bikes to meet the needs of these students while improving traffic flow and air quality.

This work describes the design, construction, and testing of the two e-bikes manufactured at KU over the last few years. For the first e-bike, the runner from a pickup truck was scavenged from a junkyard and employed as the frame to provide for the most sustainable project. After preliminary testing of this design, a re-envisioning of the effort took place to focus on the ergonomics of the e-bike. This is because a poorly designed frame can induce undue stresses on the rider if not fitted properly. Extended riding with poor posture can have adverse effects part of the riders body (e.g., the knees or lower back) [9]. Moreover, ergonomics dictates the bike's handling and given the significant pedestrian flow on campus, a good handling e-bike is desired.

In the following sections, the first year's e-bike is succinctly described followed by the ergonomic research that went into the creation of the second year's frame design. This includes how each bike was constructed, and how the teams utilized as many recycled materials as possible to build an economical e-bike. Finally, a center of mass analysis of each e-bike is performed followed by on-road testing including braking distance, turning radius, and efficiency.

E-BIKE YEAR 1 DESIGN & CONSTRUCTION

In the first year of effort, the goal of the team was to build the most sustainable e-bike. This included scavenging parts from automotive junk yards in order to reduce the embodied emissions of new part creation [10]. To this extent, the team researched other analogous efforts including Rcicla Bicycles [11] and the Bicycled project [12]. However, these projects employed only a single gear and were human powered. Moreover, the Rcicla bicycle employed a different frame design instead of the standard triangle and the Bicycled project recycled the metal instead of using it directly. As a result, the team decided to move forward with its own original multi-speed battery powered design.

Figure 1. First year constructed e-bike including a rack to support the battery pack.

For the frame, the team employed two nerf boards from a 1995 Dodge RAM 1500 as illustrated in Figure 1. These boards were used because they were hollow, relatively lightweight, sturdy, easily removable from the truck, and consisted of enough material to make the frame. A drawback of these pieces were that the cross-section is 2.7 inches by 3.3 inches (69 mm by 84 mm), which is significantly wider than a normal bike frame while also being irregular in shape. Furthermore, there was only enough material to create a frame; hence, the rear triangle was taken from a decommissioned road bicycle. Moreover, a front fork (connected directly through the head tube) was scavenged from a local charitable organization (Topeka Community Cycle Project) along with numerous other parts from scrapped bicycles (e.g., rear derailleur, rear wheel, gear cassette, crank set, etc.). Of note, the original larger back wheel employed in the first year effort (Figure 1) was subsequently replaced in the second year after finding a suitable match to the front wheel. While initially intending to design the bike for the height of an average male (5'10" – 1.78 m), due to the limited amount of frame material, concessions were made on the design (illustrated in the Testing section) in order to generate a working e-bike.

The e-bike's electric motor is the most expensive component and plays a vital role in determining the pedaling input needed by the rider. A hub drive motor was chosen for the first e-bike (and subsequently for the second e-bike), because failure of a mid-drive motor that connects to the existing bike chain would result in the rider being stranded while also being harder to implement. Furthermore, a direct drive stepper motor option was chosen over a geared epicyclic version (for both e-bikes) due to power requirements. The epicyclic system features a set of planetary gears that drive the outer motor when triggered by a throttle, and tend to be lighter and smaller than direct drive motors. However, they can only handle relatively smaller loads (typically less than 200 lbs); whereas, the chosen direct drive motor is rated to withstand a max loading of 600 lbs. This was considered necessary to be able to effectively handle the relatively heavy frame and motor system along inclines and across KU's campus.

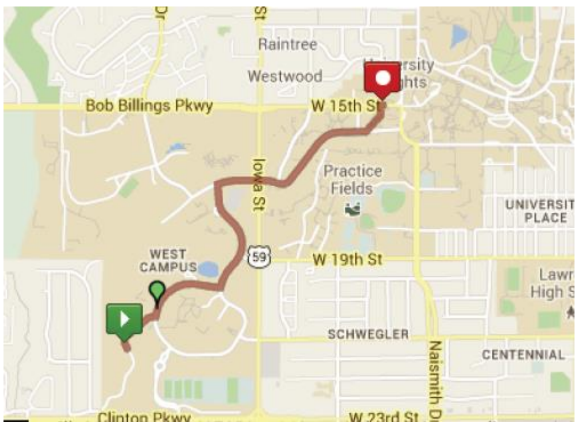

Figure 2. Mapmyride.com GPS route from Eaton Hall to Hill Center used as the representative campus route.

The e-bike motor was used as the front wheel in the initial effort because it created a separation between the traditional bicycling gearing and motor input. This reduces the stress induced in the bicycle chain and was deemed to be an easier implementation. However, for the second year, the motor was shifted to the back wheel because an integrated cassette and hub drive motor option existed. This shifts the bike's center of mass towards the rear that should subsequently improve the handling of the bike. Moreover, on wet road conditions, a bike with a front drive motor may lose its main means of stability, and might not remain upright. However, in a rear wheel drive system, the motors weight is shifted to the back, and the rider can still control the bike's stability through the front tire.

For the battery pack, a Newton's second law analysis [13] was performed using a representative route on campus (Figure 2) in order to determine the desired battery capacity. The route was determined to be 2.90 miles (4.67 kilometers) with a total incline of 213.0 feet (64.9 meters). The projected weight of the bike including the rider and frame was approximated at 200 pounds (90.72 kg). The frontal area was estimated to be 0.56 m^2, the rolling resistance coefficient to be 0.006, and the coefficient of drag to be 1.11 [14]. The motor provides 500 W of power at 36 VDC with an estimated motor efficiency of 70%. Applying a constant speed of 10 mph (4.47 m/s) over this route while assuming that the motor was running the entire round trip, 4.94 Ah is necessary to complete the route. To include a factor of safety, the total target capacity was set at 8 Ah and resulted in the parallel connection of two Greenworks model 29282 batteries (40 VDC, 4 Ah each) originally intended for electric lawnmowers. For simplicity, this same battery pack was used in the second year efforts since the representative route has not changed.

E-BIKE YEAR 2 DESIGN & CONSTRUCTION

Throughout the design and construction of the second e-bike, the first e-bike was used as a reference. Similar goals included building an e-bike that was low cost, and could be comfortably ridden over a trip of approximately three miles. Both e-bikes were designed to accommodate an average height rider and allow them commute safety with minimum fatigue. This included purchasing the motor and safety components (e.g., brake pads, brake lines, and tire tubes) new and remaining items were from recycled scrap materials, or old, unusable bicycles.

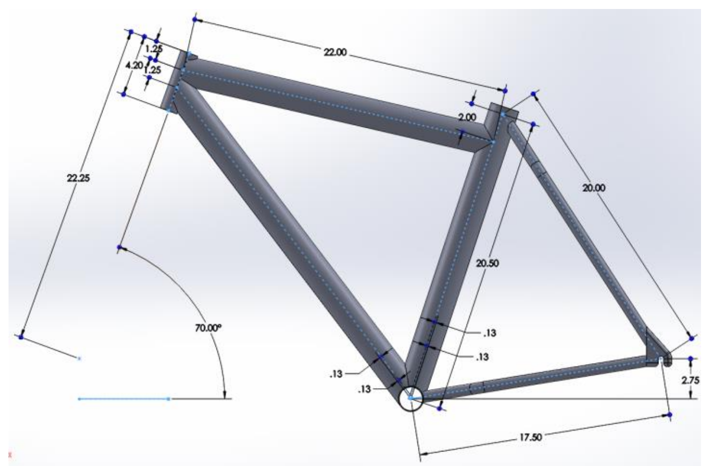

Figure 3. A rendering of the final design of the 2014-2015 e-bike frame that shows the dimensions of the chrome moly frame (in inches), as well as the other component lengths and angles (e.g., head tube angle, seat post length, etc…).

Because of the irregular cross-section that made frame construction difficult in year 1, the second year's effort used chrome moly steel pipe for its 2" uniform cross-section. Chrome moly has a high strength to weight ratio, which lowers the overall weight of the bike. In addition, the recycled bike parts are steel, allowing them to be welded to the chrome moly pipe frame with relative easy. Moreover, the uniform cross-section of the available chrome moly pipe made the construction process less complicated while resulting in a more appealing frame design.

In the second year, an emphasis was placed on ergonomics. In specific, the stability and comfort of the e-bike design is determined by the inner triangle, which is comprised of the seat post, down tube, and top tube as seen in Figure 3. They govern aspects of the design, such as head tube angle, handlebar height, and seat height that affects riding posture. This makes it important to fit the bike to the rider, as poor riding posture can induce fatigue and lead to pain or injury [15]. With this in mind, the second e-bike was designed to fit the average male height of 5'10" (1.78 meters) with an inseam length of 33" (0.84 meters). However, the seat is adjustable, so riders may fix the seat height to their own specific relaxed setting in order to avoid joint discomfort.

Figure 4. Both e-bikes were powder coated to improve their appearance with the first e-bike illustrated in the top image, and the second e-bike in the bottom image.

Table 1: The budgets for both e-bike builds

Item/Description	E-Bike Year 1	E-Bike Year 2
Motor System	$696	$534
Battery System	$276	-
Additional Bike Parts	$364	$876
Miscellaneous tools & Construction Materials	-	$62
Total Bike Cost	$1,336	$1,472
In Kind Donations	$166	$25
Monetary Donations	$400	$300
Total Project Costs	$770	$769

With respect to seat height, this is the distance from the top of the bike seat to an extended pedal. It was found that riders reach a maximum power output when the seat height was set to 109% of the rider's inseam length [16]. However, Yoshihuku and Herzog determined that a seat height of 106% of the inseam was ideal for rider comfort [9]. Because this is a priority, the 106% value was used to specify a seat height of 35" (0.89 meters). The distance from the seat to the handlebars is also an important ergonomic factor, and should be positioned so that riders have a 15 degrees lean forward (from vertical) [9]. This shifts part of the upper body weight to the arms and reduces the stress in the lower back.

Figure 5. The method used to calculate the rider's COM for the first-year e-bike (top) and second year e-bike (bottom). The points marked by (x) are the COM locations of each body segment, the dashed lines were used to find their coordinates with respect the origin (placed at the bottom bracket), the solid circle is the COM of the rider and the solid square is the overall COM of the e-bike and rider.

As for the bike's handling, it is largely determined by the front fork and head tube angle. The steering axis is the line that runs through the head tube. Rake, or offset, is the distance from the steering axis to the center of the dropout on the end of the fork. Trail is the distance between where the steering axis intersects the ground and the point at which the wheel touches the ground. Typical trail values range from of 51 mm to 64 mm [17]. Values at the lower end of this range result in sensitive steering; whereas, larger trail values result in a more stable ride [18]. However, if the trail is too large, an effect called flop becomes apparent. This is where the wheel to fall towards the direction being turned once a certain angle is reached. To balance stability and responsiveness, the e-bike was given a trail value of 60 mm. From here, the head tube angle was calculated to be 70 degrees based on the wheel size, fork geometry, and this desired trail value. Once the frame was completely built, it was powder coated (along with the first bike) to protect the metal from oxidation as shown in Figure 4 and then assembled in full. Overall, the costs for each year's efforts are provided in Table 1 broken down into main categories while also indicating donations received.

TESTING AND DISCUSSION

In order to verify the ergonomics and design improvements incorporated into the second e-bike, initial testing involved a center of mass (COM) calculation. This calculation was accomplished by taking images of a rider sitting in a riding position on both e-bikes (Figure 5). The person's frame was split into segments (i.e., lower arm and leg, upper arm and leg, torso and head) that were assumed uniform. The centers of these segments were found, and each was assigned a respective weight as shown in Table 2. This was determined from a study that related the weight of individual body parts to overall weight (e.g., torso weight is approximately 0.510×body weight) [19]. Next, an axis was added over the image, and the coordinate positions of the previously mentioned centers were found. Finally, a weight-based average was used to calculate the COM of the rider employing the following equations for the *x* and *y*-directions, respectively:

$$x_{\text{COM}} = \frac{\sum (\text{WT Dist})_i \cdot x_i}{\sum (\text{WT Dist})_i} \tag{1}$$

$$y_{\text{COM}} = \frac{\sum (\text{WT Dist})_i \cdot y_i}{\sum (\text{WT Dist})_i} \tag{2}$$

Calculating the COM of the e-bike included taking pictures of the frame hung in multiple locations from a common anchor point. Vertical lines were drawn from this anchor point in each of the images, and the point where these all connect is the COM. Finally, the body and e-bike COM calculations are combined to find the COM of the overall system as indicated in Table 3.

As can be seen in Figure 5, the rider's COM for the second year's e-bike is located slightly in front of the bottom bracket. In comparison, this COM is positioned behind the bottom bracket (i.e., over the rear wheel) for the first year's e-bike. Once the frame and components were included in the calculation, the COM was shifted slightly forward for last year's e-bike and towards the rear (directly inline with the bottom bracket) for the second e-bike. Moreover, it is lowered in both situations to approximately the seat height.

This COM positioning and rider posture play an important role in the ergonomics of each bicycle. The frame of the first e-bike has the rider sitting nearly upright; whereas, the second year's design has the rider leaning forward. This is likely caused by the relatively sharp head tube angle chosen for the initial design. While riding, the rider feels that they have to reach for the handlebars making steering seem unnatural. Moreover, the bottom bracket is positioned above the centerline of the wheels for the first e-bike. This causes the overall COM to be positioned higher relative to the subsequent design and forces the rider to sit higher on the bike. By having the bottom bracket positioned below the hubs of the wheels, the rider sits lower into the frame for a more natural feel. Hence, having a lower COM improves the stability of the ride.

Table 2. The weight distributions of each body segment and their coordinate locations relative to the bottom bracket (not respective to the image shown).

E-Bike Year 1 (Scale: 1 = 15.64 inch)					
	WT Dist	x_1	y_1	x_2	y_2
Upper Arm	0.028	-0.29	2.92	-0.29	2.92
Upper Leg	0.100	-0.41	1.35	-0.41	1.35
Lower Arm	0.022	-0.15	2.12	-0.15	2.12
Lower Leg	0.061	-0.34	0.45	0.25	1.04
Torso	0.510	-0.69	2.63	-	-
Head	0.068	-0.10	3.84	-	-

E-Bike Year 2 (Scale: 1 = 15.18 inch)					
	WT Dist	x_1	y_1	x_2	y_2
Upper Arm	0.028	0.60	2.82	0.60	2.82
Upper Leg	0.100	0.08	1.63	0.08	1.63
Lower Arm	0.022	1.14	2.09	1.14	2.09
Lower Leg	0.061	0.42	0.69	0.00	0.90
Torso	0.510	0.00	2.62	-	-
Head	0.068	0.85	3.65	-	-

Table 3. COM locations relative to the bottom bracket of the different systems with respect to the scaled images.

E-Bike Year 1					
	Weight	**COM (Scaled)**		**COM (inches)**	
System	**(lbf)**	***x***	***y***	***x***	***y***
Frame/Motor	48.0	0.47	0.36	7.38	5.63
Battery	22.5	-1.59	1.29	-24.86	20.18
Person	175.0	-0.47	2.22	-7.34	34.72
Overall	**245.5**	**-0.39**	**1.77**	**-6.06**	**27.70**

E-Bike Year 2					
	Weight	**COM (Scaled)**		**COM (inches)**	
System	**(lbf)**	***x***	***y***	***x***	***y***
Frame/Motor	52.2	-0.14	0.61	-2.06	9.24
Battery	22.5	-1.12	1.56	-16.99	23.61
Person	175.0	0.18	2.26	2.78	34.27
Overall	**249.7**	**0**	**1.85**	**0.00**	**28.07**

To gain further insight into how each e-bike handles, braking tests were completed. It is important to mention that an additional improvement in the second year's design was to implement a disc brake in the front (rim brake in the back) to aid in stopping force; whereas, the first year's design employs rim brakes for both wheels. Therefore, the second e-bike should stop more quickly, especially since it is a lighter bike due to the choice of frame material.

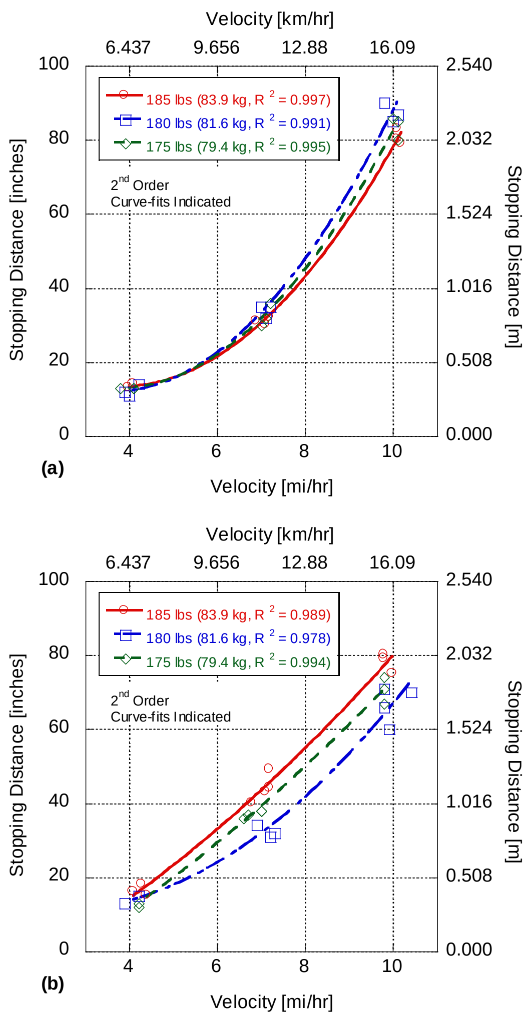

Figure 6: Braking distances for the (a) first and (b) second e-bike as a function of rider weight.

Testing of the bikes occurred by first marking a starting line on a level piece of ground. Then, different weighted operators rode the bike at a series of speeds (i.e., 4, 7, and 10 mph; 6.44, 11.27, and 16.09 km/h) across the line. The riders began braking with both front and rear brakes once the front wheel crossed the line, and the distance it took to come to a complete stop was recorded. Averages of these distances were used to determine the stopping distance for both e-bikes at a given speed. These data were collected during clear weather without water on the ground.

From the literature, Lie and Sung derive the following relationship between braking distance, velocity of the bike, and overall bicycle weight [20]:

$$S + S_1 = \frac{W}{\rho A_f C_D g} \ln\left(1 + \frac{\frac{\rho}{2} A_f C_D V^2}{\eta \mu W_b + \mu_r W}\right) + V \cdot t_1 \tag{3}$$

where S is the braking distance, S_1 is distance prior to applying the brakes, W is the total weight, g is acceleration due to gravity, ρ is the density of air, A_f is the frontal area, C_D is the coefficient of drag, V is the velocity, η is the braking efficiency, μ is the friction coefficient of the road, W_b is the effective braking weight, μ_r is the rotation friction coefficient of the tire with respect to the ground, and t_1 is the time prior to applying the brakes. From this relationship, it is expected that the braking distance should follow a 2nd order polynomial relationship with velocity. Moreover, as velocity and/or weight increases, the braking distance should also increase.

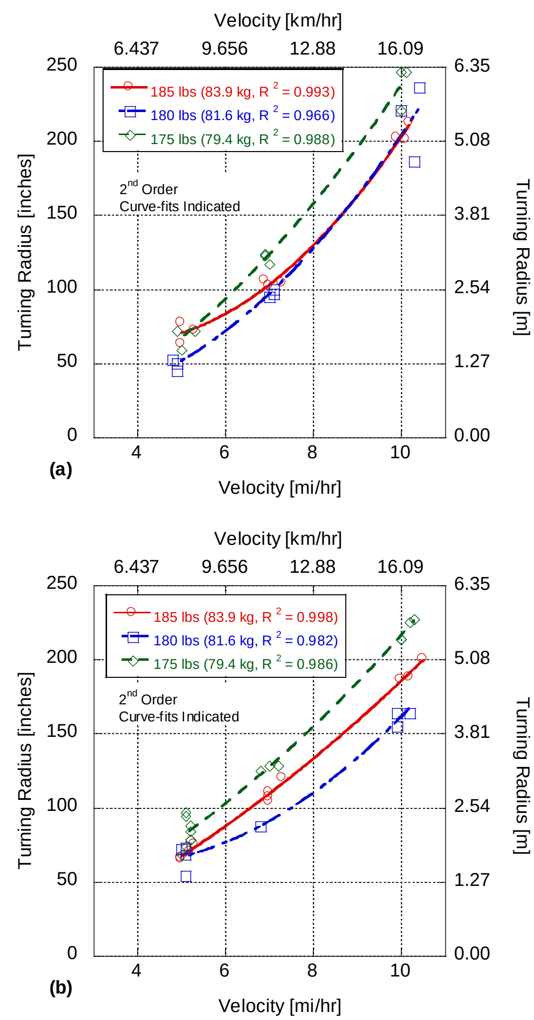

Figure 7: Turning radius for the (a) first and (b) second e-bike as a function of rider weight.

Figure 6 illustrates that the data did trend as expected with velocity; however, a conclusive trend with weight could not be determined. This may be a function of variability in the braking tests including the visual timing used to initiate braking, non-controlled surface roughness, grip strength of the riders, rider experience and willingness to brake hard, and rider body movement during braking. Further efforts should include additional velocity testing while measuring the applied manual force to the bike handles by each individual along with the speed of reaction or timing with Cain and Perkins [21] reviewed for example instrumentation.

When comparing both e-bikes at the highest rate of travel, it was found that the second e-bike stops in a shorter distance due to the use of a front disc brake and a better ergonomic design. Furthermore, it appears there is a wider variability in the stopping distance results for this bike. This could be due to the enhanced ergonomics allowing for more flexibility when it comes to rider experience. The relatively awkward (non-bike) ergonomics of first e-bike might effectively normalize the results; i.e., all riders are riding for the first time. This could prove to be an informative finding for researchers in this area who wish to remove bias with different test subjects.

For continued investigation into each bike's design, turning radius tests were accomplished. This included a similar start to the braking test; however, once the front wheel crossed the line, the riders turned to ninety degrees from their starting position according to their perceived comfort without falling. A line, parallel to the starting line, was projected at the new position and the distance between the two was recorded as the turning radius. The trials were then graphed to determine the e-bikes turning radius at different speeds. These data were collected during clear weather on dry ground.

Chen et al. [22] determined that the turning radius is dependent primarily on the steering angle with the velocity having a significantly reduced effect. However, when bike velocity increases they find that the steering angle decreases and with smaller steering angles, the turning radius grows (also found by Cain and Perkins [21]). In Figure 7, the authors find similar results with the turning radius increasing as a function of bike velocity, subsequently interpreted as a decrease in steering angle for the rider.

According to Fajans [23], the rate at which the steering angle increases is set primarily by the moment of inertia of the wheel, fork, and handlebars around the steering axis. With respect to the relationship between the inertia of the bike wheel (I_0) and the turning radius (R), Fajans derived the relationship for the second derivative of lean angle (λ) as follows:

$$I_\lambda \ddot{\lambda} = -N_f + \frac{hmV^2}{R} + hmg\lambda + \frac{V\omega I_0}{R} + \frac{hbmV}{L}\dot{\sigma} \tag{4}$$

where I_λ is the moment of inertia around the lean axis, N_f is the torque exerted on the wheel, h is the distance between the lean axis and the center of mass, m is the mass of the bike and driver, ω is the wheel's angular frequency, b is the horizontal distance from the rear wheel to the center of mass, L is the wheelbase, and σ is the steering angle. By assuming that the bike is turning under equilibrium and that the lean angle and steering angle are constant with time, this equation simplifies to:

$$R = \frac{mhV^2 + I_0\omega V}{N_f - m\lambda gh} \tag{5}$$

Therefore, under equilibrium, as the wheel inertia increases (i.e., an electric motor versus a normal wheel), the turning radius will increase. Hence, the steering angle should decrease for electric bikes in comparison to normal bikes. Moreover, with increased bike weight, the turning radius should increase. However, no defined trend with weight was found; again, due to similar variability as found during the braking tests while factoring in the natural balancing behavior of the riders.

With respect to placing the motor in the front or the back, since turning is largely a function of the front wheel, the added weight in the front makes it relatively harder to turn smoothly (not to mention if the person is using power while turning resulting in a force propelling the vehicle forward). Moreover, the head tube angle and fork geometry will play an important role in the comfort of the rider when turning. Combining all of these factors with the lower COM value illustrates that the second e-bike should have a shorter turning radius in comparison to the first e-bike as found in Figure 7 at the highest speed. Similar to the braking distance findings, there appears to be a smaller spread in data over the different riders for the first e-bike. Again, this suggests that designing an irregular bike might help normalize the experience of dissimilar riders.

The final testing involved measuring the distance that each e-bike could travel under a fully charged battery pack using each motor's on-board data acquisition system. This included charging the battery pack overnight and riding each e-bike in a large, flat parking lot at a nearly equivalent constant speed in dry conditions until the motor could no longer move the rider. For the first e-bike, an average distance of 4.73 miles (7.62 km) over three trials was found at a speed average of 14.2 miles per hour (22.9 km/hr); whereas, the second e-bike averaged 7.77 miles (12.50 km) traveled at a speed average of 15.1 miles per hour (24.3 km/hr).

Possible differences between the findings include the change in respective forces between the e-bikes. Since the first e-bike included a front motor with a reduced amount of weight placed above the motor, it is possible that the power transferred from the motor to the ground was lower because of more wheel slip. Of note, there is no literature in the area of front-wheel drive bicycles or motorcycles (i.e., two-wheel vehicles) that can confirm this finding. Furthermore, while the style of 36 VDC motor was consistent between the two years, the motor options were different. In the first year, a 500W performance motor was chosen for higher speed travel; whereas, in the second year a 500W heavy-duty motor was chosen for its greater torque because of the shift to rear-wheel drive. Therefore, further testing should be performed at different vehicle speeds in order to map the efficiency of the motor and determine the optimal driving speeds for each e-bike for maximum riding distance.

CONCLUSION

From the research indicated, it is clear that e-bikes are a sustainable and plausible solution to problematic emissions from transportation; especially when a limited number of miles is traversed. Their energy consumption is lower than the majority of motorized vehicles. While the production of some of their components, namely the battery packs, could result in harmful emissions, they are overall better for the environment. Furthermore, by using recycled parts during construction, production emissions can be reduced along with the e-bike's price; hence, they can be an economically feasible, low emission transportation option for the average consumer.

In the first year of effort, an e-bike was designed and built using used car and bicycle parts to promote sustainable outcomes. While effective, a re-imagining of the e-bike took place in the second year focusing on ergonomics with this e-bike designed to provide a comfortable and stable ride. COM testing of both e-bikes has shown that these design decisions have improved rider posture and comfort. In combination with better ergonomics, lowering the center of mass of the second e-bike improved its performance as illustrated by a reduced stopping distance and smaller turning radius at higher speeds. Trends with speed were validated via literature models; however, predictions with weight were unable to be confirmed due to differences in rider behavior. In addition, the second e-bike was found to travel around three miles (approximately five km) further possibly due to the shift from a front-wheel to rear-wheel motor improving the force delivered to the pavement. Of significant interest is the finding that the spread in testing data between three dissimilar experienced riders appeared to diminish with the oddly designed first year e-bike. Hence, if a researcher wishes to explore unique aspects of bicycle design, they may want to deviate from standard bicycle design in order to normalize the respective skill of each rider. Finally, the added weight of an electric motor and battery pack may result in a difference in rider behavior and comfort; hence, one may wish to revisit the ergonomics of the e-bike while considering the electrified drivetrain.

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