HOW VEHICLE SPEED EFFECTS BATTERY VOLTAGE DEPLETION RATE

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ABSTRACT

From 2011 to 2021, the number of EVs has gone from about 22,000 to over 2 million [1]. As this number increases, understanding under what conditions vehicles work most efficiently becomes more important, and this experiment is meant to analyze those conditions using a dynamometer to drive an electric motorcycle at varying speeds. After running the bike under different constant set speeds, the conclusion can be made that the battery depletion rate is lower during faster speeds at a nonlinear rate as speed increases. The initial voltage drop due to acceleration is 8.8% more nonlinear than linear as speed increases and the rate of voltage decrease is 26.5% more nonlinear than linear showing us that the performance of the battery is ideal at higher speeds.

INTRODUCTION

From 2011 to 2021, the number of EVs on the road has gone from about 22,000 to over 2 million [1]. As this number goes up, EV data analysis is going to become more important as understanding the system will give users a better range of their vehicles, save energy, and make a more efficient product for EV manufacturers.

Manufacturers of EVs and users of EVs want to maximize their range for many reasons including charging their vehicle less frequently, saving time charging vehicles, and wasting money on unused energy. These improvements are beneficial for customers of EV companies as well as for the companies themselves, so there is a large incentive to tackle such an issue.

It's been shown in the past that even small improvements such as circuitry algorithms like machine learning can affect battery duration and extend the range of an EV by up to 7% [3,4]. Analysis of such battery drain can make a big difference to EV companies or individuals who want to extend their battery duration and fully understand what the ideal conditions for their system are.

One of the large questions within battery discharge analysis is how the battery depletion rate is affected by varying speeds that reflect how the vehicle is used by users. To answer this question within an EV system, this experiment will use an electric motorcycle to study the relationship between speed and the battery voltage depletion rate. The dynamometer is used as a testbed to allow data collection of the battery voltage from bike's motor controller. Starting from rest, the bike accelerates to reach a certain speed, holds that speed for five minutes, then slows back to a stop. The data collected from the battery will show that going faster will have lower battery depletion rate with respect to its speed suggesting that the battery runs better at higher speeds.

BACKGROUND SCIENCE, EQUIPMENT AND COMMON PRACTICE

ELECTRIC VEHICLE ELECTRICAL SYSTEMS

In most electric vehicles, there is a common organization of electrical components. The primary source of power on an EV is the battery, which has a Battery Management System with two output terminals to power the bike [13]. This battery then goes to the inverter for the bike motor. This inverter, also called a motor controller, does commutation on a motor (makes the motor spin) which is connected to whatever drivetrain is attached to it [13]. The output of the motor is controlled by a throttle or pedal on the vehicle which goes to the motor controller. This input throttle is usually in the form of a small voltage.

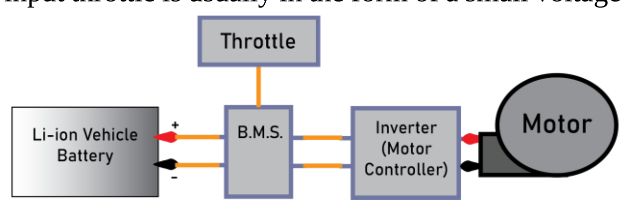


Figure 5: A schematic of a standard electric vehicle electrical system.

BATTERY STATE OF CHARGE AND DISCHARGE

In the analysis of a single battery cell (often an 18650 cell in the automotive industry), a battery cell can be modeled as a single power source, and a very small resistor (representing internal resistance) [5]. The cell is manufactured to a specific voltage (often 3.7V) and a specific capacity (ranging between 2600mAh to 3500mAh usually) [6]. In electric vehicles like the Tesla or other EVs, the primary car battery is a battery pack consisting of a combination of cells. These cells are put in series to reach a certain battery pack voltage and put in parallel to reach a needed capacity or meet a current requirement (figure 2).

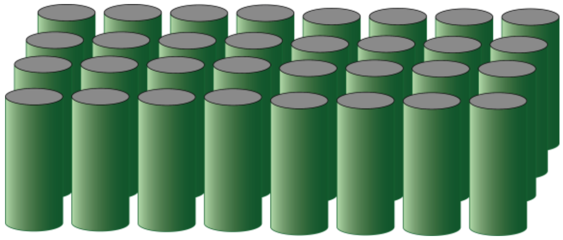


Figure 2: An interior view of a battery pack consisting of many battery cells grouped together. Wires or metal bars (not shown for viewing purposes) connect the cells in whatever orientation is needed.

A Battery Management System (BMS) is placed on the pack that controls and manages the battery pack. It ensures that the cells don't reach an exceeded temperature, don't discharge too much, and overall that the cells are all in good condition. As part of its design, it also reports the State of Charge of the battery.

A battery pack, just like a single battery cell, has what's called a State of Charge (SoC), which is a measure of the amount of battery capacity in the battery versus the nominal battery capacity [7]. When the state of charge is at 100%, the battery is completely full. When the value is 0% the battery is completely discharged. As the battery gets used and charge is taken from the battery into another form of power, the voltage goes down with time as seen in Figure 3.

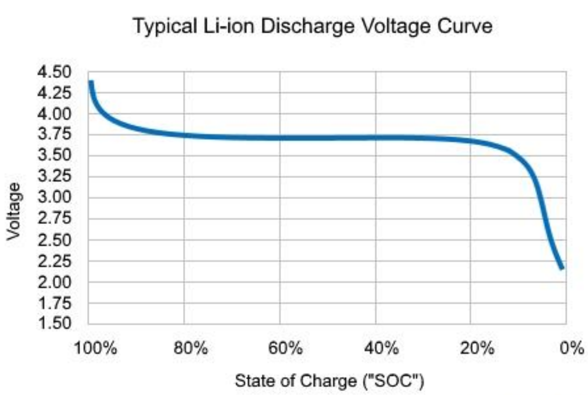


Figure 3: A graph of a typical Li-ion discharge voltage curve. Source: Silicon Lightworks [8]

This relationship is not linear, but, if the graph is focused on a small part of the curve at a time, we can treat it as a linear voltage drop which is what is done in this experiment.

DRIVE CYCLES

As an EV brakes, accelerates, turns, and does other navigation-related maneuvers, the discharge rate will change over time and is related to what's called a drive cycle. A drive cycle is a representation of the speed of a vehicle over a period showing its dynamic driving course. There has been extensive research done on driving cycles of electric vehicles with the goal of "studying the energy consumption and efficiency" to determine their "usability and performance in real-world conditions" [11]. This research has created growing interest in analysis like this and encouraged others to expand in this field.

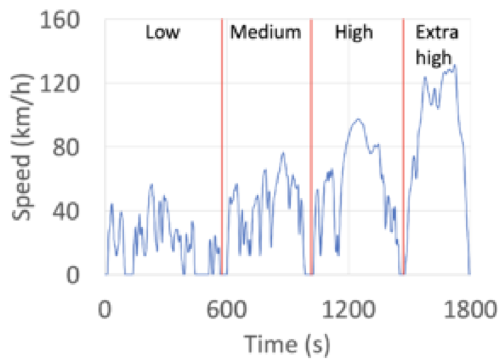


Figure 4: The Worldwide Harmonized Light Vehicle Test Procedure (WLTP) cycle for Class 3a vehicle is a test in which there are 4 sections, each representing a different speed for the vehicle to be run at [12].

EXPERIMENTAL DESIGN

DYNAMOMETER TESTBED

In the automotive industry, there are often situations where companies or developers of a vehicle will want to test their vehicle under certain drive cycles, compare different mechanical designs, or test their vehicle for any other reason on the road [14]. Testing vehicles on the road like this can be expensive, dangerous, and difficult, so instead, a "car sized treadmill" can be used instead to simulate what it's like to drive on the road while staying in place [14]. This machine is called a Dynamometer and can range in size from a tabletop machine to a warehouse sized treadmill.

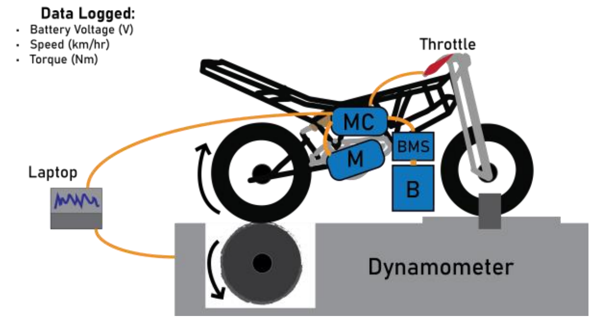
For this experiment, the EV in test is a custom hybrid-electric hydrogen powered motorcycle with the hydrogen fuel cell removed to make it only battery powered. To replicate driving on the road, a motorcycle dynamometer will be used. This machine functions by strapping the front tire and frame down while letting the back tire spin a large drum which is attached to a motor to allow data to be collected. The dynamometer logs data from these experiments in the form of torque, RPM, and power coming from the vehicle, but for this experiment, the dynamometer is simply a testbed to allow the bike to run on a simulated drive platform while data is collected from the motor controller. The motor controller outputs battery voltage, the wheel speed, the motor torque, and the temperature of the motor.

Table 1: Equipment and specifications

Measurements of Value	Model/Sensor Name	Specifications
Throttle input and Battery Voltage	SEVCON Gen4 Size-6 80V	Not provided.
n/a (testbed)	Dynojet 250i Motorcycle Chassis Dynamometer	**Timing Accuracy**: +/-1 Microsecond **Drum Speed Accuracy**: +/-1/100th MPH **RPM Accuracy**: +/-1/10th RPM
n/a	Domino 0-5kΩ Twist Grip Throttle	5k Ohm ± 10% **Nominal Voltage**: 12 VDC **Max Operating Voltage**: 40 VDC **Power Rating**: 0,25 W **Operating Temperature**: -20°/+85° **Protection Degree**: IP 54 **500,000 Cycles** **Linearity**: ± 2%

The bike begins in a resting position on the dynamometer until the logging has started and recording equipment has been confirmed on. Then, the throttle is rotated by hand until the bike reaches the desired speed of the trial. After reaching the desired speed, the throttle is maintained at that speed manually by hand by viewing the dynamometer readout of speed on the computer. After 5 minutes of running the bike, the throttle is released, and the bike slows to a halt. Even though the dynamometer is not logging any valuable data, it's critical to the experiment as it allows the speed of the bike to seen while running it.

a)



b)

Figure 6: 6.a shows a diagram of the motorcycle setup as well as the data collection process. M being the motor, MC being the motor controller, B being the battery, BMS being the battery management system, and all orange lines being connections. Image 6.b shows the motorcycle mounted onto the motorcycle dynamometer at MIT's Edgerton Center in the same orientation as the diagram.

THROTTLE-TORQUE-SPEED RELATIONSHIP

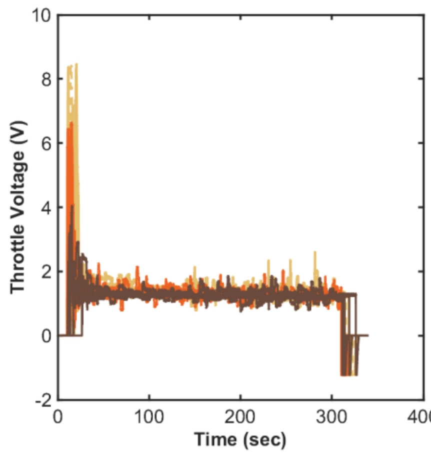
The motor controller outputs various data about a run while the raw input to the system is the user's throttle twist. When the throttle is rotated, it outputs a signal between 0 and 12V. Although the throttle voltage is the raw input to the system, the different conditions in the experiment are speed (km/hr), not throttle voltage. This is done intentionally to imitate what a drive cycle looks like (speed versus time). While the throttle voltage ranges from 0 to 12V, the motor controller maps that to torque output ranging from 0 to 110Nm or 0 to 660A in current demand. This dictates the speed of the motor which is what is used as the conditions for the experiment.

RESULTS AND DISCUSSION

DYNAMOMETER TESTBED

The conditions of the experiment are based on the speed, not throttle voltage of the bike. This means that instead of setting the throttle at a constant voltage, the speed of the bike is kept constant using the throttle to maintain this speed. As mentioned previously, the dynamometer is used as a testbed by displaying the speed and using that to manually adjust the throttle voltage. The relationship between these can be seen visually in figure 7.a and figure 7.b.

a)



b)

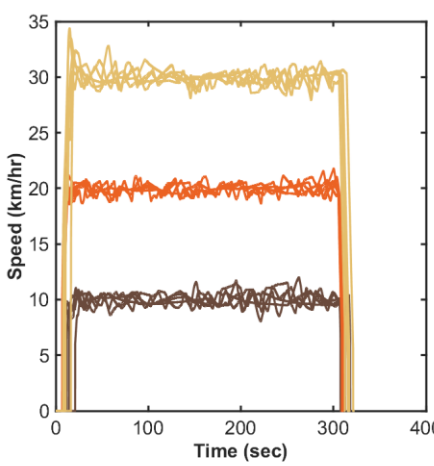


Figure 7: The raw input to the experiment is the throttle voltage as seen in 7.a, but the conditions used in the experiment are velocity of the bike as seen in 7.b with units of km/hr. Throttle voltage is not used in data, it is only meant to explain the system inputs. The nominal condition speeds are 10, 20, and 30 km/hr while the averaged speeds are, respectively, 10.21, 19.93, and 29.96 km/hr.

In figure 7.a, there is a spike towards the beginning of the data. This period of the experiment is the "Acceleration period" when the bike is reaching the speed desired seen on figure 7.b. The amplitude of the spike is dependent on the desired speed as higher acceleration demands more initial power. After the bike has reached the steady state speed, the amount of throttle voltage needed drops to less than 2V and maintains that voltage for the rest of the trial.

VOLTAGE DEPLETION ANALYSIS

For each trial, the motorcycle battery starts at 50V and decreases slowly as the battery is discharged. Shown in figure 8, the battery voltages across all 15 trials (3 speeds, 5 trials each) have a very linear relationship.

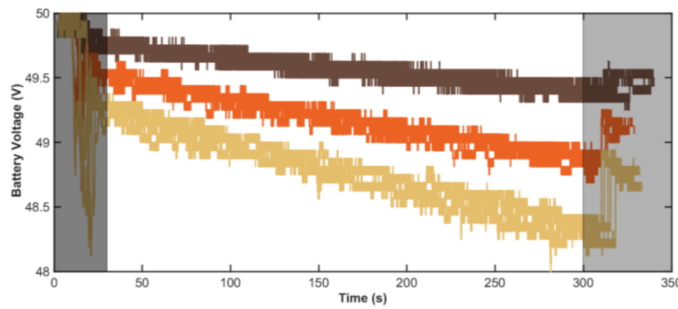


Figure 8: A plot of how voltage decreases throughout the experiment when the battery is being discharged. Note the shaded regions towards the beginning and end of the trials implying that this data is not being analyzed. The initial area is grayed out because it represents the acceleration period, and the ending area is grayed out because the regenerative braking on the bike regains energy.

During the last few seconds of the trials, the bike brakes and slows down. While doing so, it uses regenerative braking to regain some of the energy in the momentum of the wheels, thus gaining back some voltage as seen in the gray area and thus increasing its state of charge. During the first few seconds of the trials, there is a large fluctuation in voltage as the acceleration period of the trial drops the voltage almost instantaneously as seen in Figure 9.

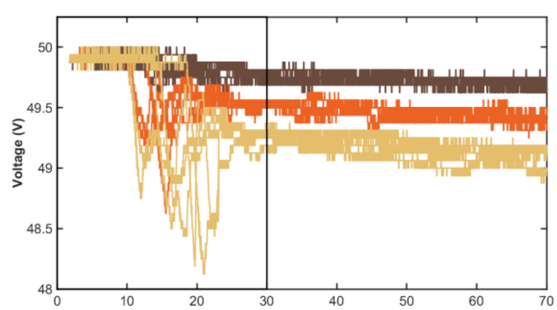


Figure 9: During the acceleration period of the trials, the battery experiences a drain which leads to a sharp drop in voltage before it reaches the steady state speed.

For the analysis of this experiment, these beginning, and end cases are not included in data analysis since they are not the primary focus.

The primary goal of the experiment is to understand the relationship between varying speed and battery voltage depletion rates. Through analyzing this relationship, we can determine what ideal speeds allow the bike to have the least battery drain. We can calculate the voltage depletion rate by finding the slopes of voltage drops for the three speeds from figure 8 and is shown in figure 10.

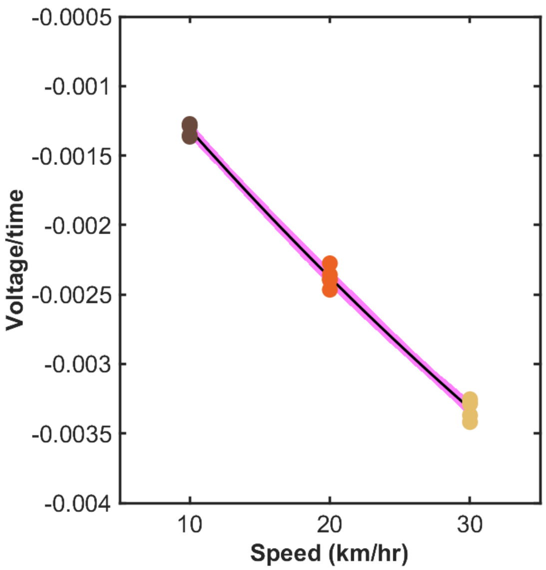


Figure 10: The slopes of voltage vs time show that there is a nonlinear relationship when speed increases. Note the lack of error bars due to the fractional uncertainty being 1%.

A second-degree polynomial is 26.5% better than a linear fit so is the preferred choice to analyze this relationship. This fit says that at higher speeds, our normalized battery voltage depletion rate goes down.

We can also graph the y-intercepts of the fitted voltage versus time graph and see that there is also a nonlinear relationship present. As speed increases, the intercepts of the curve are lower than a linear fit. This is because during the acceleration period, the higher speeds require more power at a nonlinear rate to reach their desired speed. Each trial started at nominally 50V (average of 49.8V) and concluded that the higher the speed, the larger the voltage drop in the initial acceleration period. The difference between the initial voltage and the point is how much voltage was dropped during acceleration contributing to a drop in the state of charge of the battery.

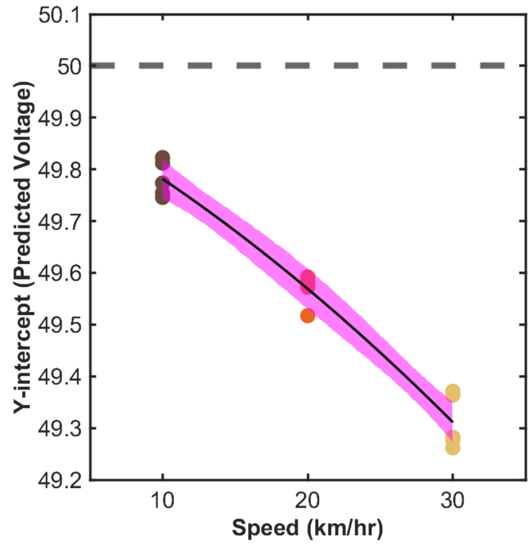


Figure 11: A nonlinear relationship between the y-intercepts of the voltage drop fits implying that each speed condition has a different nonlinear steady state starting point. The initial voltage drop line shows where the battery started, and the points indicate by how much the intercept was dropped due to acceleration.

After analyzing these slopes and intercept relationships, we can begin to see the trend that as speed increases, our battery voltage depletion rate goes down, but we also lose more energy in the initial acceleration. So, regarding battery usage, higher speeds are better for smaller discharge and worse for initial voltage drop.

Previous research on vehicle speed efficiency (often on combustion engines) conclude that engines often have a preferred speed that maximizes the efficiency of the engine which often ends up being quite high [15]. Previous research doing this kind of analysis has the exact same testing methodology as this experiment of running their system at various speeds and analyzing how fast their fuel runs out.

The conclusions made from this experiment are not an analysis of what speed the bike would run ideally at, but rather, what speed the cells of the battery would run best at. In parallel to past work done, my conclusions show that the battery runs best at higher discharge rates and speeds.

An important data analysis observation is noting that this experiment is an analysis of the cells, and not the bike. This means that it does not account for mechanical energy loss of the bike. Using a dynamometer as a testing platform makes logistics easy and repeatability ideal but eliminates some variables of the system such as drag from air resistance, system heat loss, friction, or environmental temperature. The results from this experiment conclude that higher speeds have lower rates of battery loss, but this is not fully representative of an on-road drive cycle due to missing mechanical factors of the bike.

RESULTS AND DISCUSSION

When analyzing the relationship between battery voltage depletion rate and speed, it's concluded that as speed increases, the voltage depletion rate decreases due to a nonlinear relationship implying that faster speeds are better for battery drain. We know this because a nonlinear fit is 26.5% better than a linear fit for this data. It's also concluded that while this is true, the acceleration period of the motorcycle drains the battery and causes a large initial voltage drop that increases as speed increases. Knowing these two results, we can conclude that going faster is better for battery drain in terms of how quickly the battery will discharge. We also conclude that due to the acceleration period of the bike, the battery voltage will discharge more initially due to the nonlinear power draw as speed increases.

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