MAINTAINABILITY ANALYSIS OF A BATTERY FOR A PERSONAL TRANSPORTER

by

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10163

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Mechanical Engineering Programme
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(SALMAN BIN HASAMUDDIN)

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ABSTRACT

Personal transporter (PT) started to catch world's attention by the introduction of Segway in 2001, which has been promoted as a major invention that could change the way human move from one point to another. Although it generally provides a new dimension of cleaner technology and gives a clever solution to traffic congestion in urban areas, the cost in using a personal transporter is very much higher when compared to the cost of using other vehicles, which significantly affect its popularity. The ability of a PT to be maintained as it is originally intended, or maintainability, has a significant influence on the cost incurred in using the PT. A major component of the PT that requires high maintainability is the battery. The objective of this report is to conduct an analysis of the maintainability of the PT's battery and thus provide guidance to the PT designer on the best battery to be used for specific applications. To meet the objective, the author has done a research and also gathers all the required data in order to do a simulation for the battery, based on data available. The analysis on the PT will be based on a reference PT, and the result achieved will be used to compare the performance of the batteries stated. It is found that Nickel Metal Hydride (NiMH) battery is the best battery for a PT, based on the data gathered from this project. This report will help PT designer to choose the best battery for the PT itself.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND STUDY

Cities and traffic have developed hand-in-hand since the earliest human settlements. The same forces that draw inhabitants to congregate in large urban areas also lead to sometimes intolerable levels of traffic congestion on urban streets and thoroughfares. This problem seems to add one another big problem to our mother earth – pollution. As the technology moves forwards, these problems seem worsen. Car manufacturer is producing more affordable car to meet the demands of the low-income earner hence adding more problems into the picture.

In order to overcome the problem, many ideas have been proposed. Some of it stressed the importance of altering the road infrastructure and working on urban planning and design. Among the efforts taken by car manufacturers and inventors are the invention of hybrid cars and the personal transporter, which have very good potential to solve or at least to reduce the problem stated.

Since early in 20^{th} century, the idea of having a personal transporter as an effective way to move from one point to another and also an environmental-friendly vehicle, started to increase. Ever since, there are several type of personal transporter have been introduced to the public, but only one that seems to be an eye-catching, which was Segway PT, due to its unique feature to balance itself with only two wheels.

But the drawback of the introduction of Segway to the public is its reception due to the price. To make it commercially available for the public, especially for a citizen from developing country such as Malaysia, the price tag of a personal transporter, such as Segway, need to be reviewed. For example, the price of Segway PT in Malaysia ranges from RM32000 to RM35000. Whenever the battery needs to be replaced, it costs about RM12000, because each unit of Segway requires two pack of Lithium Ion battery, which costs RM6000 per pack.[14] The maintenance cost alone is enough for one to buy a second-hand car. The author will try to see this problem from maintainability factor point of view, as this is one of a major factor that tends to be singled out during a construction period of a new product.

In this report, the author will focus on the idea to maximize the usage of personal transporter by doing a maintainability analysis of a battery for a personal transporter, as it is one of major factor that determine the maintenance cost and the life of the personal transporter itself.

1.2 PROBLEM STATEMENT

The high price of the personal transporter that exist in the market nowadays make the potential buyer to think twice before they put their money to buy it. As mentioned earlier, the battery price for the Segway PT is equivalent to a typical second-hand car in Malaysia. In order to make the personal transporter affordable for citizens, especially in the developing countries where the potential market is huge, the personal transporter needs to be redesigned to make it simple and low in cost, moreover easy and cheap to maintain. Due to this problem, the previous projects have come out with a simpler design and drive system which aims to produce a low cost personal transporter. As a continuation from previous projects, this report will conduct a maintainability analysis of a battery for a personal transporter, as it is one of the main factors that influence the cost of using a personal transporter.

1.3 OBJECTIVE AND SCOPE OF STUDY

1.3.1. Objective

The objective of this project is to conduct an analysis of the maintainability of the battery for use in a personal transporter. There are several factors that proved to be an important factor in choosing the battery itself, and it will be covered in this report. By the end of the project, a specification of the battery for use by a reference PT will be proposed based on detailed study of its maintainability.

1.3.2. Scope

In this report, the author will only cover the analysis on the battery used for a personal transporter, as nowadays there a few types of battery that suitable for electric vehicle like personal transporter. The analysis to be done will be on the battery to be installed on a particular PT design which is still under development. The key specification of the reference PT[1] is:

i. Operating using a DC Motor, 24V, 500W, maximum current of 27.4 Amp, 2500 RPM
ii. Total weight (Rider + Personal Transporter) = 165kg
iii. Maximum speed of 30km/h
iv. Time travel of approximately 30 minutes in maximum speed
v. Distance covered of approximately 10km

1.3.3. Significance of Study

This project will provide valuable information for PT designer, as they might not have resources to do a thorough study on the maintainability aspect of the battery. Battery selection proved to be one of the main factors that decide the cost of a personal transporter and its durability. Since personal transporter are being used for a short distance travel and for use in urban areas only, it is important to have a battery that withstand frequent stop and go operation and can be charged in only few hours.

CHAPTER 2
LITERATURE REVIEW

2.1 OVERVIEW

As mentioned earlier, the problems of pollution and traffic congestion have become a norm to the people at the urban areas. These problems worsen as time passed by, with the increasing numbers of vehicle on road. But in early 2000 the world was introduced to the advanced technology of transportation, such as hybrid cars and personal transporter, which seems like an ideal solution to the problem stated.

Segway Inc. is the company that introduced the personal transporter to the public in December 2001. The inventor, Dean Kamen reportedly said that the Segway PT *"will be to the car what the car was to the horse and buggy"* while venture capitalist John Doerr predicted the company would be the fastest ever to reach USD1billion in sales.[2] The Segway PT (Figure 2.1) is a two-wheeled, self-balancing personal transportation system. It applied the technology of dynamic stabilization

Figure 2.1: Segway Personal Transporter

But the reality is; only about 30,000 Segways were sold from 2001 to 2007.[3] In fact, most buyers are corporate and government bodies, such as police and private security forces.[4] It is due to its mobility and make police officer stands higher that local citizens, enhancing their range of monitoring the public.

Why is this happened? What happened to all the hype on its early launch? Based from article by David Usborne in "*Whatever Happened to the Segway*" (2007), he stated that the relatively high cost of a single unit and the reluctance of some countries and municipalities to allow them on public roads contributes to this situation. It seems that the exorbitant price of the Segway PT has become the major barrier to the people, other than the local jurisdiction factor.

Since Segway was unveiled to public, many other companies continuously tried to build a better personal transporter, namely Honda and Toyota, with many other inventors. Many of them applied the same concept; using greener technology but varies on the design. Honda U3-X (Figure 2.2), for example, is a self-righting unicycle. While Toyota Winglet (Figure 2.3) adapts the similar concept of two wheel self-balancing personal transporter, but differs on the design, weight and speed. The only similarities of the other personal transporters – it offers a lower price compared to Segway.

Figure 2.2: Honda U3-X

Figure 2.3: Toyota Winglet

2.2 MAINTAINABILITY ANALYSIS

Maintainability is the inherent characteristic of a design or installation that determines the ease, economy, safety, and accuracy with which maintenance actions can be performed.[5] It also implies the ability to restore a product to service or to perform preventive maintenance within required limits.

The principles of maintainability are applicable to any type of system or product, including transportation system. An easily maintainable system/product is less costly in terms of both its initial production and its follow-on sustaining maintenance and support. If an equipment item is functionally packaged with interchangeable components, the proper accessibility provisions, effective built-in test and condition monitoring capabilities, and so on, this should lead forward the simplification of assembly and test requirements in the manufacture of this item.

During the consumer use phase, a highly maintainable system can be repaired rapidly, with a minimum expenditure of supporting resources, without causing detrimental effects on the environment, and without inducing additional faults in the process. Again, a reduction in total cost is realized.

From the definition given, it is clear that maintainability is an important aspect during the design process. Taking Segway PT as an example, the research and development of Segway PT cost at about USD100 million[4], therefore the company have to put a high price on each item produced to cover the initial cost. It is said that now Segway Inc. has started to outsource the production to China to reduce the cost so the selling price can be lowered [5]. In order to come out with a cheaper solution than Segway PT, the maintainability should be one of the aspects that need extra attention. It is important to make sure that majority of people can afford to have one. To achieve that, the technology used in designing a personal transporter should no too advance, so it will be cheap and easy to maintain.

Maintenance includes all actions necessary for retaining a system; or restoring it to a desired operational state. There are three types of maintenance that are relevant prior to the specification that the author is working into, which are:

1. Corrective maintenance.

   Includes all unscheduled maintenance actions performed, as a result of system/product failure, to restore the system to a specified condition. (Tires, battery)

2. Preventive maintenance

   Includes all scheduled maintenance actions performed to retain a system or product in a specified operational condition. It covers periodic inspection, condition monitoring, critical-item replacements (prior to failure), periodic calibration and the like. Servicing requirement such as fueling and lubrication may be included under scheduled maintenance. (Brake fluid)

3. Predictive maintenance

   Often refers to a condition-monitoring preventive-maintenance program where direct monitoring methods are used to determine the exact status of equipment, for predicting possible degradation, and for the purposes of highlighting areas where maintenance is desired. (Brake pad, tires)

2.3 BATTERY

Battery plays a major part in constructing the personal transporter. It is the power sources that drive the motor and all electronic appliances on, hence it need to supply enough power to drive the personal transporter. Based on many hybrid vehicles and electric vehicles, the most common choice is nickel-metal hydride battery. It is a secondary battery (rechargeable battery) and has a higher reliability among other secondary battery such as lead-acid battery and nickel-cadmium battery. When used properly, nickel-metal hydride batteries can have exceptionally long lives, as has been demonstrated in their use in Toyota hybrid cars (RAV4EV) that still operate well after 100,000 miles (160,000 km) and over a decade of service [6].

2.3.1 Battery Basics and Terminologies

1. Cell and battery voltages

All electric cells have nominal voltages which gives the approximate voltage when the cell is delivering electrical power. The cells can be connected in series to give the overall voltage required. Traction batteries for electric vehicles are usually specified as 6V or 12V, and these units are in turn connected in series to produce the voltage required. This voltage will, in practice, change. When a current is given out, the voltage will fall; when the battery is being charged, the voltage will rise.

This is best expressed in terms of 'internal resistance'. The battery is represented as having a fixed voltage E, but the voltage at the terminals is a different voltage V, because of the voltage across the internal resistance R. Assuming that a current I is flowing out of the battery, then by circuit theory we can say that:

$$V = E - IR$$

Note that if the current I is zero, the terminal voltage is equal to E, and so E is often referred to as the open circuit voltage. If the battery is being charged, then clearly the voltage will increase by IR. In electric vehicle batteries the internal resistance should clearly be as low as possible.

Generally, the equation given above gives a fairly good prediction of the 'in use' battery voltage. However, the open circuit voltage E is not in fact constant. The voltage is also affected by the 'state of charge'. And other factors such as temperature.

2. Charge (Amp-hour) capacity

The electric charge that a battery can supply is clearly a most crucial parameter. The term Amp-hour is used, which means one Amp flowing for one hour. The capacity of a battery might be, for example, 10 Amp-hour. This means it can provide 1 Amp for 10 hours or 2 Amp for 5 hours or in theory 10 Amp for 1 hour. However, in practice, it does not work out like this for most batteries.

It is usually the case the case that while a battery may be able to provide 1 Amp for 10 hours, if 10 Amp are drawn from it, it will last less than one hour. The capacity of the large batteries used in electric vehicle (traction batteries) is usually quoted for a 5 hour discharge.

The capacity is affected if the charged is removed more quickly, or more slowly. Figure 2.4 shows a diagram for a nominally 100 Amp-hour battery. Notice that if the charge is removed in one hour, the capacity falls very considerably to about 70 Amp-hours. On the other hand, if the current is drawn off more slowly, for example 20 hours, the capacity rises to about 110 Amp-hour.

This change in capacity occurs because of the unwanted side reactions inside the cell. The effect is most noticeable in the lead acid battery, but occurs in all types. It is very important to be able to accurately predict the effects of this phenomenon.

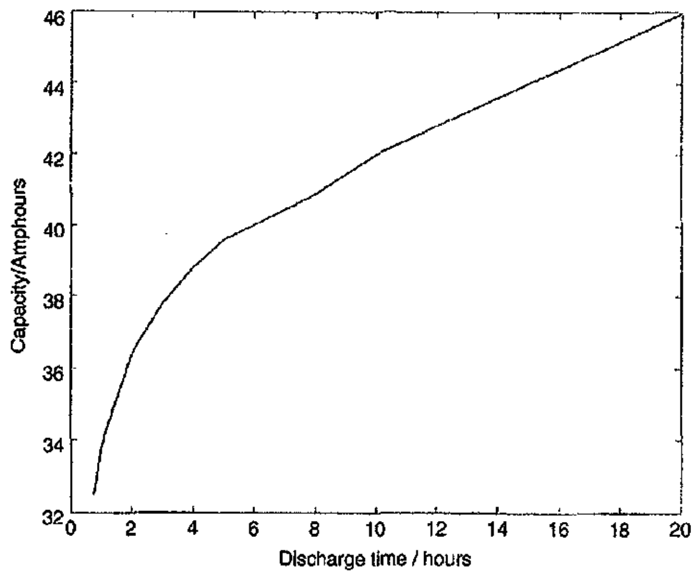

Figure 2.4: Change in battery capacity with discharge time (42 Amp-hour battery, based on measurement from lead acid traction battery.) [7]

3. Energy stored

The purpose of a battery is to store energy. The energy stored in a battery depends on its voltage, and the charge stored. The SI unit is Joule, but as this is a small unit, we use the Watt-hour instead. This is the energy equivalent of working at a power of 1 Watt for 1 hour. The Watt-hour is equivalent to 3600 Joules. The Watt-hour is compatible with our use of the Amp-hour for charge, as it yields the simple formula:

Energy in Watt-hours = Voltage x Amp-hours or Energy = V x C

This equation must be used with caution. Both the battery voltage V, and even more so the Amp-hour capacity C, very considerably depending on how the battery is used. Both are reduced if the current is increased and the battery is drained quickly. The stored energy is thus a rather variable quantity, and reduces if the energy is released quickly. It is usually quoted in line with the Amp-hour rate, i.e. if the charge capacity is given for a five hour discharge, then the energy should logically be given for this discharge rate.

4. Specific energy

Specific energy is the amount of electrical energy stored for every kilogram of battery mass. It has units of $Wh.kg^{-1}$. Once the energy capacity of the battery needed in a vehicle is known (Wh) it can be divided by specific energy ($Wh.kg^{-1}$) to give a first approximation of the battery mass. Specific energies quoted can be no more than a guide, because as we have seen, the energy stored in a battery varies considerably with factors such as temperature and discharge rate.

5. Energy density

Energy density is the amount of electrical energy stored per cubic meter of battery volume. It normally has units of $Wh.m^{-3}$. It is also an important parameter as the energy capacity of the battery (Wh) can be divided by the battery's energy density ($Wh.m^{-3}$) to show the volume of battery required. Alternatively if a known volume is available for batteries, the volume (m^3) can be multiplied by the batteries energy density ($Wh.m^{-3}$) to give a first approximation of how much electrical energy can be made available. The battery volume may well have a considerable impact on vehicle design. As with specific energy, the energy density is a nominal figure.

6. Specific power

Specific power is the amount of power obtained per kilogram of battery. It is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself. Although batteries do have a maximum power, it is not sensible to operate them at anywhere near this maximum power for more than a few seconds, as they will not last long and would operate very inefficiently.

The normal unit for specific power is $W.kg^{-1}$. Some batteries have a very good specific energy, but have low specific power, which means they store a lot of energy, but can only give it out slowly. In electric vehicle terms, they can drive the vehicle very slowly over a long distance. High specific power normally results in lower specific energy for any particular type of battery.

The difference in change of specific power with specific energy for different battery types is very important, and it is helpful to be able to compare them. This is often done using a graph of specific power against specific energy, which is known as a Ragone plot.[8] Logarithmic scales are used, as the power drawn from a battery can vary greatly in different applications. A Ragone plot for a good quality lead acid traction battery, and a similar NiCd battery, is shown in Figure 2.5.

It can be seen that, for both batteries, as the specific power increases the specific energy is reduced. In the power range of 1 to 100 $W.kg^{-1}$ the NiCd battery shows slightly less change. However, above about 100 $W.kg^{-1}$ the NiCd battery falls much faster than the lead acid.

Ragone plots are used to compare energy sources of all types. In this case we should conclude that, ignoring other factors such as cost, the NiCd battery performs better if power densities of less than 100 $W.kg^{-1}$ are required. However, at higher values, up to 250 $W.kg^{-1}$ or more, then the lead acid begins to become more attractive. The Ragone plot shows that we always cannot determine the specific power of a battery accurately.

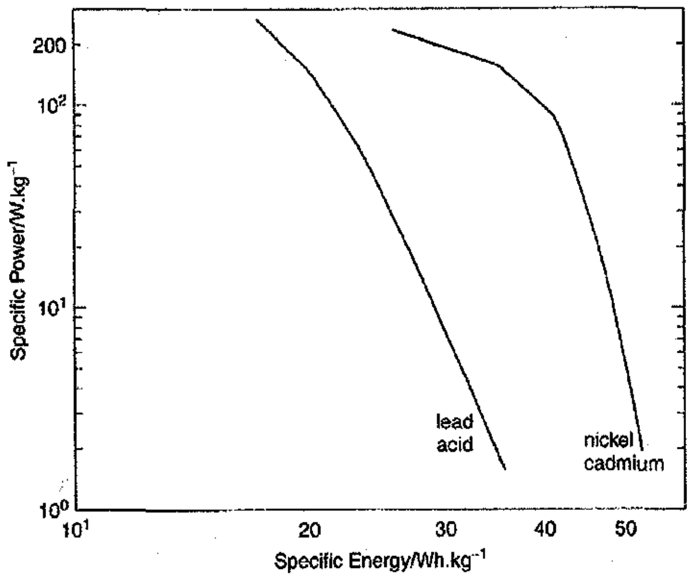

Figure 2.5: A Ragone plot – specific power versus specific energy graph – for typical lead acid and nickel cadmium traction batteries.[7]

7. Charge(Amp-hour) efficiency

In an ideal world a battery would return the entire charge put into it, in which case the amp-hour efficiency is 100%. However, no battery does; its charging efficiency is less than 100%. The precise value will vary with different types of battery, temperature and rate of charge. It will also vary with the state of charge. For example, when going from 20% to 80% charged the efficiency will usually be very close to 100%, but as the last 20% of the charge is put in the efficiency falls off greatly.

8. Energy efficiency

It is defined as the ratio of electrical energy supplied by a battery to the amount of electrical energy required to return it to the state before discharge. A strong argument for using electric vehicles is based on its efficient use of energy, with resulting reduction of overall emissions; hence high energy efficiency is desirable. It should be clear from what has been said in the preceding section that the energy efficiency will vary greatly with how a battery is used. If the battery is charged and discharged rapidly, for example, energy efficiency decreases considerably. However it does act as a guide for comparing batteries, in much the same way as fuel consumption does for cars.

9. Self-discharge rates

Most batteries discharge when left unused, and this known as self-discharge. This is important as it means some batteries cannot be left for long periods without recharging. The reasons for this self-discharge will be explained later. The rate varies with battery type, and with other factors such as temperature; higher temperatures greatly increase self-discharge.

10. Battery geometry

Cells come in many shapes: round, rectangular, prismatic or hexagonal. They are normally packaged into rectangular blocks. Some batteries can be supplied with a fixed geometry only. Some can be supplied with a wide variation of heights, widths and lengths. This helps the designer in designing the vehicle.

11. Battery temperature, heating and cooling needs

Although most batteries run at ambient temperature, some run at high temperatures and need heating to start with and then cooling when in use. In others, battery performance drops off at low temperatures, which is undesirable, but this problem could be overcome by heating the battery. When choosing a battery the designer needs to be aware of battery temperature, heating and cooling needs, and has to take these into consideration during the vehicle design process.

12. Battery life and number of deep cycles

Most rechargeable batteries will only undergo a few hundred deep cycles to 20% of the battery charge. However, the exact number depends on the battery type, and also the details of the battery design, and on how the battery is used. This is a very important figure in a battery specification, as it reflects in the lifetime of the battery, which in turn reflects in electric vehicle running costs.

CHAPTER 3
RECHARGEABLE BATTERY

3.1 LEAD ACID BATTERY

3.1.1 Lead Acid Battery Basic

Lead acid battery is the best known and most widely used battery for electric vehicles. It is widely used in internal combustion engine vehicles and as are well known. However, for electric vehicles, more robust lead acid batteries that withstand deep cycling and use a gel rather than a liquid electrolyte are used. These batteries are more expensive to produce.

In lead acid cells the negative plates have a spongy lead as their active material, whilst the positive plates have an active material of lead dioxide. These plates are immersed in an electrolyte of dilute sulphuric acid. The sulphuric acid combines with the lead and the lead oxide to produce lead sulphate and water, electrical energy being released during the process. The overall reaction is:

$$Pb + PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O$$

The lead acid battery is the most commonly used rechargeable battery in anything but the smallest of systems. The main reason for this are the main constituents (lead, sulphuric acid, a plastic container) are not expensive, that it performs reliably, and that it has a comparatively high voltage of about 2V per cell.

One of the most notable features of the lead acid battery is its extremely low internal resistance. This means that the fall in voltage as current is drawn is remarkably small, probably smaller than for any of the candidate vehicle batteries. A good estimate of the internal resistance of a lead battery is thus:

$$R = \text{No of cells} \times 0.022/C_{10} \text{ Ohms}$$

The number of cells is the nominal battery voltage divided by 2.0, six in the case of 12V battery. C_{10} is the Amp-hour capacity at the 10 hour rate.

3.1.2 Special characteristics of lead acid batteries

Unfortunately, the lead and lead dioxide are not stable in sulphuric acid, and decompose very slowly, which results in self-discharge of the battery. The lead and lead dioxide are not stable in sulphuric acid, and decompose with the reactions:

At positive electrode: $2PbO_2 + 2H_2SO_4 \longrightarrow 2PbSO_4 + 2H_2O + O_2$

At negative electrode: $Pb + H_2SO_4 \longrightarrow PbSO_4 + H_2$

This results in the self-discharge of the battery. The rate at which these reactions occur depends on the temperature of the cell: faster if hotter. It also depends on other factors, such as purity of the components (hence quality) and the precise alloys used to make up the electrode supports.

These unwanted reactions, that also produce hydrogen and oxygen gas, also occur while the battery is discharging. In fact they occur faster if the battery discharge faster, due to lower voltage, higher temperature, and higher electrode activity. This results in the 'lost charge' effect that occurs when a battery is discharged more quickly. These discharge reactions will not occur at exactly at the same rate in all the cells, and thus some cells will become more discharged than others.

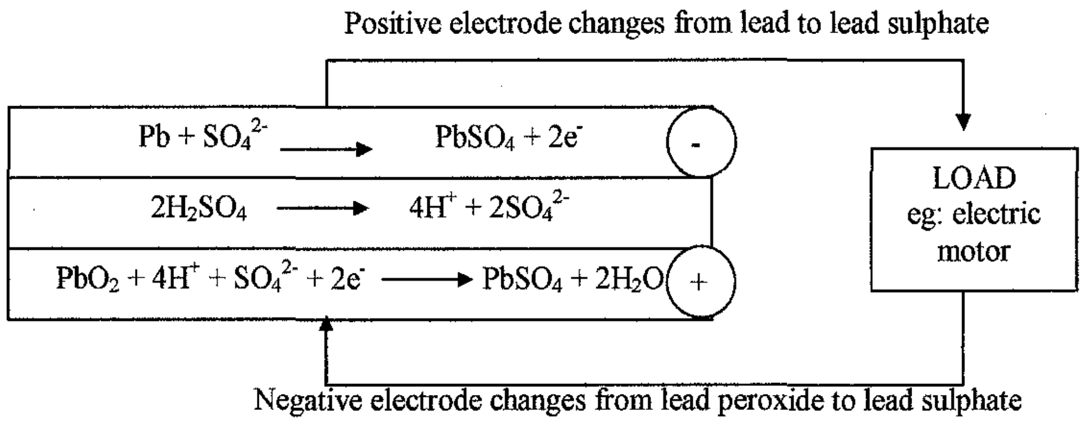

Figure 3.1: Reaction during the discharge of the lead acid battery. Note that the electrolyte loses sulphuric acid and gains water.

3.1.3 Lead Acid Battery Charging

Charging a lead acid battery is a complex procedure and if carried out incorrectly, it can quickly ruin the battery and decrease its life. The charging must not be carried out at too high voltage, or resulting in water loss. Charging and discharging reactions involve changing the concentration of the electrolyte of the cells. The change in concentration of the reactants means that there is a small change in the voltage produced by the cell as it discharges.

A notable feature of the overcharge reaction and the self-discharge reactions, is that water is lost and turned into hydrogen and oxygen. In older battery designs this gas was vented out and lost, and the electrolyte had to be topped up from time to time with water. In modern sealed batteries this is not necessary even possible. The gases are trapped in the battery, and allowed to recombine (which happens at a reasonable rate spontaneously) to reform as water. Clearly there is a limit to the rate at which this can happen, and steps must be taken to make sure gas is not produced too rapidly.

There are different views on the best way of charging a lead acid battery, but it is always important that once a battery is chosen, the best way is to follow the charging recommendation by the manufacturers. The most commonly used technique for lead acid batteries is called multiple step charging. In this method the battery is charged until the cell voltage is raised to a predetermined level. The current is then switched off and the cell voltage is allowed to decay to another predetermined level and the current is then switched on again. A problem is that the predetermined voltages may vary depending on the battery type, but also on the temperature. But it seems not a big problem as there are plenty of good quality chargers available on the market nowadays from a wide range of suppliers.

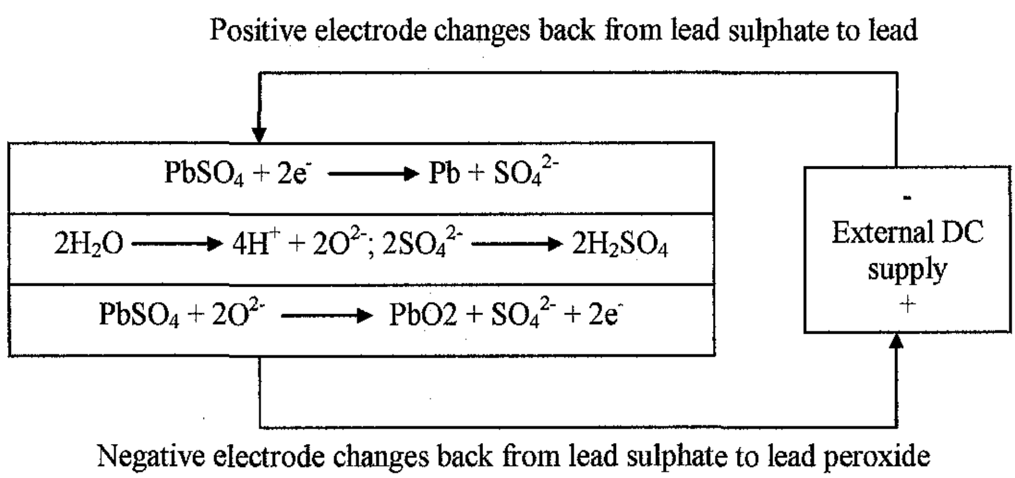

Figure 3.2: Reaction during the charging of the lead acid battery.
Note that the electrolyte sulphuric to lead peroxide.

3.1.4 Maintenance

Traditional acid batteries require topping up with distilled water from time to time, but modern vehicle lead acid batteries are sealed to prevent electrode loss. In addition the electrode is gel, rather than liquid. This means that maintenance of the electrolyte is no longer needed. However, the sealing of the battery is not total; there is a valve which releases gas at a certain pressure, and if this happens the water loss will be permanent and irreplaceable. This feature is a safety requirement, and leads to the name valve regulated lead acid battery (VRLA) for this modern type of battery. Such a build up of gas will result if the reactions, which occur on overcharge, proceed too fast. This will happen if the charging voltage is too high. This must not be allowed to happen, or the battery will be damaged. On the positive side, it means that such batteries are essentially maintenance-free.

This does not means that the batteries will last forever. Even there is no water loss, lead acid batteries are subject to many effects that shorten their life. One of the most well known is the process called sulphation. This occurs if the battery is left for a long period (i.e two weeks or more) in a discharged state. The lead sulphate on the electrodes forms into larger crystals, which are harder to convert back into lead or lead dioxide, and which form an insulating layer over the surface of the electrodes. By slowly recharging the battery this can sometimes be partially reversed, but often it cannot.

Making sure the battery is always kept in a good state of charge can prevent the problem of sulphation. Some of the problem cannot be prevented no matter how much care is taken, such as battery corrosion. Within the electrodes of the battery corrosion reactions take place, which increase the electrical resistance of the contacts between the active materials that the electrode supports. The active material will gradually form into larger and larger crystals, which will reduce the surface area, reducing both the capacity of the battery and slowing down the rate of reaction. The effects of vibration and the continual change of size of the active materials during the charge/discharge cycles will gradually dislodge them. As a result they will not make such good electrical contact with their support, and some will even fall off and become completely detached.

3.1.5 Summary of lead acid batteries

Lead acid batteries are well established commercially with good backup from industry. They are the cheapest rechargeable batteries per kilowatt-hour of charge, and will remain so for the foreseeable future. The drawback of lead acid battery is its low specific energy. Lead acid will undoubtedly continue for some considerable time to be widely used for short-range vehicles, such as personal transporter.

3.2 NICKEL CADMIUM BATTERY

3.2.1 Nickel Cadmium Battery Basic

Nickel cadmium battery was considered to be one of the main competitors to the lead acid battery for use in electric vehicles and these batteries have nearly twice the specific energy of lead acid batteries.

The NiCd battery uses nickel oxyhydroxide for the positive electrode and metallic cadmium for the negative electrode. Electric energy is obtained from the following reaction:

$$Cd + 2Ni\,O\,OH + 2H2O \longleftrightarrow Cd(OH)2 + 2Ni(OH)2$$

Nickel cadmium batteries have been widely used in many appliances, including use in electric vehicles. The NiCd battery has advantages of high specific power, a long life cycle (up to 2500 cycles), a wide range of operating temperatures from -40°C to +80°C, a low self discharge and good long term storage. This is because the battery is a very stable system, with equivalent reactions to the self discharge of the lead acid battery only taking place very slowly. The NiCd batteries can be purchased in a range of sizes and shapes, though they are not easy to obtain in the larger size required for electric vehicles, their main market being portable tools and electronic equipment. They are also very robust both mechanically and electrically and can be recharged within an hour and up to 60% capacity in 20 minutes.

On the negative side, the operating voltage of each cell is only about 1.2V, so 10 cells are needed in each nominally 12V battery, compared to 6 cells for lead acid. This partly explains the higher cost of this type of battery. A further problem is that the cost of cadmium is several times that of lead, and that this is not likely to change. Cadmium is also environmentally harmful and carcinogenic. Also, NiCd batteries may suffer from a "memory effect" if they are discharged and recharged to the same state of charge hundreds of times. The apparent symptom is that the battery "remembers" the point in its charge cycle where recharging began and during subsequent use suffers a sudden drop in voltage at that point, as if the battery had been discharged. The capacity of the battery is not actually reduced substantially. Some electronics designed to be powered by NiCds are able to withstand this reduced voltage long enough for the voltage to return to normal. However, if the device is unable to operate through this period of decreased voltage, it will be unable to get enough energy out of the battery, and for all practical purposes, the battery appears "dead" earlier than normal.

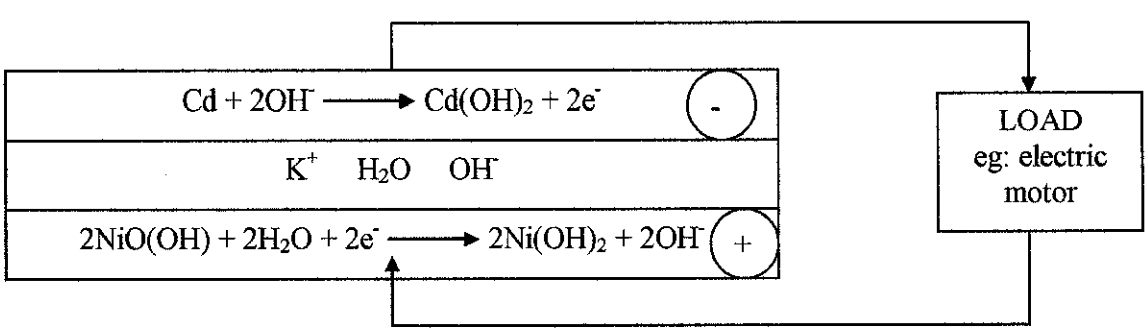

Figure 3.3: Reactions during the discharge of the NiCd battery. Note that the electrolyte loses water, becoming more concentrated. The reactions are reversed during charge.

The high cost of NiCd batteries, typically 3 times that of lead acid; is offset to an extent by its longer cycle life. Its charge efficiency decreases rapidly over 35°C but this is unlikely to affect its use in electric vehicle. It has been used successfully in cars such as electric version of Peugeot 106, the Citroen AX and the Renault Clio, as well as Ford Th!nk.

The internal resistance of the nickel cadmium battery is very low, but it is not as low as for the lead acid battery. This results in a somewhat lower maximum economic specific power. The empirical formula for the internal resistance of a nickel cadmium battery is:

$$R = \text{No of cells} \times 0.06/C_3 \text{ Ohms}$$

Comparing this equation with equation of lead acid internal resistance, it can be seen that there is a higher number (0.06 instead of 0.022).

3.2.2 Maintenance

Nickel Cadmium batteries by nature need to be "deep cycled" (fully discharged) before being placed back in their charger. Deep cycling NiCd battery maintains its maximum performance. New NiCd, un-initialized batteries can be stored in a cool dry place without significant cycle life loss for up to 2 years. Failure to "deep cycle" NiCd batteries will result in "memory effect". Memory effect will reduce the amount of energy that can be draw out each time the battery is used. It will also shorten the battery's overall cycle life. Only charge the battery when it needs charging, or it will significantly reduce battery life. NiCd batteries can be stored up to two years without suffering from significant cycle loss. If the battery is to be stored for an extended period, it is recommended to fully discharging and recharging the batteries every 90 days.

3.2.3 NiCd Battery Charging

As with lead acid batteries, NiCd batteries need to be properly charged. However, because NiCd cells are less prone to self discharge. Normally the battery is charged at a constant current until its cell voltages reach a predetermined level, at which point the current is switched off. At this point the cell voltages decay to a lower predetermined voltage and the current is switched back on. This process is continued until the battery is recharged. A good proportion of the charge can be normally be replaced within 1 hour, but the cell must be run at a fairly low current, with most of the cells being overcharged, for a longer time. Alternatively the battery can be recharged at a lower, constant current; this is a simpler system, but takes longer.

A clever feature of the NiCd battery is the way that it copes with overcharging. The cell is made so that there is surplus of cadmium hydroxide in the negative electrode. This means that the positive electrode will always be fully charged first. A continuation of the charging current results in the generation of oxygen at the positive electrode via the reaction:

$$4OH^- \longrightarrow 2H_2O + O_2 + 4e^-$$

The resulting free oxygen diffuses to the negative electrode, where it reacts with the cadmium, producing cadmium hydroxide, using the water produced by reaction stated above.

$$O_2 + 2Cd + 2H_2O \longrightarrow 2Cd(OH)_2$$

As well this reaction, the normal charging reaction will be taking place at this electrode, using the electrodes produced by reaction stated above.

$$2Cd(OH)_2 + 4e^- \longrightarrow 2Cd + 4OH^-$$

Comparing these two reactions, the rate of production of cadmium hydroxide is exactly equal to its rate of conversion back to cadmium, which makes a perfectly sustainable system, with no net of any material from the battery. The sum total of all three equation stated before is no effect. This overcharging situation can thus continue indefinitely. For most NiCd batteries their size and design allows this to continue forever at the C/10 rate, i.e. at 10A for 100 Amp-hour battery. Of course this overcharging current represents a waste of energy, but it is not doing any harm to the battery, and is necessary in some cells while charging the battery in the final phase to equalize all the cells to fully charged.

3.3 NICKEL METAL HYDRIDE BATTERY

3.3.1 Nickel Metal Hydride Battery Basic

Nickel metal hydride (NiMH) battery was introduced commercially in the last decade of the 20^{th} century. It has a similar performance to the NiCd battery, the main difference being that in the NiMH battery the negative electron uses hydrogen, absorbed in a metal hydride, which makes it free from cadmium, a considerable advantage.

An interesting feature of this battery type is that the negative electrode behaves exactly like a fuel cell.

The reaction at the positive electrode is the same as for the nickel cadmium cell; the nickel oxyhydroxide becomes nickel hydroxide during discharge, at the negative electrode hydrogen is released from the metal to which it was temporarily attached, and reacts, producing water and electrons.

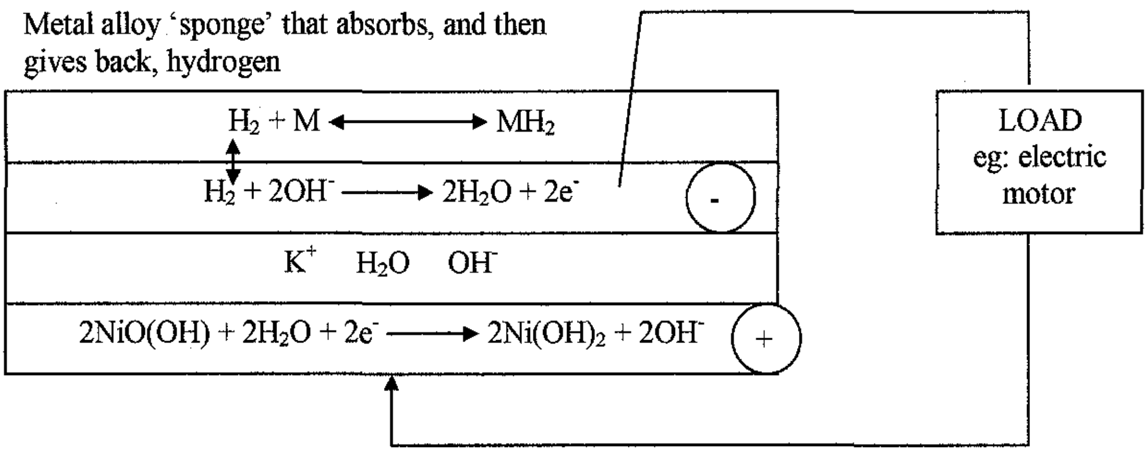

Figure 3.4: The reactions during discharge of NiMH cell. When charged the reaction reversed.

The metal that are used to hold the hydrogen are alloys. The principle of their operation is exactly the same as in the metal hydride hydrogen stores used in conjunction with fuel cells. The basic principle is a reversible reaction in which hydrogen is bonded to the metal, and then released as free hydrogen when required. For this to work the cell must be sealed, as an important driver in the absorption/desorption process is the pressure of the gas, which is maintained at a fairly constant value. A value important point about the sealing is that the hydrogen-absorbing alloys will be damaged if air is allowed into the cell. This is because they will react with the air, and other molecules will occupy the sites used to store the hydrogen.

The overall chemical reaction for the NiMH battery is written as:

$$MH + NiOOH \longrightarrow M + Ni(OH)_2$$

In terms of energy density and power density the metal hydride cell is somewhat better than the NiCd battery. NiMH battery have a nominal specific energy of about 65Wh.kg^{-1} and a nominal energy density of 150Wh.L^{-1} and a maximum specific power of about 200 W.kg^{-1}. Its performance is similar to, or a litter better than that for the nickel cadmium cell. The nominal cell voltage is 1.2V.

The NiMH battery has slightly higher energy storage capacity than NiCd systems, and is also a little more costly. There is one area where its performance is notably worse than that for NiCd batteries, and that its self discharge properties. Hydrogen molecules are very small, and they can reasonably easily diffuse through the electrolyte to the positive electrode, where it will react:

$$\frac{1}{2}H_2 + Ni\ O\ OH \longrightarrow Ni(OH)_2$$

This effectively discharges the cell; hydrogen is lost from the negative and nickel hydroxide is formed at the positive. The result is that this battery is subject to quite rapid self discharge.

An interesting feature of the cell, is that the composition of the electrolyte does not change during charge or discharge; water and OH^- ions are created and used at exactly the same rate. The result is that the internal resistance and open circuit voltage of the cell are much more constant during discharge than with either lead acid or NiCd batteries. Being backed by a metal layer, the internal resistance is also a little lower, but it is not greatly different.

3.3.2 Maintenance

Basically, to maintain NiMH battery is as same as to maintain NiCd battery, since both are nickel-based battery. A notable difference between NiCd and NiMH battery is there is no memory effect for NiMH battery. But it is highly recommended to deep-cycled the battery to maintain its maximum performance. New NiMH, un-initialized batteries can be stored in a cool dry place without significant cycle life loss for up to 1 year.

3.3.3 NiMH Battery Charging

The charging regime is similar to that of the NiCd battery, the current being switched on and off to keep the cell voltage between an upper and a lower limit. Like NiCd batteries the NiMH battery can be charged within 1 hour. Most cells can cope with an overcharge current of about 0.1C, like the NiCd cell. Overcharging is necessary in a battery to make sure each and every cell is fully charged.

One area where NiMH is better than the NiCd is that it is possible to charge the battery somewhat faster. Indeed, it can be charged so fast that cooling becomes necessary. As well as heat energy being created by the normal internal resistance of the battery, the reaction in which hydrogen is bonded to the metal adjacent to the negative electrode is quite strongly exothermic. Unless the vehicle is a cycle or scooter, with a small battery, a cooling system is an important feature of NiMH battery systems. They are available commercially in small sizes, but larger batteries suitable for electric vehicles are beginning to appear.

Of all new battery systems NiMH is considered to be one of the most advanced and has been used in a range of vehicles including the Toyota Prius, which has been by far the most successful electric hybrid to date. Nowadays, it is not hard to find NiMH batteries, as the electric vehicle enthusiastic has already aware the advantages of this battery. The market volume of NiMH batteries is still small, but with constant development of electric vehicle, the future of NiMH batteries seems bright.

3.4 LITHIUM ION BATTERY

3.4.1 Lithium Ion Battery Basic

Since the late 1980s rechargeable lithium cells have come onto market. They offer greatly increased energy density in comparison with other rechargeable batteries, though at greatly increased cost. It is a well-established feature of the most laptop computers and mobile phones that lithium rechargeable batteries are specified, rather than the lower cost NiCd or NiMH cells. Nowadays, the usage of Li-Ion battery has also broadened to the electric/hybrid vehicles area.

The lithium ion battery was introduced in the early 1900s and it uses a lithiated transition metal intercalation oxide for the positive electrode and lithiated carbon for the negative electrode. The electrolyte is either a liquid organic solution or a solid polymer.

Electrical energy is obtained from the combination of the lithium carbon and the lithium metal oxide to form carbon and lithium metal oxide. The overall chemical reaction for the battery is:

$$C_6Li_x + M_yO_z \longleftrightarrow 6C + Li_xM_yO_z$$

An important point about lithium ion batteries is that accurate control of voltage is needed when charging lithium cells. If it is slightly too high it can damage the battery, and if too low the battery will be insufficiently charged. Suitable commercial chargers are being developed along with the battery.

Lithium ion batteries offer twice the energy density of a standard NiCd battery. This means that lithium ion batteries allow the device to run much longer on a single charge. Lithium ion batteries also self-discharge at approximately one-half the rate of a NiCd battery.

Lithium ion cells are somewhat fragile, however. A special protection circuit is required to safely operate the batteries. This protection circuit is built into each lithium ion battery pack. The protection circuit limits the peak voltage of each cell while charging as well as limiting the voltage drain when discharging. The protection circuit also monitors the cell temperature to avoid temperature extremes during charging or usage.

The lithium ion battery has a considerable weight advantage over battery systems, and this makes it a highly attractive candidate for future electric vehicle. In fact, it is already been used in Segway Personal Transporter due to its advantages. The specific energy, for example, is about three times that of lead acid batteries, and this could give a car with a very reasonable range. However, large batteries are currently prohibitively expensive, and only when a commercial company has set up a production line which can produce lower-cost lithium ion batteries will their potential be fully realized.

3.4.2 Maintenance

Lithium ion batteries are low-maintenance batteries. One of the advantages of lithium ion batteries is that the batteries have no "memory effect." The batteries do not require scheduled cycling to maintain them. Despite the fact that lithium ion batteries are low-maintenance, there are some steps that can extend the life of a lithium ion battery.

Before begin to use the batteries, it is preferably to charge it overnight. To allow the batteries reach its maximum rated capacity, fully charge and discharges the batteries 3 to 4 times. It is also important to clean the battery contacts on the battery when it becomes dirty. When the batteries are not in use, make sure to keep them fully charged. Avoid regularly running the batteries too low, as it will damage the battery. Never leave lithium ion batteries discharged for long - the batteries do self-discharge and the charge could drop low enough to damage the battery. Make sure to keep the batteries out of high heat, as high temperatures may cause premature battery failure, and do store lithium ion batteries in a cool, dry place if the batteries is not being used for several weeks.

3.4.3 Li-Ion Battery Charging

The Li-ion charger is a voltage-limiting device that is similar to the lead acid system. The difference lies in a higher voltage per cell, tighter voltage tolerance and the absence of trickle or float charge at full charge. While lead acid offers some flexibility in terms of voltage cut-off, manufacturers of Li-ion cells are very strict on the correct setting because Li-ion cannot accept overcharge. Li-ion is a "clean" system and only takes what it can absorb. Anything extra causes stress.

Most cells charge to 4.20V/cell with a tolerance of +/–50mV/cell. Higher voltages could increase the capacity, but the resulting cell oxidation would reduce service life. Li-ion does not need to be fully charged, and it is better not to fully charge, because a high voltage stresses the battery. Choosing a lower voltage threshold, or eliminating the saturation charge altogether, prolongs battery life but this reduces the runtime. Since the consumer market promotes maximum runtime, these chargers go for maximum capacity rather than extended service life.

CHAPTER 4
METHODOLOGY

Figure 4.1 shows the basic flowchart of the process and activities planned for this project. Firstly, the author will do a research on personal transporter. This includes reviewing the related literature about personal transporter that available in the market nowadays. Moreover, this is the stage where the author should completely understand the topic. From the brief readings and findings, the author will identify the problem regarding the personal transporter that makes it not popular among users at urban areas although it has been sold to the market since 2001.

Since the author is focusing only to the battery, in the next stage the author will study the characteristic of rechargeable battery used for electric vehicle. Then the author will specify a few types of battery that suitable for personal transporter. It is important to know the basic of the battery, as it will help to understand the behaviour of the battery better.

After selecting the batteries, the author will do a market research on the battery. Some of the battery are being used widely by electric vehicle user, thus making the demand is quite high for certain type of it. After gathering all the required data, an analysis will be done to compare the batteries based on data obtained.

Lastly, the author will do a comparison between the batteries, to find out which one is better. The good battery should last longer than others, easy to obtained, did not need much maintenance and should be an affordable choice. All the information given in this report is useful for choosing a battery for a personal transporter.

Gantt chart is also developed to ensure the tasks are performed and finished within the time. The timeline given in the chart is subject to change whenever needed such as unforeseen circumstances that need the alteration of the time limit. Please refer to Table 4.1 and Table 4.2 for the details of the work for this project.

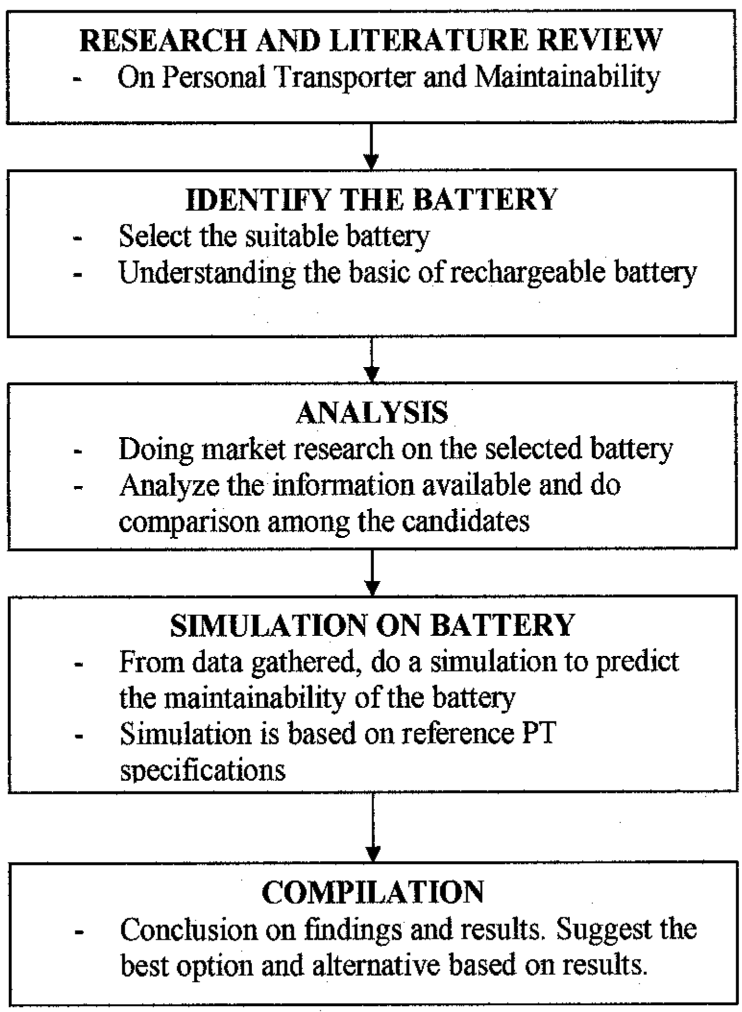

Figure 4.1: Process Flow Chart

Table 4.1: Gantt Chart (FYP 1)

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13
1	Submission of project topic	■	■						Mid Semester Break						
2	Preliminary research work on various PT		■	■	■										
3	Identifying components needed for a PT				■	■	■								
4	Identifying the possible type of maintenance needed						■	■		■					
5	Detail research on each maintainable components									■	■	■	■		
6	Compiling data and findings												■	■	■

Table 4.2: Gantt Chart (FYP2)

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13
1	Understanding rechargeable cells	■	■	■					Mid Semester Break						
2	Specifying suitable batteries for PT			■	■	■									
3	Market research - availability on market					■	■								
4	Battery analysis and comparison						■	■		■	■	■			
5	Compiling the data and result											■	■	■	■

CHAPTER 5
RESULT AND ANALYSIS

There are few types of battery that suits electric vehicle well, such as lead acid battery (most common), nickel cadmium battery, nickel metal hydride battery and lithium ion battery. Because battery is one of the main components in the personal transporter itself, the selection of the battery must follow a certain criteria, which will be discussed later.

As the electric vehicle is gaining public's attention, the battery manufacturers tend to do a research on a battery that can supply more power, can last longer, has a high recharged rate and so on. It is useful to do a detail research before decide the battery that will be used for this personal transporter. Choosing the right battery will help the designer in lowering the cost of the PT during design stage. It will help consumers to save cost by maximizing the usage of the battery while giving the power needed by the motor.

5.1 CHARACTERISTIC OF BATTERIES SUITABLE FOR THE VEHICLE'S PROPULSION

The key component of a useful personal transporter is the battery in which energy is stored. The available battery types range from lead-acid, which can deliver 30Wh/kg of battery weight, to the lithium ion batteries that can deliver 150Wh/kg.

Many factors must be considered in selecting the battery type for an electric vehicle because the requirements are complex. For example, a battery with a short life in charge-discharge cycling would need frequent replacement, which raises its life cycle cost. A heavy battery requires energy for hauling it up hills on the vehicle. This energy has to be furnished by the energy carried in the battery. Long battery life is achieved in lightweight batteries by a sophisticated charge control circuits that prevents overcharging cells in the battery. A presently available battery might be replaced in the market by an even better battery, which requires a sophisticated charge control. The older charge control might cease to be available.

5.2 BATTERY ANALYSIS

5.2.1 Characteristic of Rechargeable Battery

Table 5.1: Characteristic of Rechargeable Cells [9]

	NiCd	NiMH	Lead Acid	Li-Ion
Specific Energy(Wh/kg)	40-60	60-90	30 - 50	150-190
Energy Density(Wh/L)	150-190	300-340	80-90	350-470
Internal Resistance(mΩ)	100 to 200 (6V pack)	200 to 300 (6V pack)	<100 (12V pack)	150 to 250 (7.2V pack)
Cycle life(to 80% of initial capacity)	500-1000	500-1000	200 to 300	500 to 1000
Fast charge time	1h typical	1h	8-16h	2-3h
Overcharge tolerance	moderate	low	high	very low
Self-discharge/month(room temp.)	20%	30%	5%	<5%
Cell voltage(nominal)	1.25V	1.25V	2V	3.7V
Load current >peak >best result	 20C 1C	 5C 0.5C or lower	 10C 1C	 >2C 1C or lower
Operating temperature(discharge only)	−40 to 60°C	−20 to 60°C	−20 to 60°C	−20 to 60°C
Maintenance requirement	30 to 60 days	60 to 90 days	3 to 6 months	not required
Cost(US$/Wh)	0.25	0.5	0.5	0.8

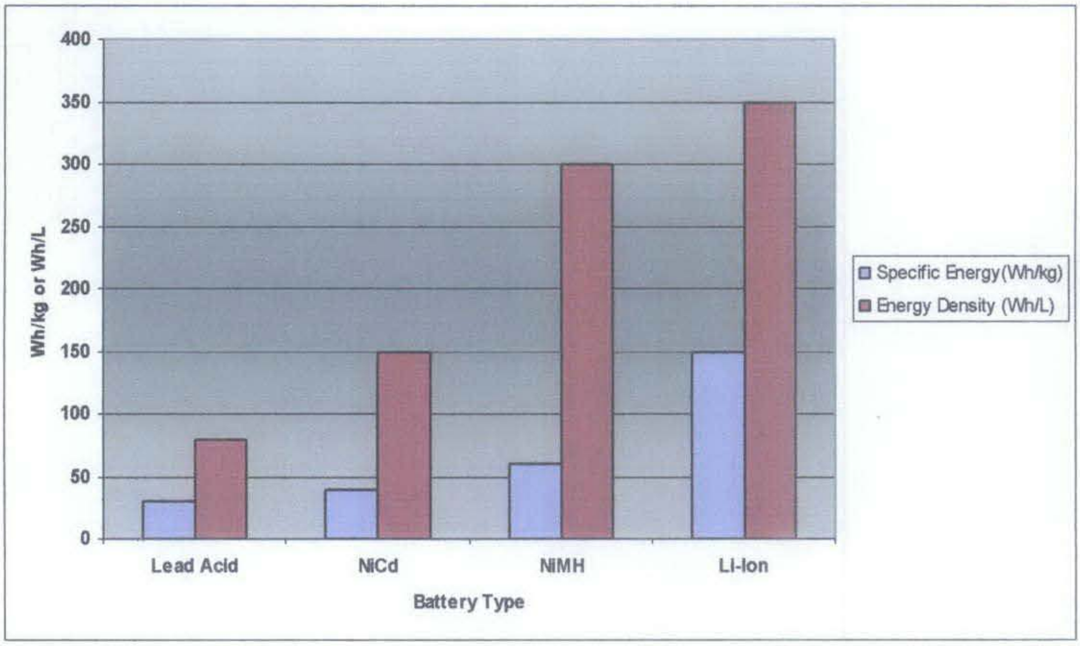

Figure 5.1: Comparison of Specific Energy and Energy Density of Rechargeable Cells

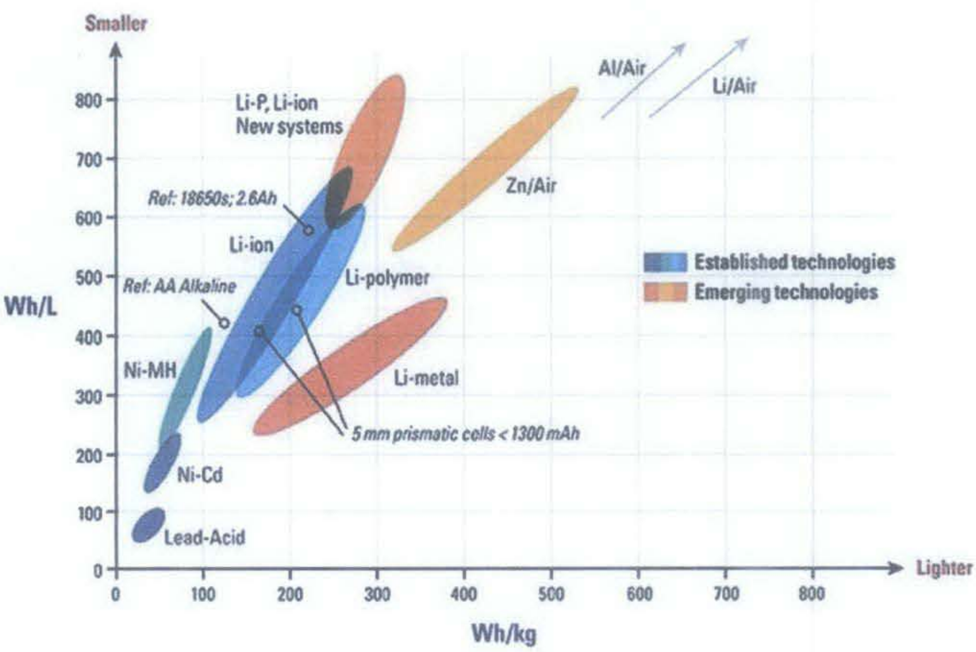

Figure 5.2: Ragone Plot. Note that Lithium Ion battery is the lightest and smallest among Nickel-based and Lead Acid battery [10]

5.2.2 Advantages and Disadvantages of Rechargeable Battery [8]

- **Lead Acid Battery**

Table 5.2: Advantages and disadvantages of Lead Acid battery

Advantages	Disadvantages
Relatively cheap	Very heavy; a 12V 12Ah battery weighs 4kg
Can deliver very high peak currents	Poor life: 200-300 cycles
Wide application and so easily available	Easily damaged if left 'flat'
Easy to charge & manage	Low energy density and energy
Wide temperature	About 1/3 energy is inaccessible
Low toxicity	
Easy to monitor capacity	

- **Nickel Cadmium Battery**

Table 5.3: Advantages and disadvantages of Nickel Cadmium battery

Advantages	Disadvantages
Good at delivering high currents	Toxic and expensive to recycle. Likely to be banned
Higher energy density than lead acid	Careful management required to avoid Memory effect (reversible), build up of large crystals (irreversible) and over-charge resulting in venting and damage
Higher Energy/Volume than lead acid	Restricted temperature range for charging and discharging
Stable output voltage: 90% of stored energy is usable	Complex charge state indication
Good cycle life: 600-800 cycles	
Good at delivering high currents	
Higher energy density than lead acid	
Relatively cheap	

- **Nickel Metal Hydride (NiMH) Battery**

Table 5.4: Advantages and disadvantages of Nickel Metal Hydride battery

Advantages	Disadvantages
Higher energy density than lead acid	Restricted temperature range for charging and discharging
Higher Energy/Volume than lead acid	Limited output current capability
Stable output voltage: 90% of stored energy is usable	Heavier than NiCd
Good cycle life: 600-800 cycles	High self discharge - around 1%/day at normal temperatures
Relatively light - a 12V 9Ah battery weighs ~1.7kg	Complex charge state indication
Cheaper than Li-Ion battery	50% overcharge needed as chemistry is inefficient

- **Lithium Ion (Li Ion) Battery**

Table 5.5: Advantages and disadvantages of Lithium Ion battery

Advantages	Disadvantages
Very light: a 37.2V 10Ah battery weighs around 2.6kg	Only provided by few manufacturer - Expensive
Very low self-discharge	Concern about stability of High capacity batteries
Good life span: 600-800 cycles	Possibility of 'venting with flame' when charging
Chargers are simple (onboard battery electronics)	Complex charge state indication
High energy density	
Most (>85%) of the stored energy is available as useful power	

5.2.3 Battery details

Base area of PT: 0.5m^2

Motor Voltage: 24V

Maximum speed: 30 km/h

Refer to Appendix 1 for the battery details

Table 5.6: Battery comparison

	Lead Acid	NiCd	NiMH	Li-Ion
Battery req.	2	1	1	1
Area of battery (m^2)	2*(0.181*0.167) = 0.06	0.32 * 0.091 = 0.03	0.224 * 0.096 = 0.02	0.204 * 0.09 = 0.018
Thickness (m)	0.076	0.063	0.060	0.075
Weight (kg)	2 * 6.15 = 12.3	3.76	3.4	2.4
Percent space used on PT	100 * (0.06/0.5) = 12%	100 * (0.03/0.5) = 6%	100 * (0.02/0.5) = 4%	100*(0.018/0.5) = 3.6%
Battery duration (single charge)	t = 17Ah/27.4A = 0.62h = 37.2 min	t = 7Ah/27.4A = 0.255h = 15.3 min	t = 10Ah/27.4A = 0.365h = 21.9min	t = 9Ah/27.4A = 0.328h = 19.7 min
Distance covered (km)	30km/h*37.2min = 18.6 km	30km/h *15.3min = 7.65 km	30km/h *21.9min = 10.95 km	30km/h *19.7min = 9.85 km
Price in USD (+charger)	34.00(+35.95)	139.95(+29.95)	299.95 (+ charger)	280.00(+32.00)

Based from Table 5.6, lead acid battery occupied a larger floor space compared to others. Li-Ion battery shows the least space required, with only 0.018m^2. Meanwhile, Li-Ion battery is the lightest of all, which means it will reduce the total weight of the personal transporter, followed by NiMH and NiCd battery. For the battery duration, lead acid maintain the longest running, followed by NiMH battery, as it offers the largest charge capacity (17Ah) compared to others. These are the common examples of batteries that available in the market nowadays.

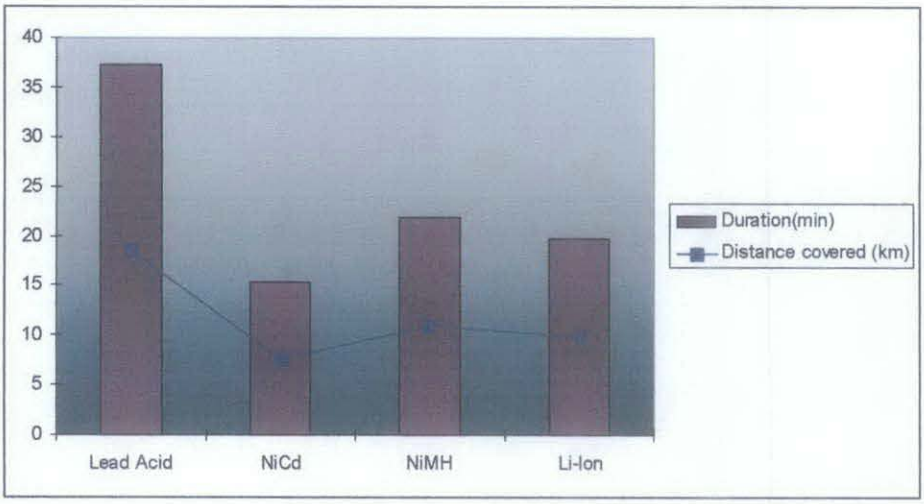

Figure 5.3: Duration of the battery on the reference PT with the distance covered

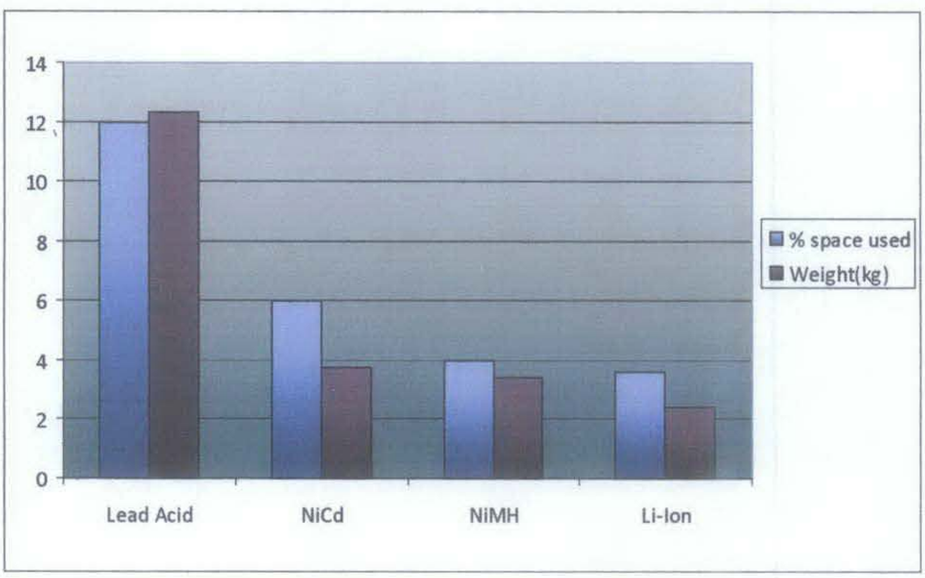

Figure 5.4: Percent space used on the reference PT and the weight of battery used

Figure 5.3 shows the distance covered for each of the battery, by assuming that the reference PT operates using maximum current and also the time duration for each of the battery. While Figure 5.4 shows the percent space used on the reference PT for each type of the battery with its weight. Lead acid battery shows the longest duration which means the farthest distance covered, due to its high capacity, but consume about 12% the area of the reference PT. NiMH battery is just behind lead acid battery in terms of distance covered, but consume only about 4% of the area and are much lighter.

5.2.4 Relationship between Torque and Current

Motor will draw a higher amount of current when the higher torque is applied. The torque of a motor is proportional to the current flowing through it. Stall current is reached at stall torque, which occurred at 0 rpm. Since the motor speed is given (2500 rpm) and the stall torque is known (16.89 rad/s) [1], we can see the relationship between rotational speed and the torque, shown in Figure 5.5.

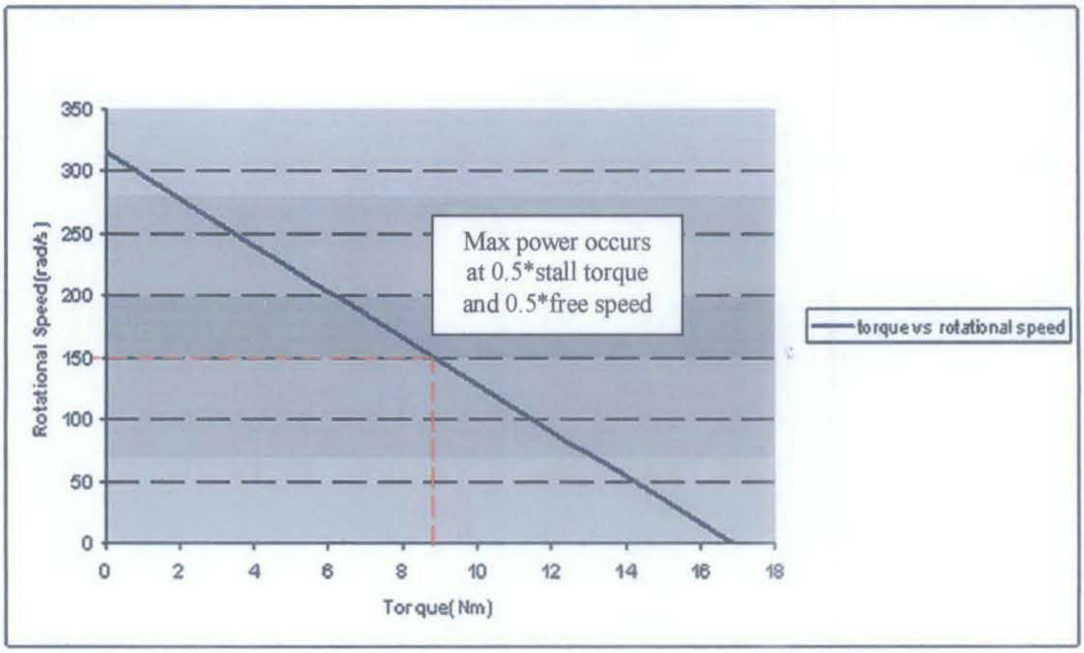

Figure 5.5: Torque vs Rotational Speed delivered by the electric motor

5.2.5 Availability of rechargeable battery for electric vehicle

Since the electric vehicle such as electric scooter and electric bikes are become commercially available in the market nowadays, the rechargeable batteries for such type of transport are easily available. Sealed lead acid battery, which is the most common battery used for electric scooter and electric bikes is the main choice, due to its price and available almost anywhere. But nowadays, other alternatives such as NiCd, NiMH and Li-Ion battery are also available, even though it is not as popular as lead acid battery.

NiCd battery was initially used for use in a range of portable equipment, before being developed to become available for electric vehicle.

But since the emergence of NiMH battery, the popularity of NiCd battery among electric vehicle enthusiastic seems faded. Battery manufacturer nowadays tend to produce NiMH battery for electric vehicle, compared to NiCd battery. The main problem that contributes to this situation is because of the memory effect and other crystalline problem. It is also because Cadmium is harmful to the environment, and also expensive to be recycled. From market research, the author found that the NiCd battery is now widely used in solar lighting and remote controls. NiMH gives the same quality as NiCd, although with a slightly higher price, it is more easy to manage (in terms of charging and discharging) and also not harmful to environment.

As for li-ion battery, the availability of li-ion based battery for electric vehicle is still limited, mainly because of low demand from the user as the cost is much higher. Although li-ion battery has a few great advantages compared to others, such as it is extremely light, have a high energy density and have a good life span, the demand of li-ion is remain low unless the manufacturing cost of li-ion battery can be lowered. Some of electric vehicle owners are also promoting the usage of li-ion battery, because of the advantages cited before. In fact, the world's most eye-catching personal transporter, Segway PT also use li-ion battery.

5.3 PEUKERT'S EQUATION

As stated before in early part of this report, that the capacity of a battery is reduced if the current is drawn more quickly. Drawing 1A for 10 hours does not take the same charge from a battery as running it at 10A for 1 hour.

This is particularly important for electric vehicles, as in this application the currents are generally higher, with the result that the capacity might be less than as expected. It is important to be able to predict the effect of current on capacity when designing vehicles and when making instrument that measure the charge left in the battery.

This is where Peukert model is become important. Although not very accurate at low currents, for higher currents it models battery behaviour well enough. The Peukert Capacity, which is constant is given by equation $C_p = I^kT$, where k is a constant, I is the discharge current in amps, and T is the time in hours. The Peukert Capacity is equivalent to the normal amp-hours capacity for battery discharged at 1A. Taking an example of 12V 17Ah lead acid battery at 20 hour rate:

$$I = 17/20 = 0.85A$$

Taking the Peukert Coefficient of 1.2 (typical value for lead acid battery):

$$C_p = 0.85^{1.2} * 20 = 16.5 \text{ Ah}$$

From the C_p value obtained, we can find the time that the battery will last at any current I. from this equation, it shows that if current I flows from a battery, based from battery capacity, the current that appears to flow out of the battery is I^k A.

5.3.1 Calculating Peukert Coefficient

The Peukert Coefficient is rarely given in the battery specification sheet, but there is always enough information in the specification sheet to calculate it. All that is required is the battery capacity at two different discharge times. Take for an example, 17Ah sealed lead battery (refer Appendix 2) that has 20 hour rating also has a capacity of 16.15Ah at the 10 hour rate. The two different rating give two different rated currents:

$I_1 = C_1/T_1$ and $I_2 = C_2/T_2$

$C_p = I^k_1 * T_1$ $C_p = I^k_2 * T_2$

Since the Peukert Coefficient is constant,

$$I^k_1 * T_1 = I^k_2 * T_2$$

$$(I_1/I_2)^k = T_2/T_1$$

Rearranging this by using logs,

$$k = (\log T_2 - \log T_1) / (\log I_1 - \log I_2)$$

So, by putting the values into the equation gives:

$I_1 = C_1/T_1 = 17/20 = 0.85$ A and $I_2 = C_2/T_2 = 16.15/10 = 1.615$ A

$$k = (\log 10 - \log 20) / (\log 0.85 - \log 1.615)$$

$$k = 1.0799 = \underline{\mathbf{1.08}}$$

From Peukert Coefficient obtained, we can calculate the Peukert Capacity of 17Ah lead acid battery, and the relationship between the current drawn and the battery time is showed in Figure 5.6. It shows the duration of the battery reduced significantly when the discharged current is bigger. Figure 5.7 shows the accuracy of Peukert model when predicting the capacity of a battery, given the currents discharged. We can see in Figure 5.8, the capacity of a battery with a Peukert's number of 1.3 has half the capacity of a battery with a Peukert's number at 1.1, at discharge rate of 25Amps, even though they both have same theoretical capacity.

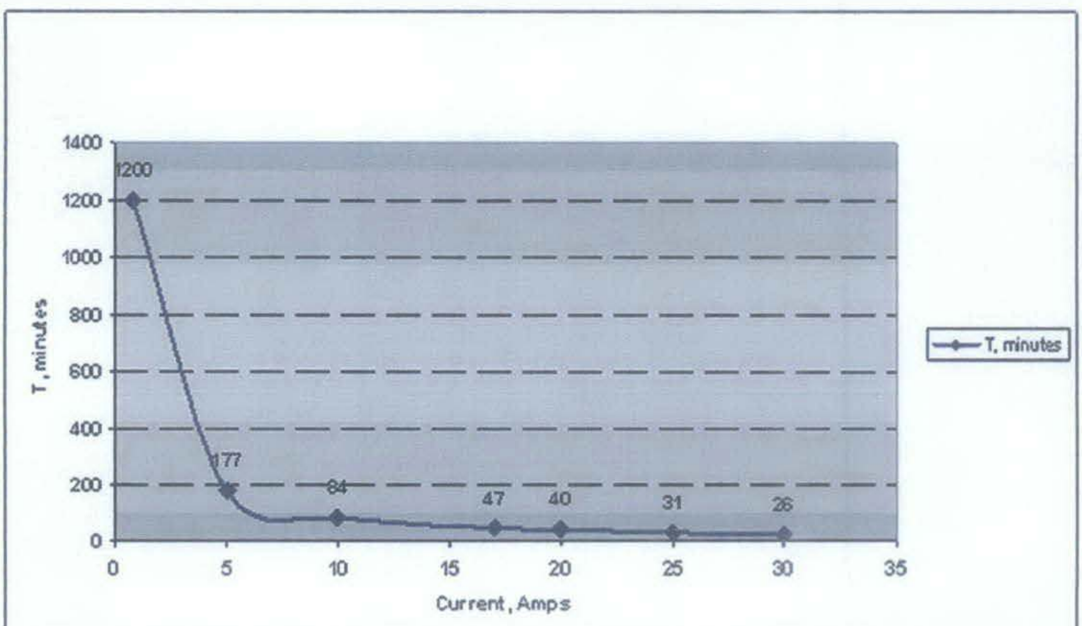

Figure 5.6: Relationship between current discharged and battery duration with Peukert Coefficient (12V 17Ah lead acid battery)

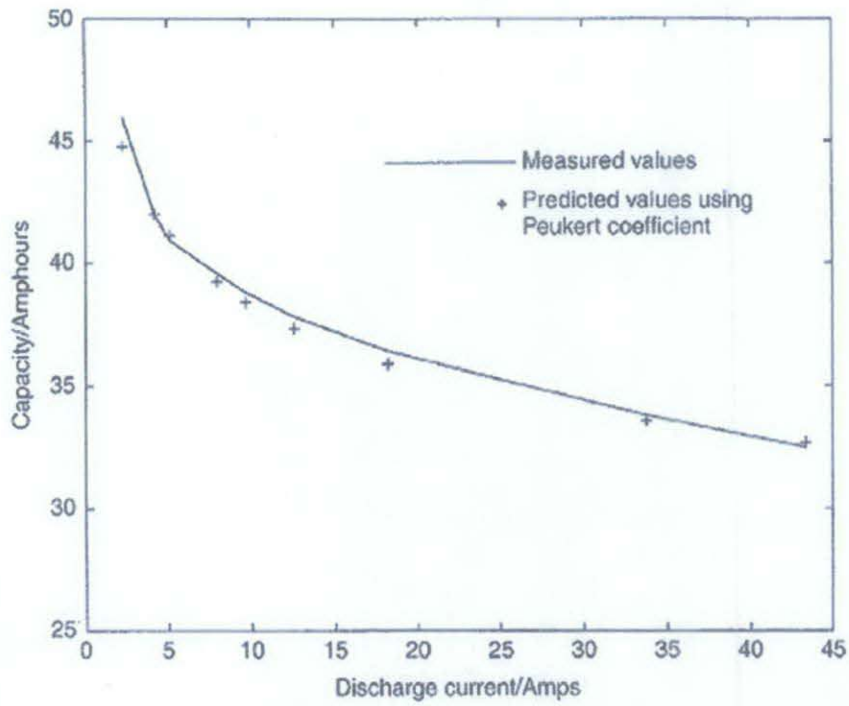

Figure 5.7: Showing the comparison between measured value and predicted value using Peukert Coefficient at different discharge currents for nominally 42V lead acid battery.

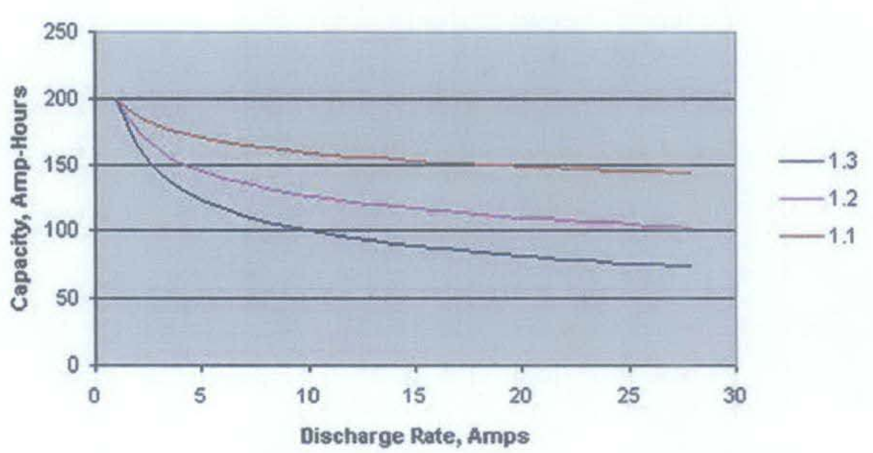

Figure 5.8: The Capacity vs Discharge Rate for different Peukert Coefficient

CHAPTER 6
CONCLUSION AND RECOMMENDATION

Based from the research from literature review and theoretical analysis on the batteries, the author managed to conclude that the best battery for a personal transporter (at the time being) is Nickel metal hydride (NiMH) battery. NiMH battery has an energy density of 300 Wh/L, and a specific energy of 60 Wh/kg, which is only lower than Li-Ion battery. In terms of its performance, it passes the requirement of a distance at least 10 km. Although it is only last for about 22 minutes, it is mainly due to its low capacity, and only lead acid battery that lasts for more than 30 minutes. NiMH battery has a good life cycle, which is about 600 – 800 cycles, compared to 200 – 300 cycles for lead acid battery. It is also much lighter than lead acid battery.

On the other hand, lead acid remains as the most popular battery, and for those who still prefers lead acid battery, one thing that is important for a better battery – is by calculating the battery capacity by using Peukert's equation. Different manufacturers offer different quality of the battery. It is good to investigate the capacity of the battery before buying it. Peukert is actually occurred on all type of battery, but worst in lead acid battery.

The author hopes that the information provided in this report manage to help the PT designer to decide on the type of battery that should be used. The author believes, that the maintenance cost of a battery can be reduced significantly, giving the right handling and most importantly, the right battery that last for a longer time.

Last but not least, the author recommends to prototyping the personal transporter, as theoretical study alone is not enough. It is also important to make an experimental analysis on the battery and the drive mechanism to practically see the data. It is important to develop the real prototype, part by part, before assembling the personal transporter to analyze the actual data obtained.

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APPENDIX

Appendix 1: The Availability of the common rechargeable battery in market

Lead Acid Battery

Sealed Lead Acid Battery 12V 17Ah
Max discharging current: 255 A
Max charging current: 5.1 A
Energy density: 3 wh/kg
181mm * 76mm * 167mm
6.15 kg
USD 34.00 (+USD 35.95 for charger)
Available at www.batteryspace.com

Nickel Cadmium Battery

NiCd Battery Pack – 24V 7Ah
Discharging rate: 5 A
Charging current: 1.5 A (standard), 3.5 A (maximum)
320mm * 63.5mm * 91.4mm
3.76 kg
USD 139.95 (+USD 29.95 for charger)
Available at www.batteryspace.com

Nickel Metal Hydride Battery

NiMH Battery Pack – 24V 10Ah
Discharging rate: 5 A (standard)
Charging rate: 1.8 A (standard), 5 A (maximum)
224mm * 96mm * 60mm
3.4 kg
USD 299.95 (with charger)
Available at www.batteryspace.com

Lithium Ion Battery

XEB0003 Lithium Ion Battery – 24V 9Ah
90mm * 75mm * 204mm
2.4 kg
USD 280.00 (+USD 32.00 for charger)
Available at www.electricbike.uk.com

Appendix 2: 12V 17Ah Lead Acid Battery Performance Specifications

PERFORMANCE SPECIFICATIONS

Nominal Voltage(V)..12 volts(6cells in series)

Nominal Capacity(AH)

20 hour rate F.V.(1.75V/cell) (850mA to 10.50volts) ....17.0A.H.

10 hour rate F.V.(1.75V/cell) (1615mA to10.50volts) ....16.15A.H.

5 hour rate F.V.(1.75V/cell) (2890mA to 10.50volts) ....14.45A.H.

1 hour rate F.V.(1.55V/cell) (10200mA to 9.30volts)..10.2A.H.

Approximate Weight..6150g.(13.56lbs.)

Appendix 3: Calculation of Peukert Capacity of 12V 17Ah Lead Acid Battery

Amps	T,hrs	T,minutes	Apparent Capacity	Peukert Effect (%)
0.85	20.00	1200	17	100
5	2.95	177	15	87
10	1.40	84	14	82
17	0.79	47	13	79
20	0.66	40	13	78
25	0.52	31	13	76
30	0.43	26	13	75

Appendix 4: Calculation of the torque for the motor

rot. speed(rad/sec)	torque(rad/sec)	stall torque	max speed
0	16.890	16.89	315
15	16.086	16.89	315
30	15.281	16.89	315
45	14.477	16.89	315
60	13.673	16.89	315
75	12.869	16.89	315
90	12.064	16.89	315
105	11.260	16.89	315
120	10.456	16.89	315
135	9.651	16.89	315
150	8.847	16.89	315
165	8.043	16.89	315
180	7.239	16.89	315
195	6.434	16.89	315
210	5.630	16.89	315
225	4.826	16.89	315
240	4.021	16.89	315
255	3.217	16.89	315
270	2.413	16.89	315
285	1.609	16.89	315
300	0.804	16.89	315
315	0.000	16.89	315