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นางสาวกันติชา ก่อเศรษฐการ

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IMPLEMENTATION OF ENERGY STORAGE SYSTEM WITH FLEET MANAGEMENT ON ELECTRIC SHUTTLE BUSES

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Mechanical Engineering
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กันติชา ก่อเศรษฐการ : การปรับรูปแบบแหล่งกักเก็บพลังงานและตารางการเดินรถสำหรับรถโดยสารไฟฟ้า. (IMPLEMENTATION OF ENERGY STORAGE SYSTEM WITH FLEET MANAGEMENT ON ELECTRIC SHUTTLE BUSES) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร.อังคีร์ ศรีภคากร, 89 หน้า.

รถโดยสารไฟฟ้าภายในจุฬาลงกรณ์มหาวิทยาลัยได้ให้บริการรับส่งนิสิตและบุคลากรมาประมาณ 7 ปีแล้ว และเนื่องด้วยความต้องการที่จะใช้บริการรถโดยสารในช่วงเวลาเร่งด่วนคือเวลากลางวันและหลังเลิกเรียนมีสูง จึงทำให้รถโดยสารมีไม่เพียงพอต่อความต้องการ จากปัญหานี้จึงมีแนวคิดศึกษาการจัดตารางเวลาการชาร์ตประจุแบตเตอรี่ให้เหมาะสมกับเวลาการใช้งาน

วิทยานิพนธ์ฉบับนี้นำเสนอการแก้ปัญหาการให้บริการของรถโดยสารไฟฟ้าสาย 3 โดยการปรับเปลี่ยนแหล่งกักเก็บพลังงานทางเลือกในรูปแบบต่างๆ โดยจะพิจารณาถึงชุดแบตเตอรี่ 3 ชนิดคือ ชุดแบตเตอรี่ตะกั่วน้ำกรด (ชนิดที่ใช้อยู่บนรถโดยสารสาย 3 ในปัจจุบัน) ชุดแบตเตอรี่ตะกั่วน้ำกรดเสริมตัวเก็บประจุความจุสูง และชุดแบตเตอรี่ลิเทียม จากนั้นนำผลการดึงประจุมาทำแบบจำลองการให้บริการและจัดทำตารางการอัดประจุแบตเตอรี่ของรถโดยสารที่เหมาะสมที่สุด โดยมีเป้าหมายคือการลดเวลาการรอขึ้นรถของผู้โดยสาร

จากผลการทดสอบกับชุดแบตเตอรี่ขนาดย่อส่วน พบว่า ชุดแบตเตอรี่ตะกั่วน้ำกรดเสริมตัวเก็บประจุความจุสูงและชุดแบตเตอรี่ลิเทียมสามารถยืดระยะเวลาคายประจุได้เพิ่มขึ้นถึง 14% และ 45.7% ตามลำดับ เมื่อพิจารณาถึงการลดเวลาและแถวคอยของผู้โดยสารที่แล้ว พบว่า เมื่อจัดตารางการอัดประจุของรถโดยสารอย่างเหมาะสม โดยไม่ต้องปรับเปลี่ยนแหล่งกักเก็บพลังงานจะช่วยลดเวลาการรอรถของผู้โดยสารได้อย่างมีนัยสำคัญเทียบเท่ากับการปรับเปลี่ยนชุดแบตเตอรี่เป็นชุดแบตเตอรี่ตะกั่วน้ำกรดเสริมตัวเก็บประจุความจุสูง และการปรับเปลี่ยนชุดแบตเตอรี่เป็นชุดแบตเตอรี่ลิเทียม แม้ว่ามีราคาเริ่มต้นที่สูงกว่ามาก แต่จะสามารถลดเวลาการรอรถของผู้โดยสารได้ดีที่สุดถึง 25 % และยังสามารถลดความถี่ของการเข้าอัดประจุของแบตเตอรี่รถโดยสารได้อีกด้วย จากนั้น ได้นำผลการทดสอบของการดึงประจุของแบตเตอรี่ขนาดจริงมาเปรียบเทียบกับขนาดย่อส่วน ผลการทดสอบพบว่า ระยะเวลาการคายประจุของแบตเตอรี่มีความใกล้เคียงกัน โดยสรุปแล้ว การศึกษาการคายประจุของชุดแบตเตอรี่ขนาดย่อส่วน จึงถือเป็นทางเลือกที่น่าสนใจและมีความสะดวกในการทดสอบการจ่ายพลังงานของแหล่งกักเก็บพลังงานของรถโดยสารไฟฟ้า

ภาควิชา	วิศวกรรมเครื่องกล	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมเครื่องกล	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก	....
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KEYWORDS: ELECTRIC BUS / SUPERCAPACITOR / BATTERY / SIMULATION / PUBLIC TRANSPORTATION

KANTICHA KORSESTHAKARN: IMPLEMENTATION OF ENERGY STORAGE SYSTEM WITH FLEET MANAGEMENT ON ELECTRIC SHUTTLE BUSES. ADVISOR: ASSOC. PROF. ANGKEE SRIPAKAGORN, 89 pp.

Electric public bus scheduling problem is studied for the service in Chulalongkorn university campus. This thesis presents an integrated bus scheduling simulation combined with options of energy storage system with the target to minimize the wait time. The bus system is simulated by Arena software for the bus scheduling. The solution dictates the change of the bus schedule; the resulting change of wait time is then observed. Lead-acid equipped with supercapacitor and lithium-ion batteries were compared in this study to exhibit the improved performance. The supercapacitor hybrid and lithium-ion battery provides an improvement of 14% and 45.7% in discharge energy, respectively. The supercapacitor hybrid was shown to reduce battery stress as well as improved driving dynamics. The optimized lead-acid case can reduce the waiting time significantly and at the similar level to the supercapacitor hybrid. With much higher cost, the lithium-ion battery reduce the waiting time the most by 25% due to its superior energy efficiency as well as shorter charging period. The full-scaled battery testing also performed and compared with the lab-scaled battery. There is no discernible difference between both experiments. This study concludes that, compared to full-scaled test, the lab-scaled test is an alternative way to test the energy storage system on electric shuttle buses.

Department:	Mechanical Engineering	Student's Signature	....
Field of Study:	Mechanical Engineering	Advisor's Signature	....
Academic Year:	2013		

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CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The global warming and the world energy crisis since the late 20th century have brought up the interest in technological advancement automobile field to combat such problems. Globally greenhouse gases emission is strongly contributed by transportation sector. In 2012, transportation sector stands almost 27% of the total world energy consumption with 33.7% emission of the greenhouse gas [1]. Conventional Internal Combustion Engine (ICE) that operates through fossil fuels emits gases such as carbon dioxide, carbon monoxide, hydrocarbon, nitrogen oxide, water etc.

Electric Vehicles (EVs) are currently being pursued as an alternative to conventional ICE vehicles [2]. By using electricity, they are not only providing cleaner and quieter ambience but also reducing operating costs drastically compared to gas-powered car [3].

Recently, local electrical public bus transportation becomes the new trends for urban city transportation. EV has the advantages of efficient use of energy and less maintenance cost due to the use of electric motor [4]. The key weakness of EVs is the time required to recharge the battery [5]. Since 2005, Chulalongkorn University operates the shuttle buses with the hybrid and EVs system to reduce the exhaust gas and pollutions in the campus. Figure 1-1 shows that there are 4 different routes covering the campus area and operates outside connected with metro. Hybrid shutter buses operate in route number 1 and number 4 and EVs buses operate in route number 2 and 3. The carrier currently uses a trial-and-error approach based on experience for bus scheduling. The data and timetable record provided by operator indicate that the operator adjust the bus schedule by considering the limitation of vehicle restrictions and crew restrictions. Most of these restrictions are involved with fleet size, passenger demands, trip durations and bus capacities. Also, crew and safety restriction such as the maximum number of working hour in one day and rest periods are the constraints [6]. This scheduled approach is set up manually without fleet optimization and make the bus schedule currently used less efficient especially with increased demands. The limitation of the EVs is the energy storage system that leads to a short drive cycle.

Vehicle routing and scheduling problem (VRSP) are found in many academic literatures since the scheduling can intensely reduce and optimize costs, fleet size and passenger wait time. Normally, the objective of VRSP is to reduce operation costs. Due to the complexity of transportation problem, VSRP can be classified in many ways depending on characteristics of the service delivery system, such as the delivery fleet, vehicle capacities and scheduling objectives. Generally, VSRP is divided into vehicle routing problem (VRP) and vehicle scheduling problem (VSP).

In present work, the VSP of Chulalongkorn University electric bus is focused and aims to adjust the bus schedule for a transit route with the given fixed fleet size by minimizing passenger wait time with respect to vehicle restrictions.

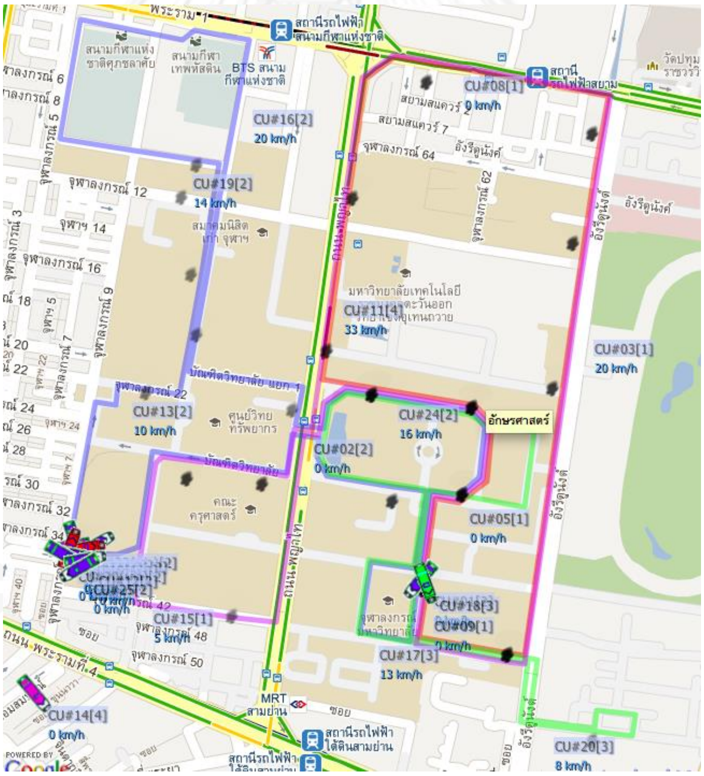


Figure 1-1 Bus routes inside Chulalongkorn University

1.2 Problem Statement

Due to the limited fleet size that is being operated in Chulalongkorn University, passengers have long wait time especially at rush hour. It was found that at least one bus must be charging during peak hour and as a result, the bus service cannot serve all of demands in time. To make it more complicated, the passenger demands are unpredictable in each day. Therefore, the average number of passengers over 1 month will be the representative data in this study.

From Figure 1-2, there are 2 peak intervals for the number of passengers; 11.30 - 13.00 and 16.00 – 17.30. Bus can operate at the maximum of 4 hours then the bus needs to recharge batteries. The charging takes about 1 hour 25 minutes.

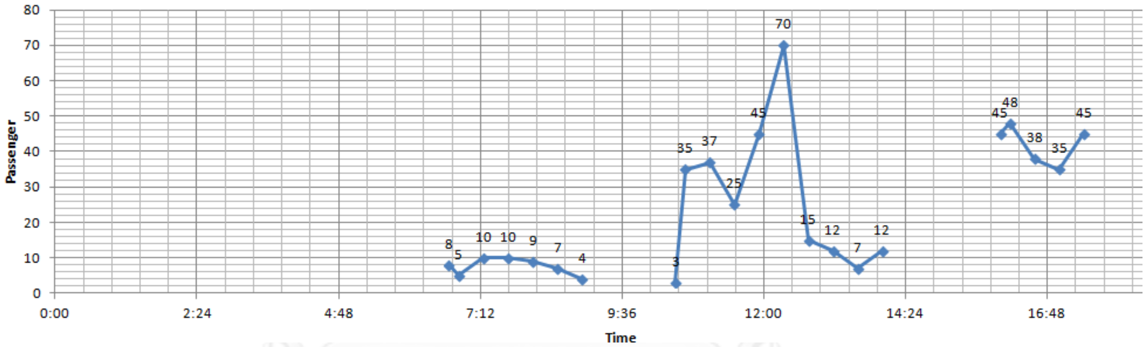


Figure 1-2 Average demand passengers over 1 month for bus #3

1.3 Research Objectives

Based on problem statement, the objective of this study is to improve bus operation service in the campus in two ways. The first is to optimize the bus scheduling such that the wait time is minimized. The second is to study the influence of two alternatives in energy storage systems on the optimized bus schedule and the resulting wait time. Actual data from running the electric bus on the route as well as from the test bench will be employed. The simulation will be performed via Arena simulation software to obtain passenger satisfaction with the same fleet size.

1.3 Scope of Thesis

The present work focused on one of the four bus lines, bus #3. The bus model considered is a 4-ton battery electric bus. The capacity of bus is 20 seats. The electric drive operates on a set of 24 deep-cycle lead-acid batteries connected in series. A group of seven bus stations are included in this route. Bus #3 now runs on the fleet size of 3 buses. Routes and bus scheduling are set up (Fig.1-3) to transport the students and faculty members between departments and to the metro station during the weekdays. The route is in the university campus in its entirety. Figure 1-3 shows the appearance of the electric bus and the bus route inside the Chulalongkorn University campus.

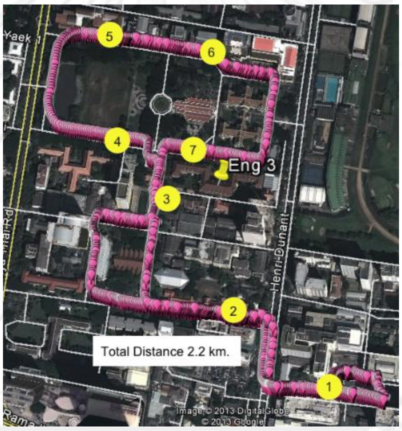


Figure 1-3 Bus Route (line#3) inside the Chulalongkorn University

1.4 Research Methodology

1. Review literatures and theories related to this study
2. Formulate the problem and block diagram in Arena environment
3. Develop conceptual model
4. Collect data from the real driving cycle and passengers
5. Discharge three types of energy storage systems: lead-acid battery, supercapacitor hybrid and lithium-ion battery followed by power load profile
6. Write the simulation routines
7. Optimize the bus schedule with alternative energy storage system
8. Validate the simulation results with statistical approaches
9. Discuss the simulation results

1.5 Benefits

Research results will help the bus carrier to make better decision in managing the bus schedules with different energy storage systems and also provide an insight into shuttle bus service problems. This study can be implemented and applied to other routes or vehicle models in the long term.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the review of the research literatures related to the vehicle scheduling problem (VSP) and energy storage system in EV application.

2.1 Vehicle Scheduling Problem

The objective of most routing and scheduling problems is to minimize the total cost of providing the service. This includes vehicle capital costs, mileage, and personnel costs. But other objectives also may come into play, particularly in the public transport. For example, in school bus routing and scheduling, a typical objective is to minimize the total number of student-minutes on the bus. Thus, in the case of transportation services, an appropriate objective function considers more than the cost of delivering a service. The “subjective” costs associated with failing to provide adequate service to the customer must be considered as well. Table 2-1 shows the list of different objectives in vehicle scheduling problems.

Scheduling problems are often presented as graphical networks. The use of networks to describe these problems has the advantage of allowing the decision maker to visualize the problem under consideration. Vehicle transit scheduling problems normally consist of four components [7]: (1) timetable creation, (2) design of routes, (3) scheduling vehicles to trips and (4) assignment of drivers. The third part is one of the most critical issues faced by transit agencies [8].

Table 2-1 List of different scheduling objectives

Objectives	Authors (Year)
Minimize the total costs by fleet size and dead head time	Gavish, Schweitzeter and Shifer (1978) [9]
Minimize dead head time for single depot by heuristic procedures	Bodin and Golen (1981) [10]
Maximize system profit with fixed passenger demand	Yan and Chen (2002) [11]
Minimize costs based with combined bus and driver scheduling	Valouxis and Housos (2002) [12]
Maximizing the probability that the operation is complete on or before a prespecified target time	Kenyon and Morton (2003) [13]
Minimize the number of vehicles, crew or extra duty minutes	Rodrigues et al. (2006) [14]
Minimize electric bus charging time	Wang and Shen (2007) [15]
Minimize the expected sum of planned costs and costs caused by disruptions	Naumann et al. (2011) [16]
Minimize the mean cost of waiting time for passengers or the mean total cost of waiting time, travel time and operating cost	John D. Lees-Miller (2012) [17]
Minimize net present costs of the transit fleet resource allocation	Mishra et al. (2013) [18]

2.1.1 The Solution Approaches for Solving VSP

VSP belongs to the class of NP-hard and can be solved only by heuristic procedures proved by Bertossi et al. (1987) [7]. Several papers proposed the model to solve the problem.

In the past, the solving of VSP with the complexity set of constraints was often not possible to find an optimal solution because the computer performance was not adequately developed. Since then computer performance has been developed, the ability to solve the combinatorial optimization problem such as VSP is enhanced. Mathematical Programing techniques, linear programming and mixed integer programing, are applied for VSP. With linear programming, the scheduling problem is modeled as a set of linear inequalities whose solution provides the required scheduling information. For mixed integer programming, this modeling scheme borrows ideas from traditional linear programming modeling techniques for scheduling problems; it provides a new modeling framework to address the specific characteristics that are unique to stimuli generation. These characteristics include constraints that improve the quality of the generated stimuli and need to provide random solutions [19]. There are two commonly approaches to solve VSP namely “Cluster First – Schedule Second” and “Schedule First – Cluster Second” [20]. The computational time of the mathematical programming is very large, and many mathematical programing sometimes cannot obtain a feasible solution for long time. Therefore, the researchers who are interested in this method approach try to improve the computational time.

Haghani and Banihashemi (2003) [21] introduced the new model for multiple depot vehicle scheduling problems for the real operational restrictions such as fuel consumption using two techniques to decrease the size of problems. The model was tested and studied on bus transit in Baltimore. It was formulated as an integer-programming problem and Heuristic procedures were used to find acceptable solutions.

The urban transportation problems in Sao Paulo, Brazil based on integer programming models combined with heuristics were solved by Rodrigues et al. (2006) [6]. The model produced good feasible solutions and schedule can meet the demand passenger with restrictions from daily operation. Marc Naumann el al. (2011) [22] presented the new stochastic programming for robust bus scheduling in public transport to minimize the expected sum of planned costs and costs caused by disruptions. Stochastic programming problems are obtained as a result of modeling uncertainty about problem data by specification of probability distributions over these data. If the underlying deterministic problem, the problem induced by a single realization of the random data, is an integer or combinatorial optimization problem. This sets research on stochastic integer programming closer to that in traditional stochastic linear programming than to that in combinatorial optimization. A method to construct the schedule of multi-vehicle sizes is developed by heuristic algorithm (Ceder, 2011) [23]. Indeed, most of the theoretical research on these problems has developed along the paradigmatic lines of stochastic linear programming research. On the other hand, more practice oriented research in the field has concentrated on the use of combinatorial optimization techniques [24].

In 2013, Soares et al. [25] solved the energy resource management problem with EVs and gridable capability (V2G) in order to minimize operation costs and energy costs using Particle Swarm Optimization (PSO) methodology. Particle swarm optimization is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. PSO optimizes a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. This approach performed about 2600 times faster than Mixed- Integer Non- Linear programming. A study to establish a vehicle scheduling model with specific constraints concerning the operation features of electric buses to solve the electric vehicle scheduling problem. Two independent objective functions of minimizing the capital investment for the electric fleet and the total charging demand in stations are involved in the model by Zhu C. and Chen. X. (2014) [8].

Vehicle Scheduling Problem using linear programming and PSO algorithm seems inappropriate with this study. Since these approaches suit for problems which known data parameters such as number of demand passengers in the system. Therefore, the simulation will be used in this regard to simulate unpredictable demand passengers.

2.1.2 Transportation Simulation Model

A simulation of a system is the operation of a model of the system. The model can be reconfigured and experimented with; usually, this is impossible, too expensive or impractical to do in the system it represents. The operation of the model can be studied, and hence, properties concerning the behavior of the actual system or its subsystem can be inferred. In its broadest sense, simulation is a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time.

Simulation usually is divided in two form; discrete event and continuous, based on the manner in which the state variables change. Discrete event refers to the fact that state variables change instantaneously at distinct points in time. In a continuous simulation, variables change continuously, usually through a function in which time is a variable (Martínez, 2002) [26].

2.1.2.1 Simulation Software

Although a simulation model can be built using general purpose programming languages which are familiar to the analyst, available over a wide variety of platforms, and less expensive, most simulation studies today are implemented using a simulation package. The advantages are reduced programming requirements; natural framework for simulation modeling; conceptual guidance; automated gathering of statistics; graphic symbolism for communication; animation; and increasingly, flexibility to change the model. The two types of simulation packages are simulation languages (Table 2-2) and application-oriented simulators. Simulation languages offer more flexibility than the application-oriented simulators. On the other hand, languages require varying amounts of programming expertise. Application-oriented simulators are easier to learn and have modeling constructs closely related to the application. Most simulation packages incorporate animation which is excellent for communication and can be used to debug the simulation program; a "correct looking" animation, however, is not a guarantee of a valid model. More importantly, animation is not a substitute for output analysis.

According to practitioners, simulation modeling and analysis is one of the most frequently used operations research techniques [27]. When used judiciously, simulation modeling and analysis makes it possible to: obtain a better understanding of the system by developing a mathematical model of a system of interest, and observing the system's operation in detail over long periods of time, test hypotheses about the system for feasibility, experiment with new or unknown situations about which only weak information is available, employ a systems approach to problem solving, develop well designed and robust systems and reduce system development time [28].

Table 2-2 Simulation languages

Simulation Language	Description
GPSS H	IBM developed the original version of this langue in 1969. This language provides iterating debugging environment and statistical function.
SIMSCRIPT II	This complete general programming language can be used to build discrete event simulation, continuous simulation and combined simulation.
SIMAN/ARENA	This is a combined simulation language and animation system. This software can be used to build discreet event simulation, continuous simulation and combined simulation.
SLAM II	This language is used for process-oriented simulation and event oriented simulation and the combine of the two. This language represent model in a network like structure that include node and branches.

2.1.2.2 SIMAN/Arena

SIMAN is a powerful general propose simulation language for modeling discrete, continuous and combined systems. Arena is the animation component of the SIMAN simulation (Pegden, 1990) [29]. SIMAN is designed around a logical modeling framework in which the simulation problem is divided into different modules in the system. This division is based on the theoretical concept about system developed by Zewigler (1976) [30]. The model describes the physical element and logical element of the systems. The experiment specifies the experimental condition under which will run including the initial condition, running time and replications.

2.1.3.3 Arena with Transportation Problems

O. Koch (2003) implemented the simulation model used in the analysis of the transport logistics of the Austrian Red Cross rescue organization [31]. The emphasis is on the details of modeling the scheduling of ambulance service associated with different criteria for the performance of the system is discussed. The simulation results show the validity of the model and also give hints on possible improvements.

Some scholars have conducted research for the public transport vehicle scheduling problem. Francisco E. Martínez designed the SIMAN/Arena model of the heavy rail operation in the United States [32]. To visualize the system performance, the model must include an animation of traffic process. The simulation model gives the capability to use a realistic model of the rail network including a group of four consecutive stations simulate the vehicle operating and compute special system performance parameters such as waiting time in platforms and on time performance. Moreover, a simulation will allow analyzing the track layout, operation strategies, modeling coordination, on time performance and comparing schedule operation and headway operation of the system.

The simulation models of shutter bus transportation were designed by Al-Sabban and Ramadan (2005) [33] in the annual Islamic pilgrimage between two segments using Arena simulation system. The simulation model is used to conduct a series of experiments designed with the characteristics and the limitations of the system. The optimization of transport solutions using evolutionary algorithms coupled with the simulation model using Arena simulation software to optimize the complex mail transportation network in Sweden was described by S. J. Mason, R. Hill, L. Moench, and O. Rose (2008) [34]. Some authors simulated bus metro transit system to analyze bus schedules from passenger responsive mainly on waiting time in queues and the length of queue to give the feasibility studies for new bus schedule can be carried out to obtain certain levels of user satisfaction [35],[36].

The main reason for simulation’s popularity is its ability to deal with very complicated models with correspondingly complicated systems. This makes it a versatile and powerful tool. Arena is one of the most popular commercial simulation environments at the moment, and it was one of the first simulation environments that allowed for the development of building blocks by simulation experts. However, many transportation problems are solved using Arena simulation. Finally, advances in the simulation power, flexibility, and ease of use have moved the approach from the realm of tedious and error-prone low-level programming to the Arena of quick and valid decision making. Effectiveness of Arena simulation are now even greater and precisely due to these advances in computer hardware and software.

Because many real systems are affected by uncontrollable and random inputs, many simulation models involve random input components, causing their output to be random also. In many simulations, as the time frame becomes longer like months instead of a day, most results averaged over the run will tend to settle down and become less variable, but it can be hard to determine how long is “long enough” for this to happen. Moreover, the model or study might dictate that the simulation stop at a particular point, so it needs to run longer to calm the output in inappropriate.

2.2 Energy Storage System for Electric Bus

Conventional transportation has gradually changed from fossil fuels to battery powered electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Battery is a storage device which consists of one or more electrochemical cells that convert the stored chemical energy into electrical energy. There are several characteristics that one should take into account in selecting the most appropriate battery for EV [37]. As of now, the Lead-acid, Lithium-ion and Nickel Metal Hydride (NiMH) are three of the most popular candidates for the EV battery [38].

Lead-acid batteries, the oldest and most developed battery, are a rechargeable battery types and composed of a sponge metallic lead anode, a lead-dioxide cathode and a sulfuric acid solution electrolyte. Having a lot of advantages such as relatively low cost, simplicity of manufacture, quick electrochemical reaction kinetics and good cycle life under measured conditions made them quite attractive and dominate the market [39]. Various types of lead-acid battery have been developed namely, Lead Antimony Batteries, SLI Batteries (Starting Lighting and Ignition), Valve Regulated Lead Acid (VRLA) Batteries, Lead Calcium Batteries, AGM Absorbed Glass Mat Battery, Gel Cell, and Deep Cycle Batteries. [40].

Lithium batteries are primary batteries composed from lithium metal or lithium compounds as an anode. The advantages such as lightweight, safe, abundant and low cost cathode material make them a promising technology for future mobile applications. Li batteries offer higher charge densities of 100–150 Wh/kg and have limited environmental impact since the lithium oxides and salts can be recycled. However, the high cost of the battery due to special packaging and internal overcharge protection circuit Lithium batteries is their main obstacle to compete with another type of battery [41]. The significant improvement of storage capacity makes Li-ion batteries become more attractive to electric car manufacturers.

With the drawbacks of short range and long recharge time, the candidate of energy storage system is supercapacitor. Supercapacitor also offers a great advantage over batteries such as the ability to be charged and discharged continuously without degrading. Hybridization of energy storage system made up of a supercapacitor integrated with a lead–acid battery cell. is developed to meet an efficient, low emission power source for hybrid electric vehicles that could also provide a solution to the intermittency of electricity production from renewables. Commonly, supercapacitors are used for starting engines, actuators, and in electric/hybrid-electric vehicles for transient load leveling and regenerating the energy of braking. Many authors studied and designed an appropriate energy storage system based on supercapacitors with lead-acid battery [42], lithium-ion battery [43],[44] and NiCd bettery [45] to optimize and derive the best solutions of components sizing and control strategy.

CHAPTER 3

RELATED THEORIES

3.1 Energy Storage System

3.1.1 Battery

A more challenging issue to EV is the energy capability of battery. Though the energy consumption during driving depends on many factors such as vehicle size, weight, body shape, and the driving behavior, the key factor is the capability of the energy storage device. The high value of specific energy of gasoline gives a conventional internal combustion engine powered vehicle a range of 300 – 400 mils with a full tank of gasoline. Gasoline has a theoretical specific energy of 13,000 Wh/kg, which is over 100 times higher than the specific energy of 120 Wh/kg of typical Li-ion batteries. However, since the electric propulsion is much more efficient than an ICE, less energy needed to propel an EV. Considering the efficiency of 80% for EV propulsion and 20% for ICE, the total amount of energy stored for EV can be a quarter of what a regular ICE powered vehicle needs for the same mileage. Based on the current battery technology, it is not practical to consider a pure BEV with a mile range of 300–400 miles since it would require a battery pack larger than 100 kWh that can weigh over 900 kg. Nevertheless, it is realistic to have a battery pack around 30 kWh to achieve 100 miles range even based on current battery technologies.

3.1.2.1 Lead – Acid Battery

3.1.2.1.1 Basic Chemistry

The electrolyte contains aqueous ions (H^+ and SO_4^{2-}). The conduction mechanism within the electrolyte is via migration of ions via drift and diffusion (Figure 3-1).

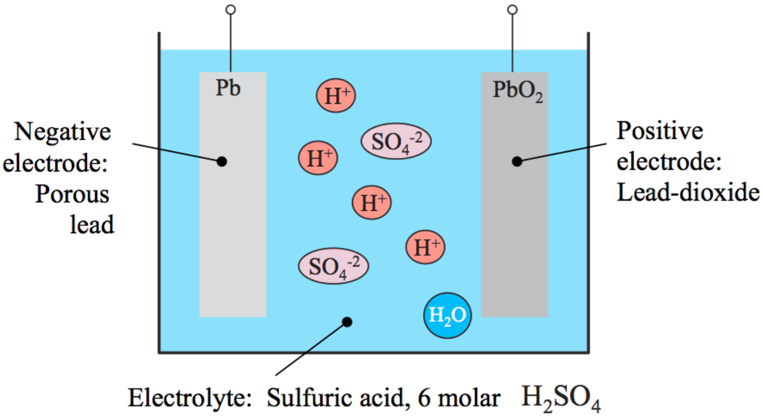


Figure 3-1 Lead-acid battery cell chemistry

3.2.2.1.1.1 Cathode Reaction

Charged sulfate ion approaches uncharged lead electrode surface, dipole attraction kicks in on close approach then lead atom becomes ionized and forms ionic bond with sulfate ion. Two electrons are released into lead electrode as shown in Figure 3-2

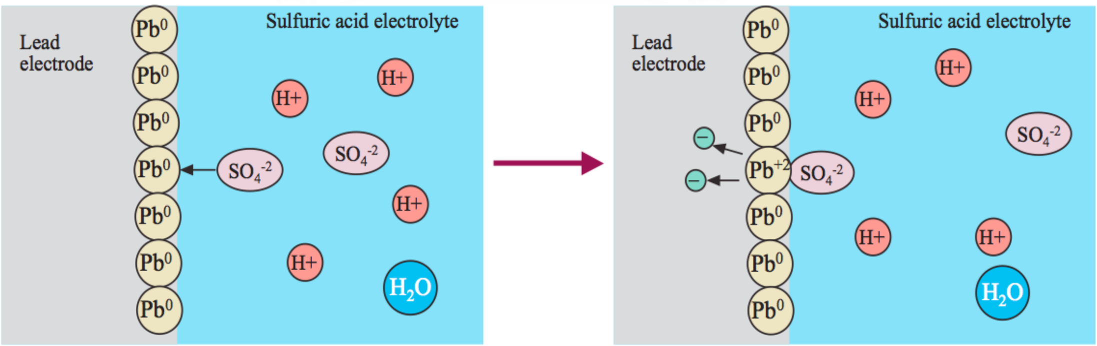


Figure 3-2 Reactions at negative (Pb) electrode

The reaction equation becomes

$$\text{Pb (s)} + \text{SO}_4^{2-}\text{ (aq)} \rightarrow \text{PbSO}_4\text{ (s)} + 2e^- \qquad (3.1)$$

This reaction releases net energy $E^0 = 0.365$ eV under standard conditions ($T = 298$ K, 1 molar concentration). As electrons accumulate they create an electric field, which attracts hydrogen ions and repels sulfate ions, leading to a double-layer near the surface. The hydrogen ions screen the charged electrode from the solution which limits further reactions unless charge is allowed to flow out of electrode.

3.2.2.1.1.2 Anode Reaction

Charged sulfate and hydrogen ions approach lead-dioxide molecule (net uncharged) on surface of electrode then lead atom changes ionization and forms ionic bond with sulfate ion. Two water molecules are released into solution as shown in Figure3-3.

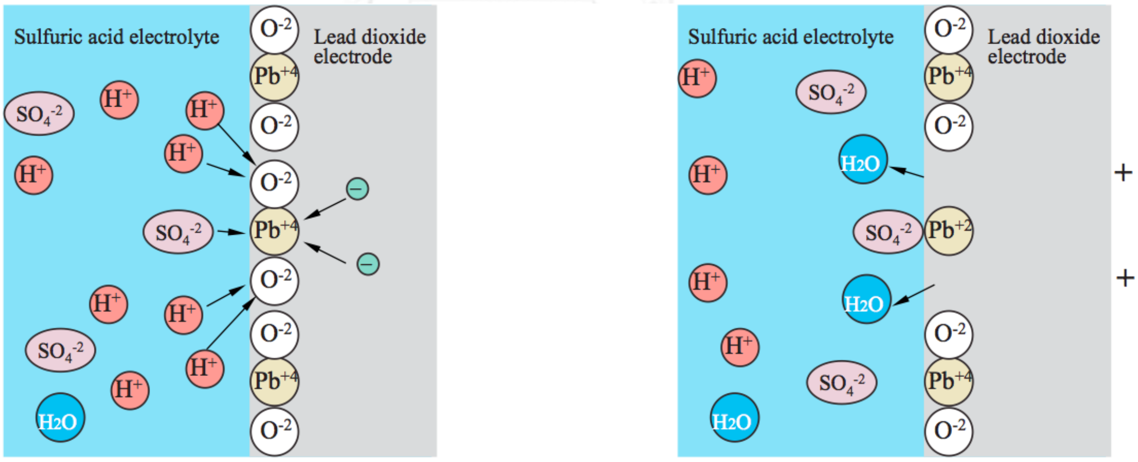


Figure 3-3 Reactions at positive (PbO_2) electrode

The reaction equation becomes

$$\text{PbO}_2\text{ (s)} + \text{SO}_4^{2-}\text{ (aq)} + 4\text{H}^+\text{ (aq)} + 2e^- \rightarrow \text{PbSO}_4\text{ (s)} + 2\text{H}_2\text{O (l)} \qquad (3.2)$$

This reaction releases net energy $E^0 = 1.685$ eV. As positive charge accumulates an electric field is created which will attract sulfate ions and repel hydrogen ions (charge screening) limiting further reaction unless charge is allowed to flow out of electrode.

3.1.2.1.2 Discharge through External Load

As battery is discharged, additional sulfating of electrodes occurs and acid electrolyte becomes weaker, lowering the terminal voltage. Note that the current must flow through electrolyte to complete the circuit. The conductivity of electrolyte and the contact resistance of sulfated electrodes contribute to internal resistance of battery.

3.1.2.1.3 Charging from External Source

The chemical reactions are driven in the reverse direction, converting electrical energy into stored chemical energy. As the battery is charged, the lead sulfate coating on the electrodes is removed, and the acid electrolyte becomes stronger.

3.1.2.1.4 Battery State of Charge (SOC)

SOC is defined as the remaining capacity of a battery and it is affected by its operating conditions such as load current and temperature.

An easy method to estimate the State-of-Charge (SOC) of the battery is by measuring the Open Circuit Voltage (OCV). This measurement should be made after the battery has been at rest for a minimum of four hours with the battery shut off from its charging source and load. The voltage is listed as Volts/cell and for a 12V (6 cell) battery at 25 C (77 F)

Table 3-1 SOC vs. OCV

State of Charge (%)	OCV per cell	OCV per 12V battery
100	2.13 or greater	12.8 or greater
75	2.08	12.5
50	2.03	12.2
25	1.98	11.9
0	1.93 or less	11.6 or less

These voltage levels are approximate and give an indication of the state of charge of a battery at rest. As the battery ages these voltage measurements will be lower.

3.1.2.1.5 Battery Equivalent Circuit

During discharge, ohmic losses in electrolyte and contacts lower voltage. Internal impedance increases due to lowering electrolyte concentration and electrode sulfation. During charging, effective resistance is low while sulfate buildup on electrodes is removed, resistance increases once electrolyte concentration is restored. Continued charging beyond this point leads to electrolysis of water and gassing as shown in Figure 3-4.

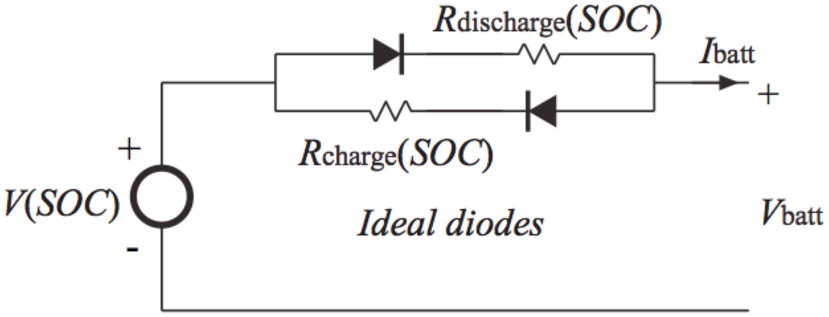


Figure 3-4 Battery equivalent circuit

3.1.1.2 Lithium-Ion Battery

The Lithium-ion battery was first proposed by Exxon with lithium metal in 1970 and then the rechargeable battery was developed with lithium cobalt oxide in 1979. Due to safety issue, Lithium metal electrode is replaced with lithium ion even though the energy density is less. In 1991, Sony commercialized the Lithium-ion Battery. Now, more than 60% of portable rechargeable batteries used are Lithium-ion Battery. The lithium is the lightest metal of all metals. Lithium-ion has a nominal single cell voltage of 3.6 V, which is fixed by the battery chemistry. In order to obtain higher voltages, cells are put together in series. Lithium-ion replaces Ni-MH batteries in portable electronics.

The Lithium-ion battery is one of rechargeable battery types that lithium ions move from anode to cathode during discharge, and back when charging. With Lithium-ion batteries currently gaining much attraction in electric vehicle and the concern for global warming with clean environment may be well served with advances in such systems.

Lithium-ion cells are being built in many different shapes and configurations button, flat, rectangular and cylindrical. The cell components (electrodes, electrolyte, and separator) are designed to accommodate a particular cell shape and design. The separators are either stacked between the electrodes or wound together with electrodes to form jellyrolls, as shown in Figure 3-5.

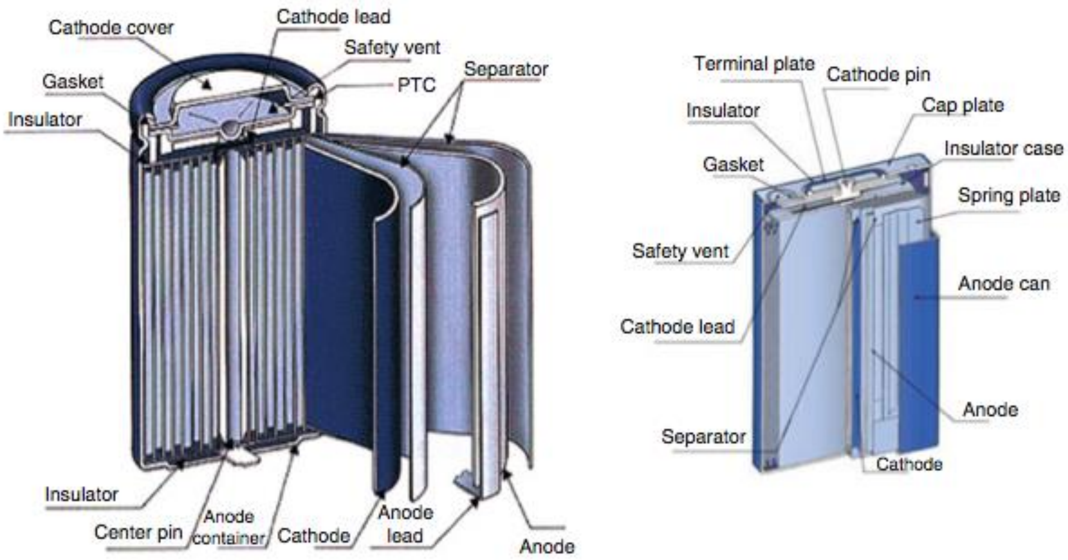


Figure 3-5 Typical Li-ion battery configuration: (a) spirally wound cylindrical cell, (b) wound type prismatic cell

The Specific Energy refers to the amount of energy that can be stored per unit weight. This value is very important for portable equipment as heavy batteries will be difficult and energy consuming to move around. The Specific Energy of Lithium-ion batteries are much higher than all the batteries. The cost of Lithium-ion is higher than the Ni-MH Batteries.

Energy Density describes how much energy can be stored per unit volume. For portable electronic equipment, the space required for a given storage capacity is an important figure. The Energy Density is twice than that of Ni-Cad, approximately equal to the NiMH Lead-acid batteries.

Specific Power refers to the maximum amount of power can that can be delivered. In electrical terms, this is the maximum Discharge Rate of the battery. Performance is better compared to alkaline batteries in higher drain devices. Specific power of Lithium-ion is less compared to NiMH but higher than Ni-Cad and lead acid batteries.

The Charge/Discharge efficiency is also an important factor for the practical use of the battery. Their efficiency for Lithium-ion is too high and no maintenance is required. The higher volumetric and gravimetric energy storage capability are key characteristics of the Li-ion battery system compared to the conventional sealed nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), and valve-regulated lead acid (VRLA) battery systems. Figure 3-6 presents the energy density and specific energy comparisons of small sealed rechargeable battery systems. Some of the distinct advantages of Li-ion system over other commercial rechargeable systems are the choice of chemistry with highest energy and lightest weight, good cycle life, no memory effect, higher energy efficiency, and better high rate capability. Of course there are also certain issues for Lithium-ion system similar to any other high-energy storage devices that include higher charging times, thermal runaway concerns, relatively more expensive, and requiring advanced protection circuitry for safety and to prevent overcharge and over discharge.

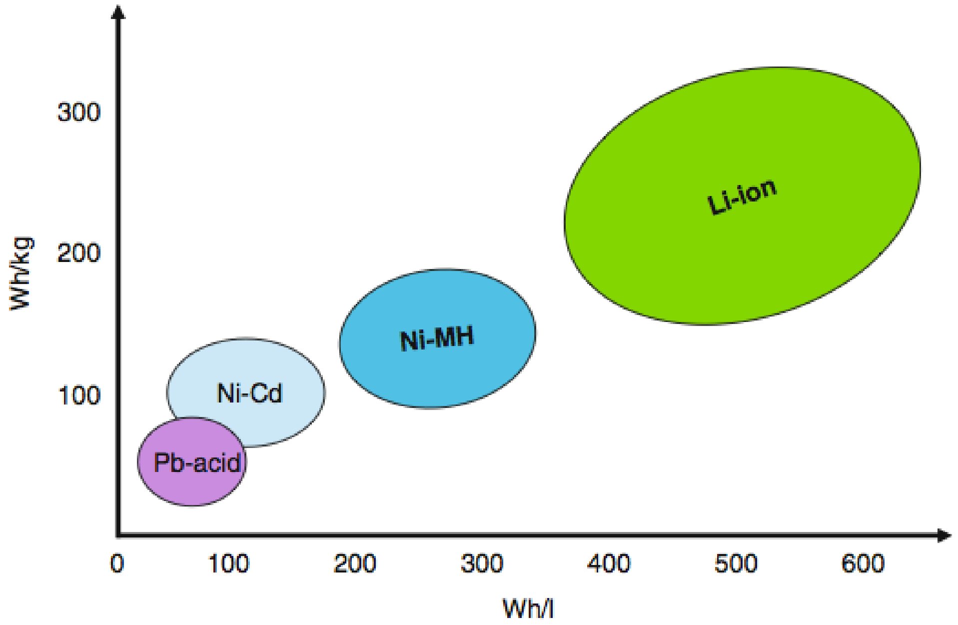


Figure 3-6 Volumetric energy density (Wh/l) and gravimetric energy density (Wh/kg) for major rechargeable battery systems

3.1.1.3 Battery Capacity

Battery Capacity is defined as the current that discharges the battery in 1 hour, so battery capacity can be said to be C Ampere-hours. In practice, the relationship between battery capacity and discharge current is not linear, and less energy is recovered at faster discharge rates.

Peukert's Law relates battery capacity to discharge rate

$$C_p = I^k t \tag{3.3}$$

Relationship between C and C_p becomes

$$C_p = C^k \tag{3.4}$$

The Amp-hr capacity is then

$$It = Ct^{1-\frac{1}{k}} \tag{3.5}$$

where C_p is the amp-hour capacity at a 1 A discharge rate

I is the discharge current in Amperes

t is the discharge time, in hours

k is the Peukert coefficient, typically 1.1 to 1.3 for Lead-acid battery

3.1.2 Supercapacitor

Electric double-layer capacitors or supercapacitors, electrochemical double layer capacitors are electrochemical capacitors that have the high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor.

In a conversional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be amassed in an external circuit. The total energy stored is proportional to both the amount of charge stored and the potential between the plates so it is limited by breakdown of the dielectric. Optimizing the material leads to higher energy density for a given size of capacitor. Supercapacitors do not contain a dielectric block. The electrical double layers are formed in the electrolyte surrounding the particles, leading to effective separation of charge on the order of nanometer scale. The area of the electrical double layer depends on the surface area of the particles. High capacitances result from the practical –sized packages. In an electrical double layer, each layer by itself is quite conductive, but the physics at the interface where the layers are effectively in contact means that no significant current can flow between the layers.

For series combination, the capacitance is reduced by the number of cells placed in series becomes

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ... + \frac{1}{C_N} \tag{3.6}$$

When placing capacitors in parallel, the capacitance is increased by the number of cells placed in series become

$$C_{Total} = C_1 + C_2 + C_3 + ... + C_N \tag{3.7}$$

Supercapacitor differs from batteries that produce electricity through chemical alterations. Accordingly, it will show very little degradation regardless of the number of times it is charged and discharged, and is capable of being operated in harsh environments without affecting performance.

In term of both environment and energy issues, “idling stop” to stop automobile engines at red lights is attracting worldwide attention. Idling stop forces an automobile engine to stop and start-up approximately 1 million times during the life of the vehicle. To solve this, electricity is accumulated in the supercapacitor from the battery is used to start up the engine

Electric vehicles and hybrid cars are designed to use energy efficiently, and reuse the energy generated and accumulated during automobile deceleration. The time period for this energy generation is very short, meaning that batteries can recover only 30% of the energy but supercapacitor can recover approximately 80% of this energy.

3.2 Vehicle Scheduling Problems

Scheduling problems are characterized by delivery-time restrictions. The starting and ending time for a service may be specified in advance. Subway or bus schedules fall into this problem since the arrival times at each stop are known in advance and the train or bus must meet the schedule. The general input for a scheduling problem consists of a set of tasks, each with a starting and ending time, and a set of directed arcs, each with a starting and ending location. The set of vehicles may be housed at one or more depots. The network in Figure 3-7 shows a five-task scheduling problem with a single depot. The nodes identify the tasks. Each task has a start and an end time associated with it. An arc may join node I to node j if the start time of task j is greater than the end time of task i. An additional restriction is that the start time of task j must include a user-specified period of time longer than the end time of task i. In this example, the time from one point to another point is 45 minutes. This is referred to as deadhead time and is the nonproductive time required for the vehicle to travel from one task location to another or return to the depot empty. Also, the paths are not restricted in length. Finally, each vehicle must start and end at the depot.

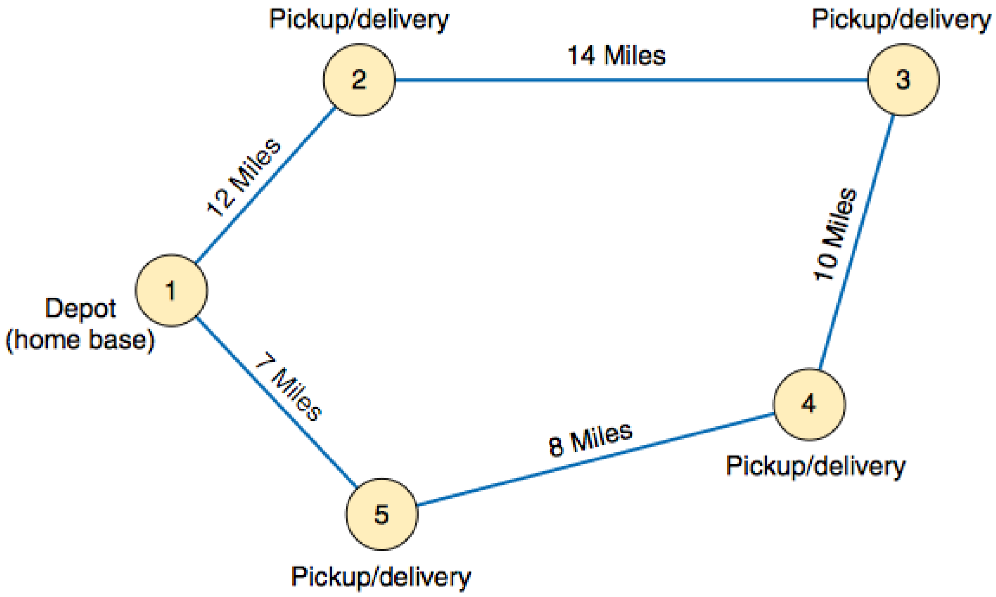


Figure 3-7 An example of vehicle scheduling problem

To solve this problem, the nodes in the network must be partitioned into a set of paths and a vehicle assigned to each path. Scheduling workers is often concerned with staffing desired vehicle movements. The two are of necessity related in that vehicle schedules restrict staffing options, and vice versa. In general, vehicle scheduling is done first, followed by staff scheduling. This approach is appropriate for service such as airlines, where the cost of personnel is small in comparison to the cost of operating in airplane. It is less appropriate, however, for services such as mass transit systems, where personnel costs may account up to 80% of operating costs. For such systems it is more appropriate to either schedule personnel first, then schedule vehicles, or to do both at the same time.

3.3 Simulation Model

Simulation model is gathering the various solutions or the behavior of the systems using computer software in order to study the flow of events and help to demonstrate, predict and measure system strategies. Arena simulation is discrete event simulation and automation software developed by Rockwell Automation.

To build a simulation model and to carry out simulation runs with Arena, a basic model is constructed and Arena will provide the model window flowchart view, which is a flowchart-style environment for building a model then connect them to define process flow of the model.

The model is a functional description of the system component and their interactions. This framework presents the logic of the model, the creation of an entity and the entity movement through the different queues and resources in the system. In the framework some blocks are presented that, assign values to an attribute or variable and other blocks, which can compute any system statistics.

The experimental framework defines the experimental condition of the model such as run length and initial conditions. In this framework the modeler defines all the resources, queues, attributes, variables, specific statistics that are used in the model. In addition, the modeler establishes the number of repetitions and the desired results in the report. The system compiles the discrete modules. When the modules are compiled, SIMAN sends an extended listing of the source file to the screen as each input statement is compiled. During this process, SIMAN presents the errors, if any, in the model and the experiment. Once the model and the experiment source files have been compiled without error in to the object file, the next step is to link the tool resulting object in to the program file. The link file combines the experiment and the model object file in form that can be read and executed by the SIMAN simulation program.

When the files are successfully linked; the system is ready to execute the simulation. This program reads in the program file and executes the simulation. In this task, SIMAN creates and writes the data to any output files in the experiment and the result of the simulation.

3.4 Queuing Theory

Queuing theory is the mathematics of waiting lines. It is extremely useful in predicting and evaluating system performance. Queuing theory has been used for operations research. Traditional queuing theory problems refer to customers visiting a store, analogous to requests arriving at a device. Queuing theory is the mathematics of waiting lines. Queuing theory provides long term average values. It does not predict when the next event will occur. Input data should be measured over an extended period of time. Arrival times and service times are assumed as random.

3.4.1 Assumption of Queuing Theory

1. Independent arrivals
2. Exponential distributions
3. Customers do not leave or change queues
4. Large queues do not discourage customers

3.4.2 Queuing Model

Queuing is a common phenomenon in our daily lives. It is impossible to avoid queuing as long as the number of people arrived is greater than the capacity of the service facility as shown in Figure 3-8.

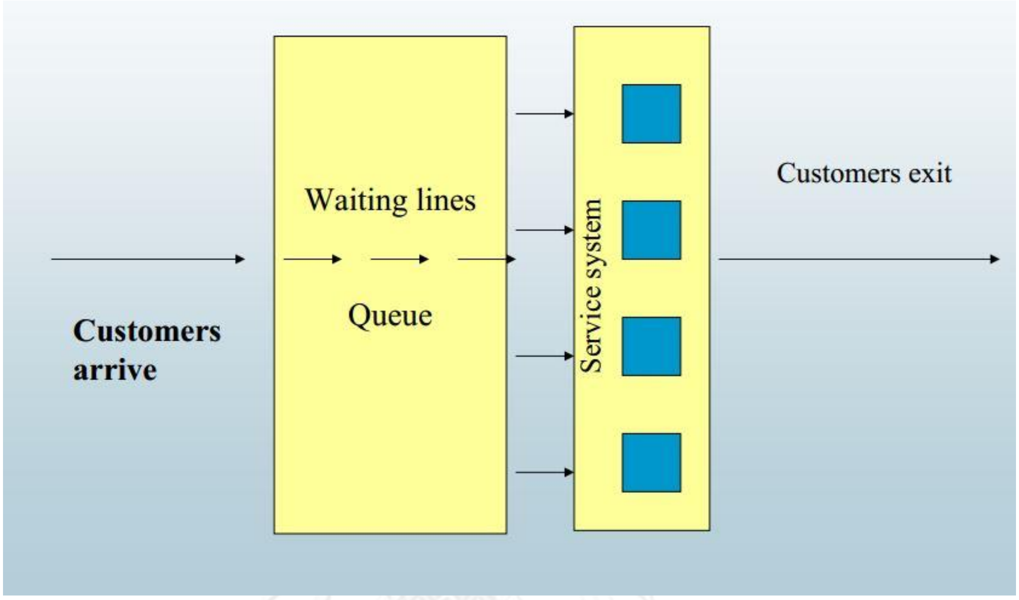


Figure 3-8 Queuing model

Parameter of Queuing Theory

1. Passenger arrival rate (λ) is the average rate at which customers arrive measured in arrivals per time period. Common units are access/second.
2. Passenger boarding time (S) is the average time required to service one customer.
3. Waiting queue (W) is the average number of customers waiting.
4. Number in the system (Q) is the average total number of customers in the system.
5. Time in the system (T_q) is the average time each customer is in the system, both waiting and being serviced.
6. Time waiting (T_w) is the average time each customer waits in the queue.

$$T_q = T_w + S \tag{3.8}$$

The inter-arrival time, A, is the average time between customer arrivals. It is measured in time per customer. A common unit would be seconds/access.

$$A = \frac{1}{\lambda} \qquad (3.9)$$

3.4.3 Exponential Distribution

The exponential distribution is used for the waiting time until the first event in a random process where events are occurring at a given rate. It is a relatively simple distribution; a random variable having this distribution is necessarily positive, and it is one of the more important distributions among those used for positive random variables.

3.5 Hypothesis Test using T-Test Distribution

T-tests are widely used statistical methods to compare group means. For a t-test, the mean of a variable to be compared should be substantively interpretable. Technically, the left-hand side (LHS) variable to be tested should be interval or ratio scaled (continuous), whereas the right-hand side (RHS) variable should be binary (categorical). The t-test can also compare the proportions of binary variables. The mean of a binary variable is the proportion or percentage of success of the variable. The t-test assumes that samples are randomly drawn from normally distributed populations with unknown population variances. The variables of interest should be random variables, whose values change randomly. A constant such as the number of parents of a person is not a random variable. In addition, the occurrence of one measurement in a variable should be independent of the occurrence of others. In other word, the occurrence of an event does not change the probability that other events occur. This property is called statistical independence. Time series data are likely to be statistically dependent because they are often autocorrelated.

The t-test can be conducted on a one sample, paired samples, and independent samples. The one sample t-test checks if the population mean is different from a hypothesized value (oftentimes zero). When two samples have the same population variance, the independent samples t-test uses the pooled variance when computing standard error. Otherwise, individual variances need to be used instead in computation, and degrees of freedom should be approximated. The folded F test is used to evaluate the equality of two variances. In both cases, the null hypothesis is two samples have the same mean.

While the independent sample t-test is limited to comparing the means of two groups, the one-way ANOVA (Analysis of Variance) can compare more than two groups. ANOVA use F-statistic to test if all groups have the same mean. Therefore, the t-test is considered a special case of the one-way ANOVA. When comparing means of two groups (one degree of freedom), the t statistic is the square root of the F statistic of ANOVA ($F=t^2$).

CHAPTER 4

BUS FLEET MANAGEMENT

4.1 Bus Operation Descriptions

The present study focused on one of the four bus line, bus #3. The bus model considered is a 4-ton battery electric bus with 20 seats capacity and now runs on the fleet size of 3 buses (Fig. 4-1). The electric drive operates on a set of 24 deep-cycle lead-acid batteries connected in series. The bus specifications are shown in Table 4-1.

Table 4-1 Specification of bus #3

Capacity (seats)	45 (20)
Wheel base	3.3m
Length/width/height	6.75m / 2.1m / 2.8m
Battery type	Lead-Acid (24 batteries, 307.2V)
Top speed	60 km/h

Figure 4-1 Appearance of electric bus

Routes and bus scheduling are set up to transport the students and faculty members between departments and to the metro station during the weekdays between 6.40 AM and 7.00 PM. There are different schedule for each bus. The route is in the university campus in its entirety; hence the traffic is not influenced by the city traffic outside the campus.

4.2 Data Collection and Analysis

The shutter-bus service consists of 3 buses each bus maximum capacity is 45 persons with the fixed bus schedule for each bus. The charging time is approximately 1 hour and 25 minutes. Probability distributions are made from time arrivals of bus arrivals and frequency of passenger arrivals. Bus schedules are required for the purpose. They are collected from bus carrier. These data includes the departure time from depot to each stations, cumulative number of passengers for each trip and battery voltage at different time segments of the day. These data was collected in all stations by three observers for two hours. One hour of rush hour and one hour of non-rush hour data. The data is used in Arena Input Analyzer to make arrival distributions. The input data parameters required for this model are described in Table 4-2.

Table 4-2 Input data parameters

Shuttle bus	Fleet size Bus velocity Bus capacity Boarding time
Station	Number of stops Bus direction Route distance
Customers	Customer arrival rate
Schedule	Bus schedule Bus charging time

Assumptions

1. The simulation is based on passenger activities on isolated stations. Effects on adjacent bus stoppages are not considered.
2. Boarding into bus is simplified into 10 seconds for each passenger.
3. Passenger arrival rates for each stop are exponential distribution and estimated the demand passengers from driver log book schedule in the percentage (Table 4-3).

Exponential probability distributions and estimates are made to simulate the service system. They are passenger arrival rate, passenger boarding time and drop off time, waiting queue for bus and distribution of people from each station to other stations. The distributions of passenger required to the model the passenger arrivals are in the following Table 4-3.

Table 4-3 Passenger demand percentage estimation

No.	Station	Percentage
1	Medical	25%
2	Political Science	10%
3	Sala phrakaew	25%
4	Science	10%
5	Architecture	10%
6	Arts	10%
7	Engineering	10%

4.3 Simulation Model

The simulation proposed bus transit system and passenger arrivals. Events like passenger arrival, waiting in queue and boarding are considered between bus stations and buses then leave the system. A model developed in Arena environment is composed of a set of modules; each of that reproduces the behavior of the physical objects or entities in the specific observed case or changes their characteristics. Prior to the execution of the model, these modules are transformed by Arena into instructions handled by a simulation engine named Siman. In addition, the Arena environment is made more flexible and adaptable to the needs of the model to realize and allows easily building the new specific required functionalities and creating user forms to collect parameters required to run tests. Moreover it is also able to communicate in an efficient manner with databases in order to record the simulation results or to acquire information for further tests to be carried out. Finally Siman through the use of dedicated statements can easily exchange values whenever it is required and therefore fully interface with each other.

4.3.1 Building Blocks of Model

The Arena building blocks used in the present study are Create, Waiting, Assign, Pickup, Decide, Delay, Hold and Dispose. The architecture of the proposed simulation model is made up of a series of modules dedicated respectively to: the acquisition of requests to be evaluated and carried out, the simulation of movement of bus and passengers, the monitoring of possible delays and display of events that actually occur while the simulation runs. Finally, during the simulation a set of performance indicators is calculated to evaluate the robustness of the schedule produced by the Heuristics in response to disturbing elements introduced in the simulation. The simulation model is made up of a series of modules dedicated respectively: Schedule module, Queue module and Bus movement module.

4.3.1.1 Schedule module

The bus schedule was gathered from the bus carrier. These schedules were inserted in the block diagram with mixed bus schedule each day to calculate passenger arrival rates. Service time has been processed and grouped into 12 sections by the number of passengers (Table 4-4).

Table 4-4 shows the passenger arrival rates at the bus stops. The cumulative numbers of passengers from the log book were divided following by the different percentage (Table 4-3). During the time 11.00 - 12.55, the maximum number of total passengers and passengers decreased until 16.00 then again become increasing. It meant that there are 2 peak periods in a day

.

Table 4-4 Passenger arrival rates at the bus stations

Section	Time Arrival	Average Passengers	Duration (Minutes)	Total Passenger	Passenger Arrival Rate per 1 hr.
1	6.40 – 7.50	18.57	90	73.57	0.020390
2	8.05 – 8.30	33.87	60	106.42	0.009396
3	9.05 – 9.55	33.40	60	67.10	0.014903
4	10.10 – 10.45	43.20	60	99.96	0.100040
5	11.00 – 11.55	60.00	60	258.62	0.003867
6	12.05 – 12.55	66.42	60	285.75	0.003500
7	13.05 – 13.55	48.50	60	109.56	0.009127
8	14.00 – 14.50	46.83	60	136.43	0.007330
9	15.00 – 15.50	40.60	60	103.34	0.009677
10	16.00 – 16.50	51.16	60	192.85	0.005185
11	17.00 – 17.50	29.16	60	203.22	0.009688
12	18.00 – 19.00	39.43	60	98.56	0.010146

4.3.1.2 Queue module

This module obtained the passenger arrival rates from the schedule module to generate the waiting time and passenger arrival rate at each bus stop with exponential distribution. For the weight percentage of passenger waiting at each stop, three persons were allocated to collect the number of passengers waiting in queue at the bus stop for three days focused on one hour of rush hour and one hour of normal hour. They reach the bus stop and await the bus arrival. The average passenger agreed time is 12.18 minutes.

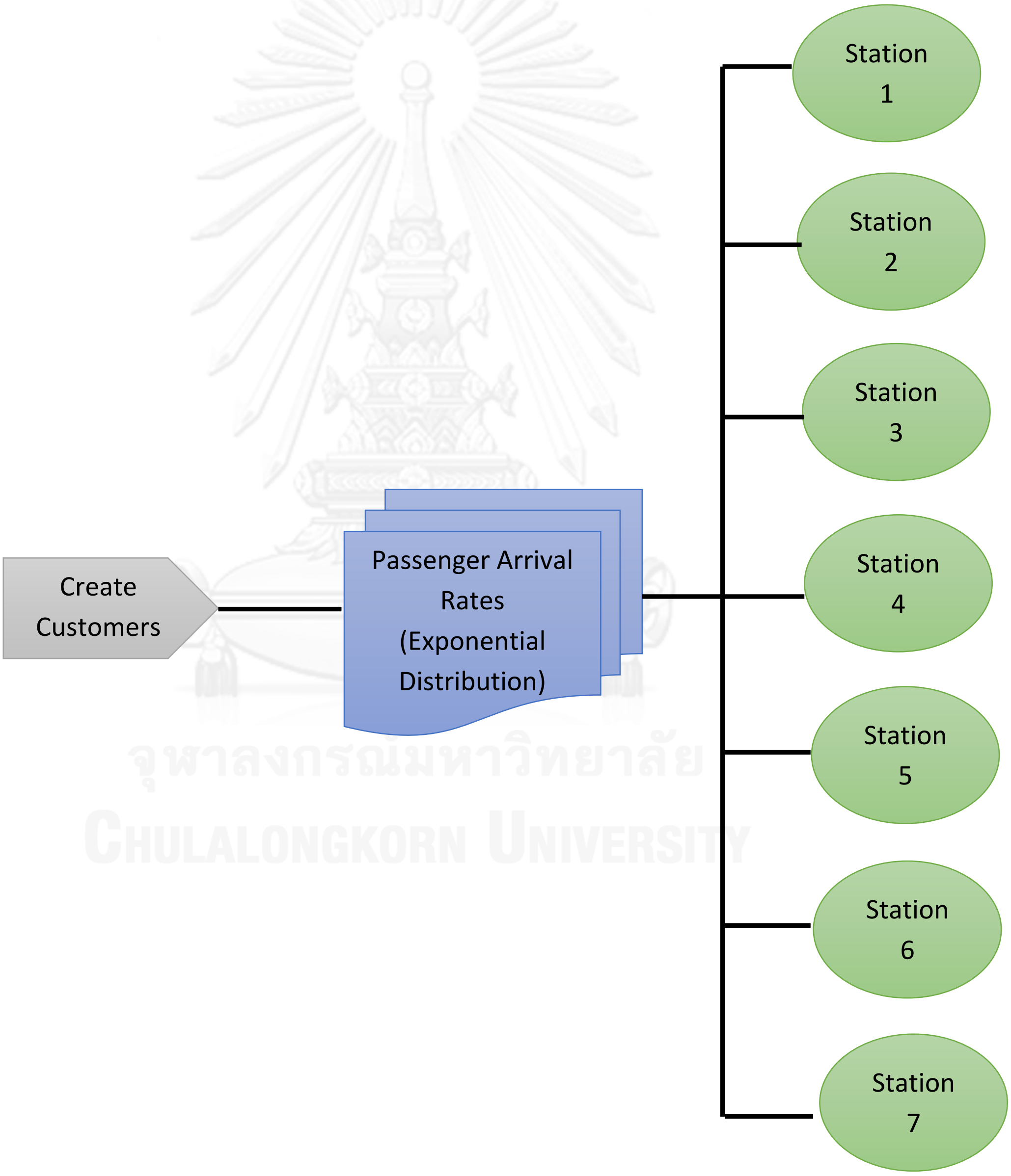


Figure 4-2 Arena model for passenger arrival rate at each bus stop

4.3.1.3 Bus movement module

Bus movements are described through various steps starting from depot to Sala phrakaew. The bus moves directly from depot to Sala phrakaew (station 3) then waiting for passengers then go to Political Science (station 2) then drop off and pick up passengers from this stop and so on for the other stations. For the block 'delay' means the time that the bus takes from one station to another station.

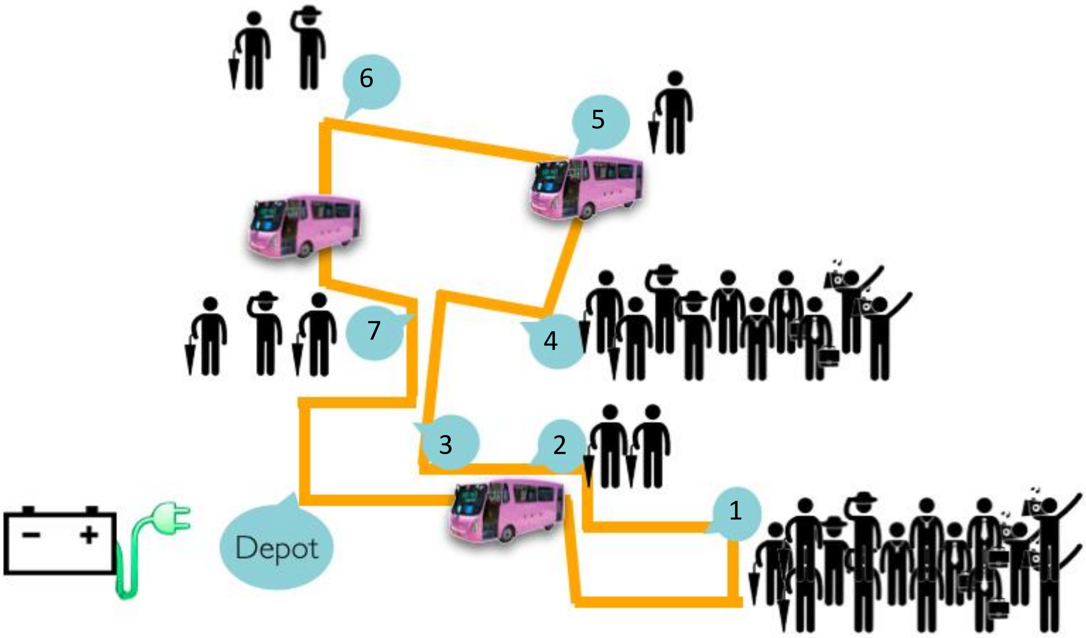


Figure 4-3 Arena model for bus movement module

This module described the movement of the buses through various steps starting from depot to other stations included the bus activities such as pickup, drop off, boarding and waiting for the passenger. In addition, bus charging module is included. When voltage of the batteries dropped below 260V, the bus driver must decide to go back and charge batteries at the depot.

4.3.2 Model Validation

The model validation was performed by comparing the simulation model behavior with real system behavior. The comparison is carried out by one-sample T-test distribution. Two parameters were used to validate the model:

1. The number of passengers in the system

In this model, the cumulative numbers of passenger were validated by comparing the data obtained from the driver logbook with the simulation model output. The percentage difference value between the real system and the simulation output is 2.76% and significant with P-value 0.331 at 95% confidence interval.

2. Waiting time

These data were validated by comparing direct observation and simulation model output. The data is divided into two intervals, one hour for rush hour and one hour for normal hour. The percentage difference in values are for the two intervals 11.47% and 10.63% and also significant with P-value 0.384 and 0.225 respectively at 95 % confidence interval.

CHAPTER 5

ENERGY STORAGE SYSTEM

The experiment consists of two parts. The first part is to gather a driving cycle to be used in energy storage system evaluation. The second part is the evaluation of an alternative types of energy storage systems on the discharge characteristics. The results of this evaluation will be used in the bus operation simulation.

For the present study, the lead-acid battery is considered the base-line energy storage system. Two alternatives will be explored for the possible improvement namely, lead-acid battery equipped with supercapacitor and lithium-ion battery. The energy storage system parameters are summarized in Table 5-1.

Table 5-1 Parameters of the energy storage options

	Lead-acid Battery YUASA EB130 Deep Cycle	Supercapacitor Boostcap Maxwell	Lithium-ion Battery Calb CA100
Battery Characteristics	130 Ah, 12.8 V, 35.2 kg.	16.2 VDC, 250 F, 1.68 kg.	100 Ah, 12.8 V (4 cells), 13.6 kg.
Nominal Energy Density	40 Wh/kg	5.4 Wh/kg	110 Wh/kg
Specific Energy	1.408 kWh per unit	1.52 kWh per unit	1.496 kWh per unit

5.1 Driving Cycle Characteristics

The driver followed the usual driving route and obtained the data of voltage and current measured from the batteries and velocity profile by using Kayaba® drive-recorder and GPS. The goal of this test is to gather the power data provided by batteries and use the power profile (Fig.5-1) to run with the electric load to discharge the lab-scaled battery packs.

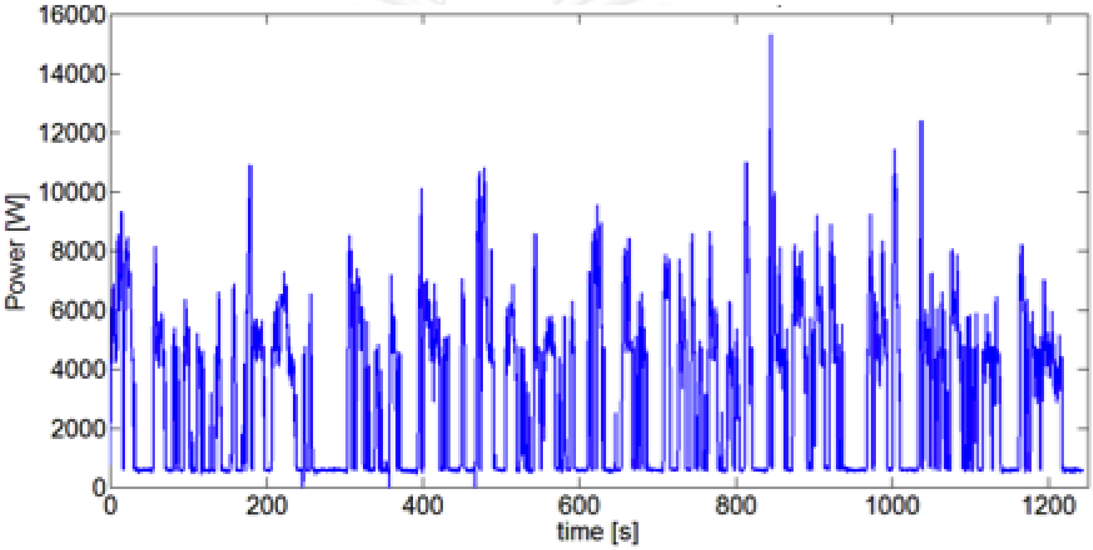


Figure 5-1 Power load profile on the representative cycle

The real driving cycles have been scaled down and trimmed to 251 points in order to represent the driving cycle yet stays within the limitation of the electronic load (KikusuiPLZ1004W) by reducing every 30 points to 1 point (Figure 5-2). These data were synthesized by sampling data 13 points using average without hold peaks and hold peaks (Figure 5-3) from 251 points then discharged by electronic load. The discharge comparison were compared in Table 5-2

From Table 5-2 indicated that the power load profile that trimmed to 13 points using average data has discharge duration longer than 251 points power load profile 35.36%. However, the discharged duration from holded peaks data considered small difference (2.66%) from actual power load profile.

Table 5-2 Discharge duration of lead-acid battery with different power load profile

Power Load Profile	Discharged Duration
256 points	4 hours 30 minutes
13 points (averaged data)	5 hours 56 minutes
13 points (hold peaks)	4 hours 16 minutes

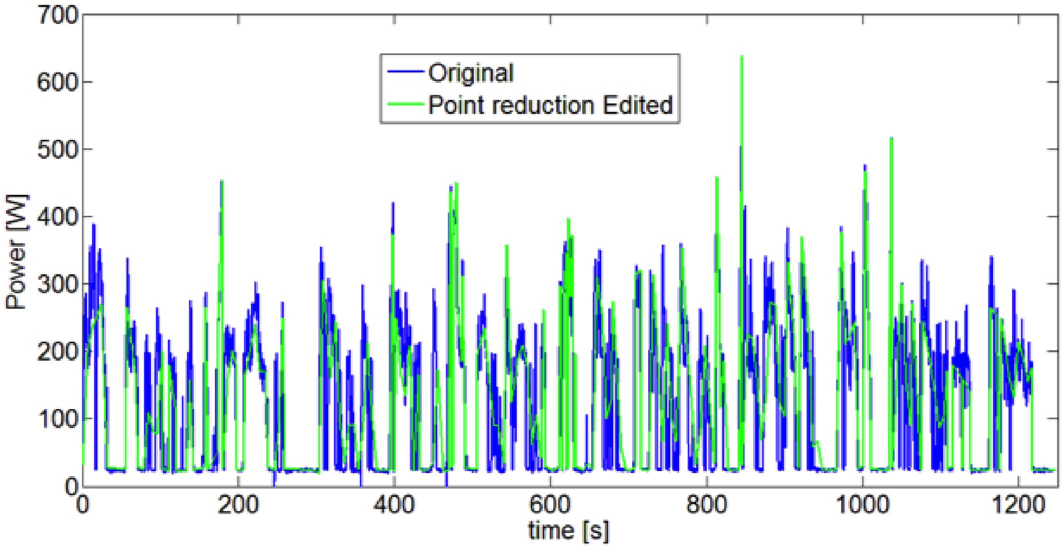


Figure 5-2 Point reduction from real power load profile to 251 points

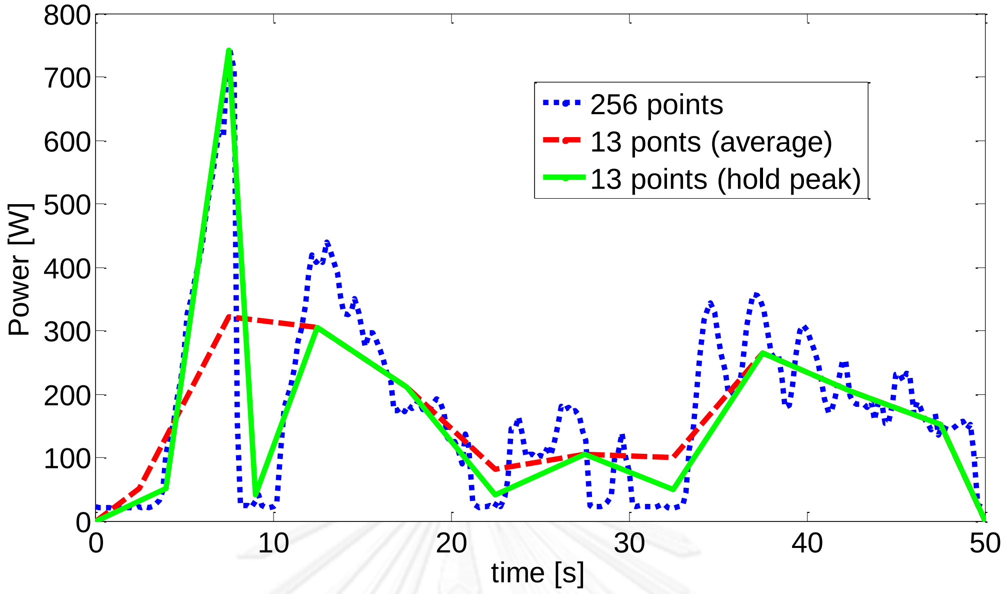


Figure 5-3 Power load profile comparison between 251 points and 13 points

5.2 Mass Transit Passenger vs. Power Consumption

Since the numbers of passengers using the bus#3 are vary during the day and one trip takes 20 minutes. These data were simplified by using average cumulative number of passengers for each trip.

Assume one passenger is 57.7 kg. The pack of 15 and 30 lead acid batteries which represent 9 and 18 passengers respectively were loaded into the bus and represented the weight of passengers (Figure 5-4). The effect of mass and power consumption was determined from the real experiment. The results indicated that mass has affected directly proportional to the bus energy consumption (Figure 5-5).

From Figure 5-4, a regression equation can be derived:

$$E = 0.1518w + 360.87 \tag{4.1}$$

Where w is Total weight of bus including weigh of passengers (Kg),

E is Energy consumption (Wh).

Figure 5-4 Pack of batteries represented mass transit passenger

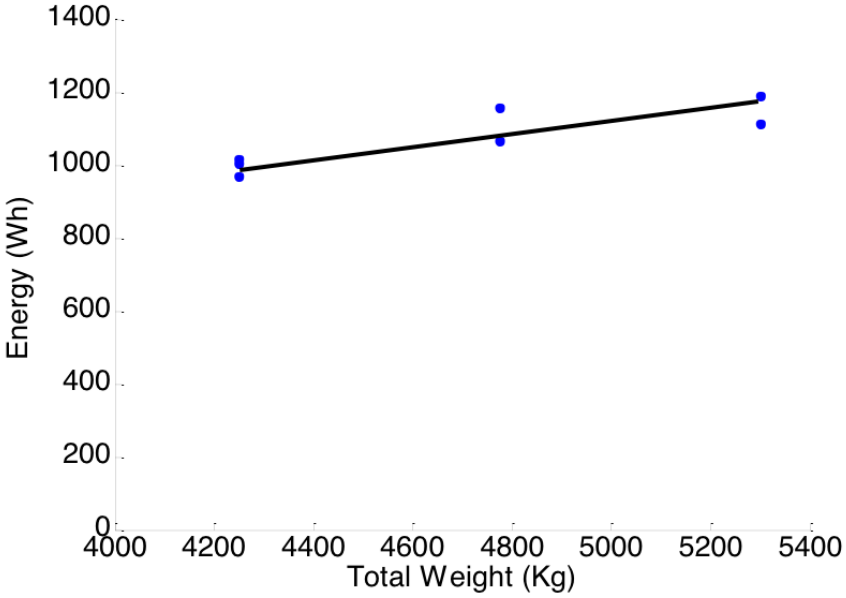


Figure 5-5 Relation of total weight and energy consumption

5.3 Experimental Setup

5.3.1 Lab Scale Test

For the lab scale, the electronic load setting on the test-bench applied to this system of the set of batteries based on a set of real data and related to a continuous measurement of whole driving cycle (Figure 5-6). A dedicated data acquisition system supplied by National Instrument was employed to monitor the voltage and current signals from batteries.

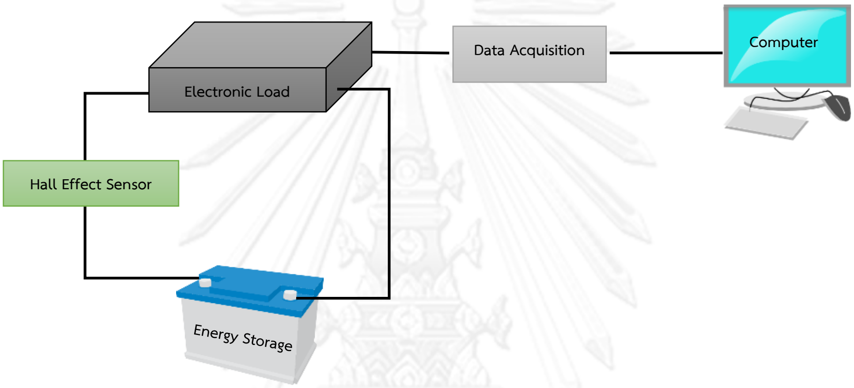


Figure 5-6 Configuration of electronic load and energy storage system on the test-bench

The lead-acid battery (YUESA Deep cycle EB130) 12.8V and 130Ah capacity is considered the base-line energy storage system (Figure 5-7). Lead-acid equipped with supercapacitor (Boostcap Maxwell) 250F, 16.2 VDC (Figure 5-8) and lithium-ion batteries (Calb Ca100) will be explored for the possible improvement (Figure 5-9). A direct connection between the supercapacitor and the battery is chosen to assess the improvement without resorting to the intermediate power electronics such as dc-dc converter which is heavy and very expensive.

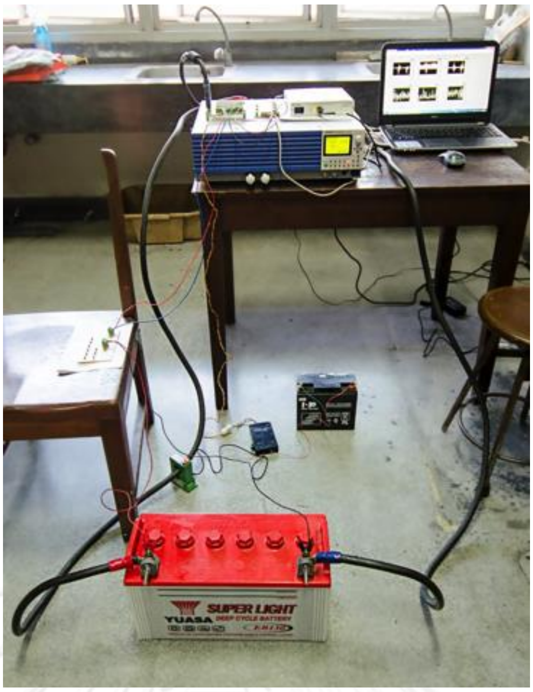


Figure 5-7 Configuration of electronic load and lead-acid battery on the test-bench

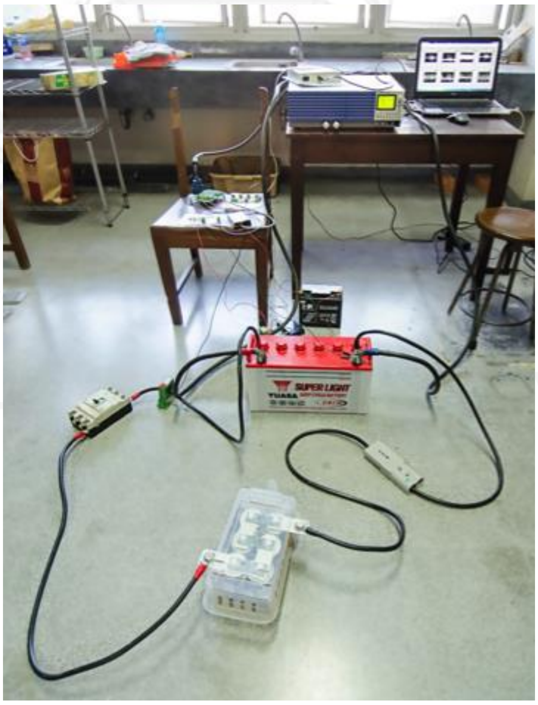


Figure 5-8 Configuration of electronic load, supercapacitor hybrid on the test-bench

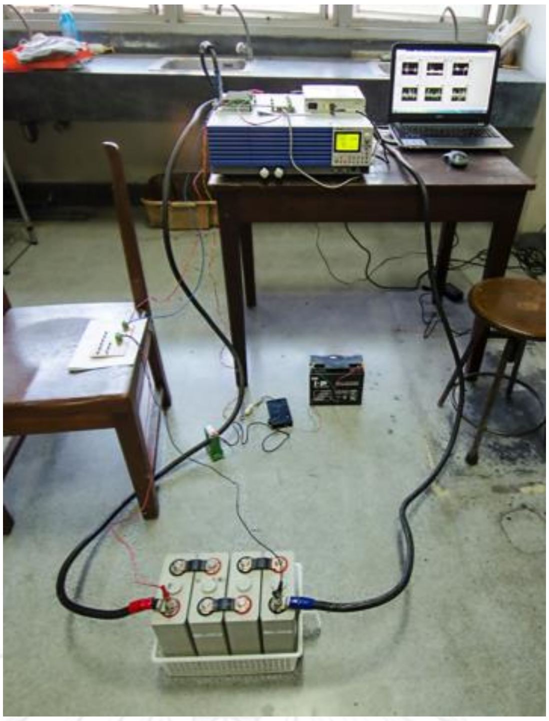


Figure 5-9 Configuration of electronic load and lithium-ion batteries on the test-bench

5.3.2 Full Scale Test

For the full scale test, the a set of 24 deep-cycle lead-acid batteries and a set of 96 lithium-ion batteries connected in series (Figure 5-10) will run with the bus following the regular route then discharge duration time were measured until reach cut off voltage.

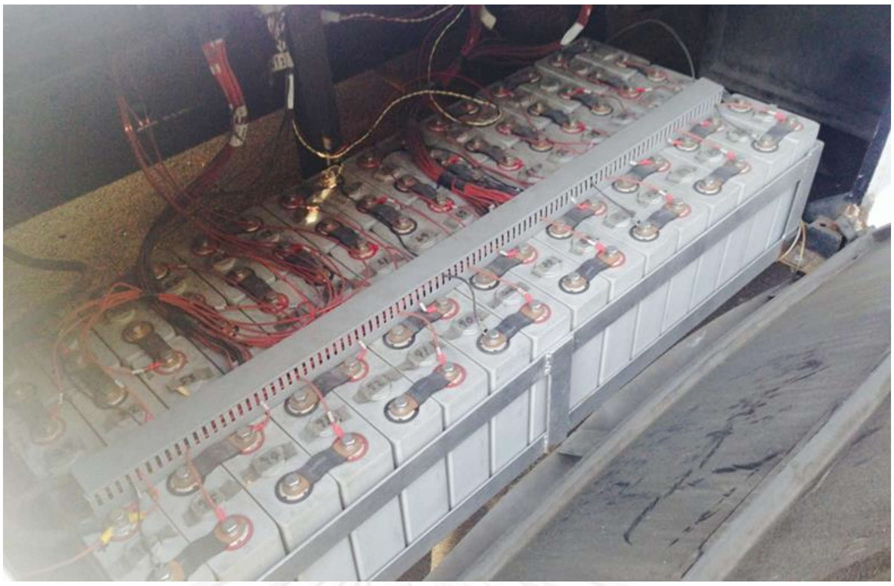


Figure 5-10 Configuration of full-scaled lithium-ion batteries on shuttle bus

5.4 Lab Scale Experimental Results

Under the representative driving cycle, lab scale discharge comparison between the three options of energy storage is summarized in Table 5-3.

Table 5-3 Lab scale discharge comparison between the three types of energy storage

	Lead-acid Battery	Lead-acid Battery Equipped with Supercapacitor	Lithium-ion Battery
Cut-off voltage	10.52 V	10.52 V	10.10 V.
Discharged duration	4 Hours 30 Minutes	5 Hours 12 Minutes	7 Hours 38 Minutes
Energy	64.1 Ah	73.2 Ah	93.4 Ah
Efficiency	63.6%	72.6%	98.5%

Concerning the discharged duration provided by battery packs, lithium-ion battery pack has the maximum capacity and discharged duration with 69.62% larger than lead-acid battery pack while the lead-acid battery pack equipped with supercapacitor can help increasing the driving range since the discharge duration was extended by 15%. This value will be input to the simulation in the next chapter.

When looked into more details, Figure 5-11 demonstrated that the coupling with supercapacitor helps lessen the internal power losses in the lead-acid battery. Due to rapid changes in current drawn from the realistic driving cycle, the low internal resistance of the supercapacitor help shaving the peak current from the lead-acid hence lower the power loss. This allows more energy to be extracted from the same unit of lead-acid battery as well as lower thermal stress level and opportunities of longer life. Under this driving cycle, the discharged energy is increased by 14%. In addition, the bus voltage also shows less variation. This means a better driving dynamic for the electric bus.

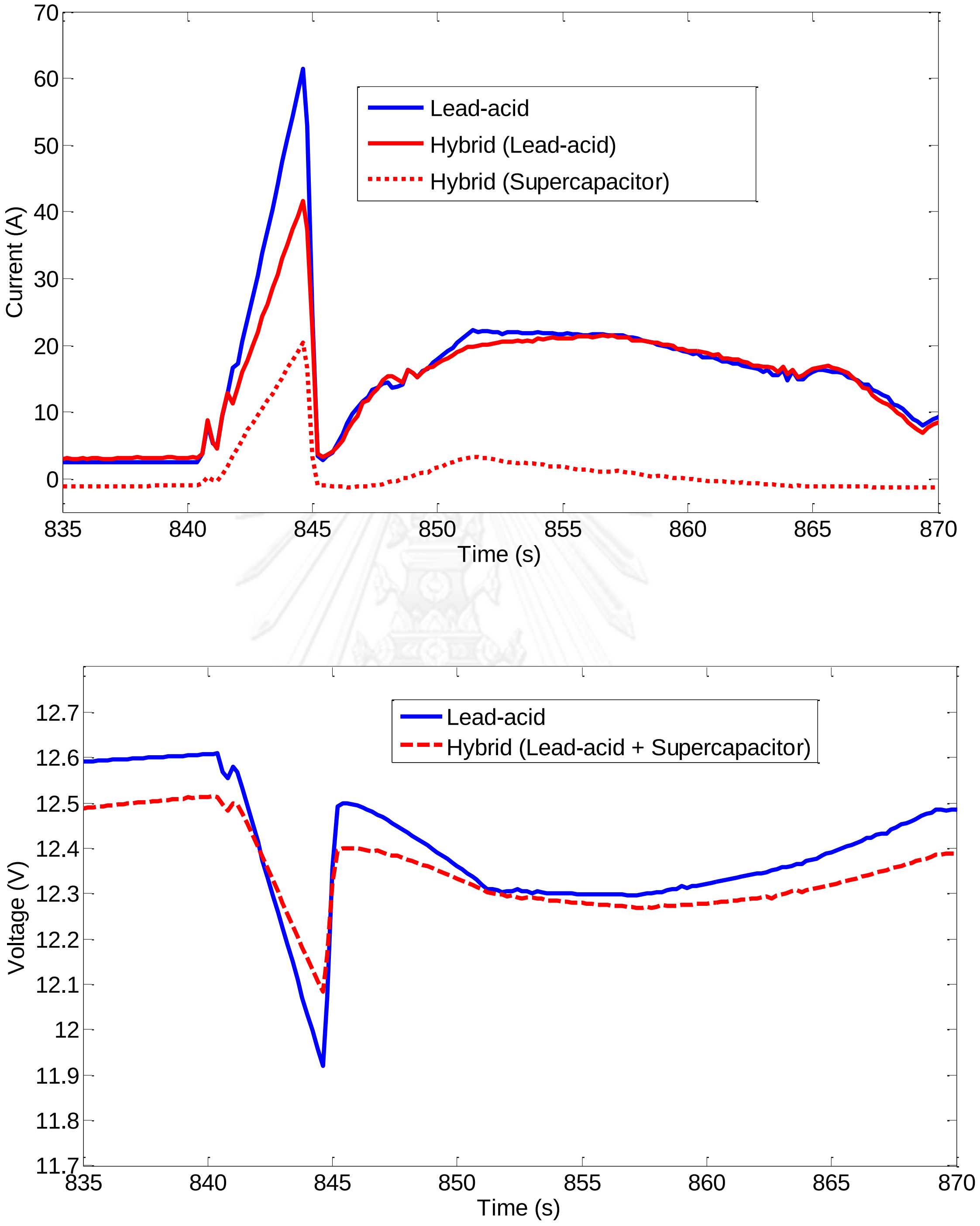


Figure 5-11 (a) Current and (b) voltage comparison between lead-acid battery and hybrid battery pack (lead-acid with supercapacitor)

Lithium-ion batteries provide the best result due to a lower internal resistance and a slightly lower cut-off voltage. Instantaneous voltage drop of lithium-ion is also lower than lead-acid battery with the same power load profile (Figure 5-12).

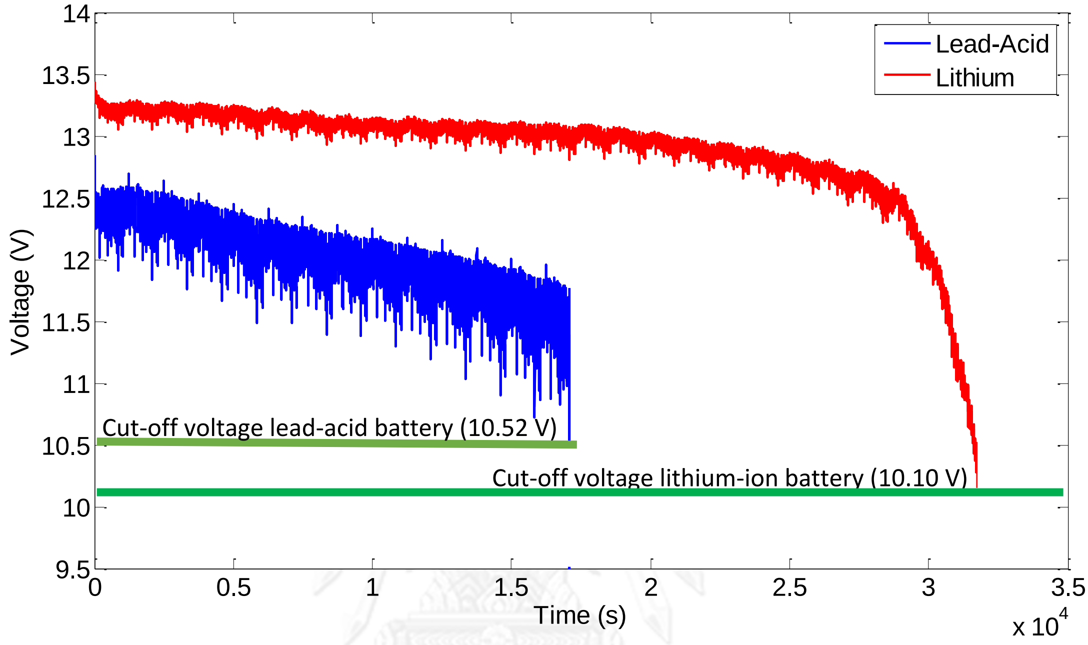


Figure 5-12 Discharge comparison between lead-acid battery and lithium-ion battery

5.4.1 Battery Capacity Test

The capacity of lead-acid battery and lithium-ion battery were measured. Then a load is connected to discharge the batteries. The procedures are repeated three times each constant current. The Peukert's equation is written as:

$$C = I^k t \qquad (4.2)$$

Where C is Peukert's capacity (Ah) for a constant load of I amperes

k is Peukert's constant

t is total time required to discharge battery (hour)

Test results were presented that the battery capacity has relation with the current and discharge time. Lithium-ion battery shows the superior capacity compared to lead-acid battery. For the lead-acid battery, Peukert’s constant is 1.33 for lead-acid battery and 1.02 for lithium-ion battery. When k value is 1.00, it means ideal case for the battery. The efficiency of the battery can be determined from discharge energy and capacity. Although the lithium-ion battery has lower capacity than lead-acid battery but provides greater efficiency by almost 30% under this load profile.

Table 5-4 Discharge comparison between lead-acid battery and lithium-ion battery under the representative driving cycle in Fig.5-2

	Lead-acid Battery	Lithium-ion Battery
Capacity	100.77 Ah	94.85 Ah
Efficiency	63.6%	93.5%
Charging Time	1 hour 25 minutes	30 minutes

5.5 Full Scale Experimental Results

Under the representative driving cycle, full scale discharge comparison between the lead-acid and lithium-ion battery is summarized in Table 5-5. Due to the lower internal resistance of lithium-ion battery with the lower cut-off voltage, they provided the discharged duration 77.95% longer than the lead-acid battery.

Table 5-5 Full scale discharge comparison between lead-acid battery and lithium-ion battery

	Lead-acid Battery	Lithium-ion Battery
Cut-off voltage	260 V	250 V.
Discharged duration	4 Hours 14 Minutes	7 Hours 32 Minutes

It is noted that, in full scale test, the bus was run until complete the driving cycle before the voltage of the batteries dropped until reach cut-off voltage. But for the lab scale test, the electronic load discharged the battery until reach cut-off voltage without concerning about completed driving cycle.

When compared the results from full scale test and lab scale test, the results from full scale test show slightly shorter discharged duration from the condition that was mentioned above. The percentage difference of discharged duration are 6% and 1.31% for lead-acid battery and lithium-ion battery respectively. This concludes that there is no discernable different results between lab scale and full scale test.

CHAPTER 6

SIMULATION RESULTS

The simulation model was run for 1 day in computer time and 5 replications to represent the shuttle bus service on weekday with data from lab scale and full scale experiments. Three separate results arrived from the base case (Lead-acid battery) and the two alternatives energy storage systems. The model simulated the bus movement and demand passengers at the bus stops.

6.1 Lab Scale Simulation Results

From the base line case with the waiting time of 13.52 minutes, the bus schedule has been designed and the energy storage was changed to be lead-acid with supercapacitor and lithium-ion battery to extend the bus service time with the eventual target to reduce the waiting time. Table 6-1 shows the results of average passenger waiting time from simulation model during rush hour from 4 options; lead-acid battery, lead-acid battery with optimized schedule, lead-acid battery equipped with supercapacitor and lithium battery.

Table 6-1 Waiting time in the system during rush hour and P-values from paired T-test comparison compared to based case schedule (Lab scale test)

	Lead-acid Battery (Base case schedule)	Lead-acid Battery (Optimized schedule)	Lead-acid Battery with Supercapacitor	Lithium-ion Battery
Waiting Time in System	13.52 Minutes	11.26 Minutes	11.08 Minutes	10.18 Minutes
% Reduction		16.71%	18.05%	24.70%
P-value		0.005	0.007	0.001

After running the based case model successfully, the output data was analyzed to design and make the improvement. To reduce the passenger waiting time, the bus schedule has been designed (Fig.6-1) and changed the batteries to extend the bus service time.

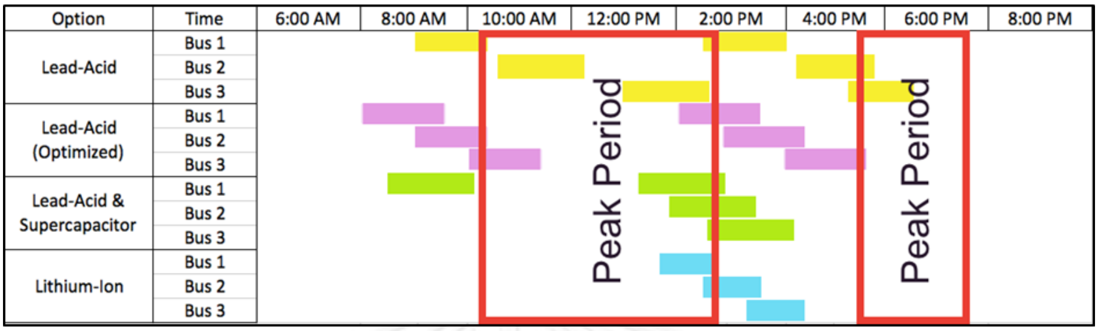


Figure 6-1 Bus charging time schedules for three types of energy storage

The two-sample T-test distribution was used to check the results with the based case model. For the new bus schedules, supercapacitor and lithium battery can reduce the frequency of charging time to be 1 time per day and avoid peak time. For optimized bus schedule, it can reduce the waiting time almost equal to lead-acid battery with supercapacitor schedule but cannot reduce the charging frequency. It meant that supercapacitor and lithium-ion battery can reduce energy and extend driving range. The P-values indicate that the waiting time of the based case schedule is significantly larger than the optimized lead-acid battery, lead-acid battery with supercapacitor and lithium-ion battery schedule by using the same fleet size.

6.2 Full Scale Simulation Results

Based on the discharged duration of the full scale lead-acid batteries and lithium-ion batteries from previous chapter, the simulation models were performed in Arena environment to design and make improvement using the same approach as in previous section. Table 6-2 shows the results of average passenger waiting time from simulation model during rush hour from 3 options; lead-acid battery, lead-acid battery with optimized schedule and lithium-ion battery.

Table 6-2 Waiting time in the system during rush hour and P-values from paired T-test comparison compared to based case schedule (Full scale test)

	Lead-acid Battery (Base case schedule)	Lead-acid Battery (Optimized schedule)	Lithium-ion Battery
Waiting Time in System	14.01 Minutes	11.29 Minutes	10.21 Minutes
% Reduction		19.41%	27.12%
P-value		0.012	0.008

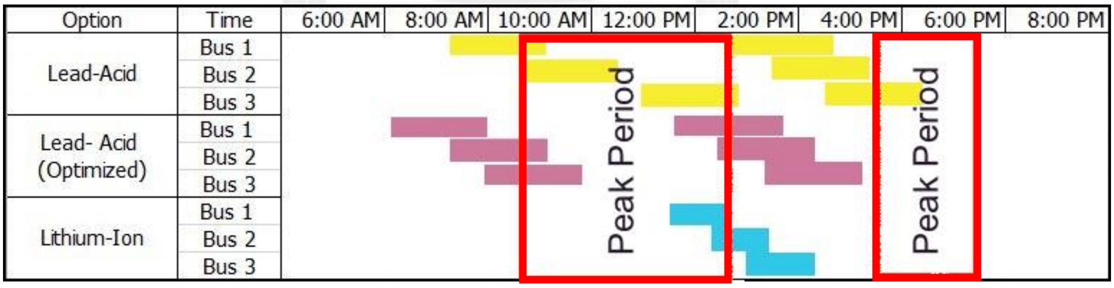


Figure 6-2 Bus charging time schedules for two type energy storage (full scale)

The new bus schedule has been designed to make an improvement in order to minimize waiting time in the system as illustrated in Figure 6-2. From the base line case with the waiting time of 14.01 minutes, lithium-ion battery provided the best result of waiting time and charging frequency was reduced to 1 time per each day. In order to check the simulation results, two samples T-test hypothesis was used to examine whether the average waiting time in the system of improved bus schedule differs from the base case schedule and specified 95% confidence level. P-value from T-test hypothesis indicated that the simulation results of waiting time are significantly different since they are less than 0.05.

When compared the results from full scale test and lab scale test, the percentage different of waiting time are 1.08%, 0.44% and 0.48% from lead-acid battery (base-case schedule), lead-acid battery (optimized schedule) and lithium-ion battery. Since the discharged duration from lab scale test and full scale test are no discernable difference, as a result, the waiting time from simulation results are not significantly difference.

CHAPTER 7

CONCLUSION

The electric bus transit scheduling was designed to improve the bus service using data from the bus service in Chulalongkorn university campus in order to reduce passenger waiting time especially during rush hours. Linear programming approach seems not appropriate with this study since the demand passengers is unpredictable and the shuttle bus service system is complex vehicle scheduling problem. The bus movement and passenger arrival at bus stations were simulated in Arena environment. Energy storage system and fleet management have affected with the bus service time.

Lead-acid battery, Lead-acid battery with supercapacitor and lithium-ion battery in the lab scale were discharged with realistic load power profile from driving cycle to obtain the bus service time in the test-bench and full scale test on the shuttle bus. The sampling data from representative driving cycle were trimmed down to 251 points with hold peaks due to the limitation of electronic load. For the lab scale test, concerning the discharged duration provided by battery packs, lithium-ion battery pack has the maximum capacity and discharged duration with 69.62% larger than lead-acid battery pack. When consider the test condition between these tests, for the full scale test, the bus was run until complete the driving cycle before the voltage of the batteries dropped until reach cut-off voltage. But for the lab scale test, the electronic load discharged the battery until reach cut-off voltage without concerning about completed driving cycle. The percentage differences of discharged duration from the full scale test are 6% and 1.31% for lead-acid battery and lithium-ion battery respectively.

The capacity of lead-acid battery and lithium-ion battery were measured in this regard. Test results were presented that the battery capacity has relation with the current and discharge time. Lithium-ion battery shows the superior capacity compared to lead-acid battery. For the lead-acid battery, Peukert’s constant is 1.33 for lead-acid battery and 1.02 for lithium-ion battery. The efficiency of the battery can be determined from discharge energy and capacity. Although the lithium-ion battery has lower capacity than lead-acid battery but provides greater efficiency by almost 30% under this load profile. The effect of mass and power consumption was determined from the real experiment. The results indicated that mass has affected directly proportional to the bus energy consumption

Adding the supercapacitor bank to battery increase vehicle dynamics performance and reduce battery stress by assisting with transient currents during acceleration. Supercapacitor and lithium-ion battery also can extend the bus service time and both schedules reduce the frequency of bus charging time. Lithium-ion batteries provide the best result significantly with the same fleet size due to a lower internal resistance and a slightly lower cut-off voltage.

The simulation results show that lithium-ion battery provided the best result of waiting time and charging frequency was reduced to 1 time per each day. In order to check the simulation results, two samples T-test hypothesis was used to examine whether the average waiting time in the system of improved bus schedule differs from the base case schedule and specified 95% confidence level. The model validation was performed by comparing the simulation model behavior with real system behavior. The comparison is carried out by one-sample T-test distribution. Two parameters were used to validate the model: The number of passengers in the system and waiting time at the bus stations.

This study concludes that the discharged duration from the energy storage system and waiting time results from both lab scale and full scale experiment are no discernable different. Therefore, the lab scale test is the alternative approach to test the energy storage system on electric shuttle bus.

REFERENCES

1. U.S. Energy Information Administration and I.E. Agency, *International Energy Outlook 2011*. 2011.
2. Tie S.F. and T. C.W, Renewable and Sustainable Energy Reviews, 2013. **20**: p. 82-102.
3. Oge MT. and G. C., *Light-duty automotive technology, carbon dioxide emissions,and fuel economy trens: 1975 through 2011.* Transportation and Air Quality, National Vehicle and Fuel Emissions Laboratory of U.S. Environmental Protection Agency 2012.
4. Feng W. and F. M, Transportation Research Part C, 2013. **26**: p. 135-145.
5. al., P.R.e., *Willingness to pay for vehicle to grid (V2G) electric vehicles and their contact terms.*
6. Rodrigues M.M. et al., European Journal of Operational Research, 2006. **170**: p. 844-862.
7. Bertossi A. et al., *On some Matching Problems arising in Vehicle Scheduling* 1987: p. 271-281.
8. Zhu Chao and Chen Xiaohong. *Optimizing Battery Electric Bus Transit Vehicle Scheduling with Battery Exchanging: Model and Case Study*. in *13th COTA International Conference of Transportation Professionals (CICTP 2013)*. 2013. Elsevier.
9. Gavish, B., Schweitzer P., and Shlifer E., *Assign Buses to Schedules in a Metropolitan Area.* Computer and Operations Research 1978. **5**.
10. Bodin L. and B. Golden, *Classification in Vehicle Routing and Scheduling.* 1981.
11. Yan S. and Chen H.L., *A Scheduling Model and a Solution Algorithm for Inner-city Bus Carriers.* Transportation Research, 2002. **36A**: p. 805-825.
12. Valouxis and Housos, *Combined Bus and Driver Scheduling.* Computers & Operations Research Journal 2002.
13. Kenyon A. and Morton D.P., *A survey on stochastic location and routing problems routing with random travel times.* Transportation Science 2003. **37**: p. 69-82.
14. Rodrigue M. et al., *Vehicle and crew scheduling for urban bus lines.* European Journal of Operation Research, 2006. **170**: p. 844-862.

15. Wang H. and Shen J., *Heuristic Approaches for Solving Transit Vehicle Scheduling Problem with Route and Fueling Time Constraints.* Applied Mathematics and computation 2007(190): p. 1237-1249.
16. Nauman et al., *A stochastic programming approach for robust vehicle scheduling in public bus transport.* Social and Behavioral Sciences 2001. **20**: p. 826-835.
17. John D. and Lees-Miller, *Minimizing Average Passenger Waiting Time in Personal Rapid Transit Systems* 2012.
18. Mishra et al., *Preserving an aging transit fleet: An optimal resource allocation perspective based on service life and constrained budget.* Transportation Research Part A, 2013. **47**: p. 111-123.
19. Bin E., et al., *Using a constraint satisfaction formulation and solution techniques for random test program generation.* IBM Systems Journal, 2002. **41**(3): p. 386-402.
20. Nigel H.M., *Computer-Aided Transit Scheduling* 1999.
21. Haghani A. et al., *A comparative analysis of bus transit vehicle scheduling models.* Transportation Research Part B: Methodological 2003. **37**: p. 301-322.
22. Marc Newman et al., *A stochastic programming approach for robust vehicle scheduling in public bus transport.* Procedia - Social and Behavioral Sciences 2011. **20**: p. 826-835.
23. Cedar A., *Optimal Multi-Vehicle Type Transit Timetabling and Vehicle Scheduling.* Procedia - Social and Behavioral Sciences, 2011. **20**: p. 19-30.
24. Leen Stougie and Maarten H. van der Vlerk, *Stochastic Integer Programming*. University of Amsterdam.
25. Soares J., *Multi-objective parallel particle swarm optimization for day-ahead Vehicle-to-Grid scheduling.* Computational Intelligence Applications in Smart Grid, 2013.
26. Martínez J.C., *Validating complex construction simulation model using 3D visualization. Systems Analysis Modeling Simulation.* 2002. **43**: p. 455-467.
27. Naylor T. H., et al., *Computer Simulation Techniques*. 1966: Wiley.
28. Law A. M. and W.D. Kelton, *Simulation Modeling and Analysis*. 2 ed. 1991: McGraw-Hill.
29. Pegden et al., *Introduction to simulation using SIMAN* 1990.
30. Zewigler P., *Theory of Modeling and Simulation*. 1976, New York.
31. Koch O. et al. *Modeling Ambulance Service of the Austrian Red Cross*. in *Simulation Conference*. 2003.

32. Francisco E. Martinez, *Application of SIMAN ARENA Discrete Event Simulation Tool in the Operation Planning of a Rail System*, in *Advances in Engineering and Technology: A Global Perspective* 2005.

33. Al-Sabban and Ramadan, *A Simulation Study of the Shuttle-Bus Pilgrim Transportation System between the Holy Sites for the 1422H Hajj Season.* Journal of King Abdulaziz University, 2005.

34. Mason S. J., et al. *The Mathematics of Continuous-Variable Simulation Optimization*. in *Winter Simulation Conference*. 2008.

35. Aurup and Cai, *Simulation of an interdependent Metro-Bus transit system to analyze bus schedules from passenger perspective.* International Journal of Logistic & Transportation Research, 2010.

36. Carotenuto et al., *A Dynamic Simulation Model of a Flexible Transport Services for People in Congested Area.* Procedia - Social and Behavioral Sciences, 2012. **54**: p. 357-364.

37. Siang Fui Tie and C.W. Tan, *A review of energy sources and energy management system in electric vehicles.* Renewable and Sustainable Energy Reviews 2013. **20**: p. 82-102.

38. Tsai-Hsiang Chen , et al., *Evaluation of advantages of an energy storage system using recycled EV batteries.* Electrical Power and Energy Systems, 2013. **45**: p. 264-270.

39. RA., H., *Energy Storage*. 2010: Springer.

40. Electropaedia. *Battery and energy technologies: lead acid battery*. Available from: http://www.mpoweruk.com/leadacid.htm.

41. Naish C, M.I., Edberg O, Harfoot M.,, *Outlook of energy storage*

technologies Brussel: Policy department economic and scientific policy. 2007.

42. Schaltz and Khaligh, *Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle.* Vehicular Technology, 2009.

43. Hung and Wu, *An integrated optimization approach for a hybrid energy system in electric vehicles.* Journal of Applied Energy, 2012. **98**: p. 479-490.

44. Masih-Tehrani et al., *Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement.* Journal of Power Sources, 2013. **244**: p. 2-10.

45. Vulturescu B. et al., *Implementation and test of a hybrid storage system on an electric urban bus.* Transportation Research Part C: Emerging Technologies 2013. **30**: p. 55-66.

APPENDIX

APPENDIX A Passenger Arrival Rate

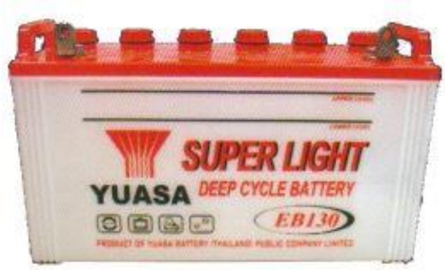
Row Labels	Count of Scheduled -time	Min of Passenger	Average of Passenger	Max of Passenger	Mean	SD
6:40	10	1	4	15		
6:50	10	4	7.3	10		
7:15	10	6	11.2	21		
7:15	10	1	13.6	22		
7:25	10	7	9	12		
7:40	10	10	16.1	25		
7:50	10	6	12.3	25	18.57	5.73
8:05	10	9	22	46		
8:15	10	5	13.4	42		
8:30	10	5	14.8	35		
8:40	10	4	10.5	18		
8:45	10	1	26.1	45		
8:55	10	2	8.8	25		
8:55	10	5	10.9	26	33.85	10.21
9:05	10	6	10.5	19		
9:20	7					
9:20	10	3	10.8	35		
9:30	10	6	17.3	45		
9:45	7					
9:45	10	3	13.4	25		
9:55	10	5	15.1	43	33.4	10.27
10:10	7					
10:10	10	8	21.8	45		
10:20	10	6	13.44444	33		
10:30	10	3	18	38		
10:35	10	8	22.6	60		
10:40	10	6	24.1	40		
10:45	6				43.2	9.24
11:00	10	10	26	50		
11:05	10	12	32.5	45		
11:10	6					
11:25	10	16	34.8	75		
11:30	10	4	44.7	70		
11:35	6					
11:50	10	26	43.4	63		
11:55	9	8	45.5	75		
11:55	10	22	31.7	42	60	13.13

12:05	10	16	34.8	60		
12:15	10	5	46	80		
12:20	9	35	65.25	90		
12:30	10	18	38.2	70		
12:40	10	15	15	15		
12:45	9	15	52.5	90		
12:55	10	10	34	60	66.42	24.01
13:05	6					
13:10	9	12	37.3	62		
13:20	10	6	24.7	45		
13:30	6					
13:35	9	6	23.3	42		
13:45	10	11	24.2	45		
13:55	6				48.5	7.89
14:00	9	10	17.3	26		
14:10	10	10	21.9	40		
14:20	6					
14:25	9	7	16	25		
14:35	10	14	29.6	65		
14:35	10	1	17.5	50		
14:45	10	6	34.1	75		
14:50	7				46.83	18.67
15:00	10	8	21	30		
15:10	10	10	33.2	72		
15:15	7					
15:25	10	7	16.14	33		
15:35	10	13	33	68		
15:40	7					
15:50	10	0		0	40.6	26.66
16:00	9	3	37.75	56		
16:00	10	7	34.2	50		
16:10	9	10	27.8	48		
16:15	6					
16:25	10	12	35.9	50		
16:35	9	16	34.8	60		
16:40	6					
16:50	10	6	22.25	43	51.66	5.48

17:00	9	25	34.8	42		
17:05	6					
17:10	10	2	2	2		
17:25	9	7	18.6	45		
17:25	10	5	14.3	28		
17:35	10	10	25.4	45		
17:35	6					
17:50	9	5	8	13	29.16	16.66
18:00	10	8	22.4	45		
18:00	10	1	10.11	45		
18:10	10	7	21.44	50		
18:15	9					
18:25	10	3	9.6	18		
18:35	10	5	9.7	23		
18:50	10	4	14.8	55		
18:50	1					
19:00	10	3	10.42	40	39.42	12.79

APPENDIX B Energy Storage Specifications

B1. Lead-Acid Battery



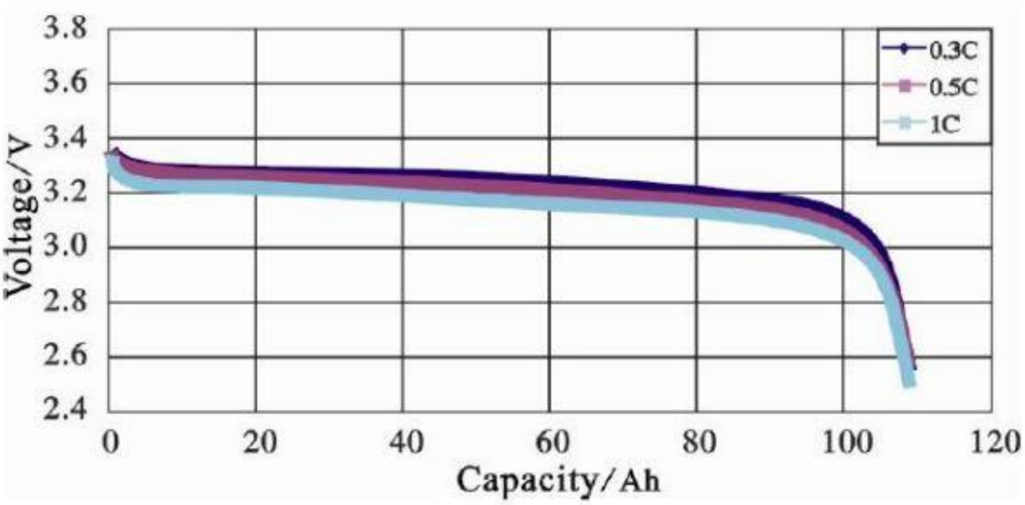
1.General Performance 1.1 Battery capacity Discharge condition		
Current	Amp (20HR)	6.5
	Amp (5HR)	20
	Final Voltage	10.5V. (1.75V/cll)
Result	Ah (20HR)	130
	Ah (5HR)	100
1.2 Float charge		base on charger
1.3 Equalized Voltage		14.4V
1.4 Nominal Open Circuit Voltage		12.8V
1.5 Operation Temperature		Up to 70 C discharge up to 60 C discharge 30 ~ 35 ºC
1.6 Charging current		25 Amp (MAX)
2. Specification: Battery Characteristic 2.1 Case and cover material		Durable Polypropyene

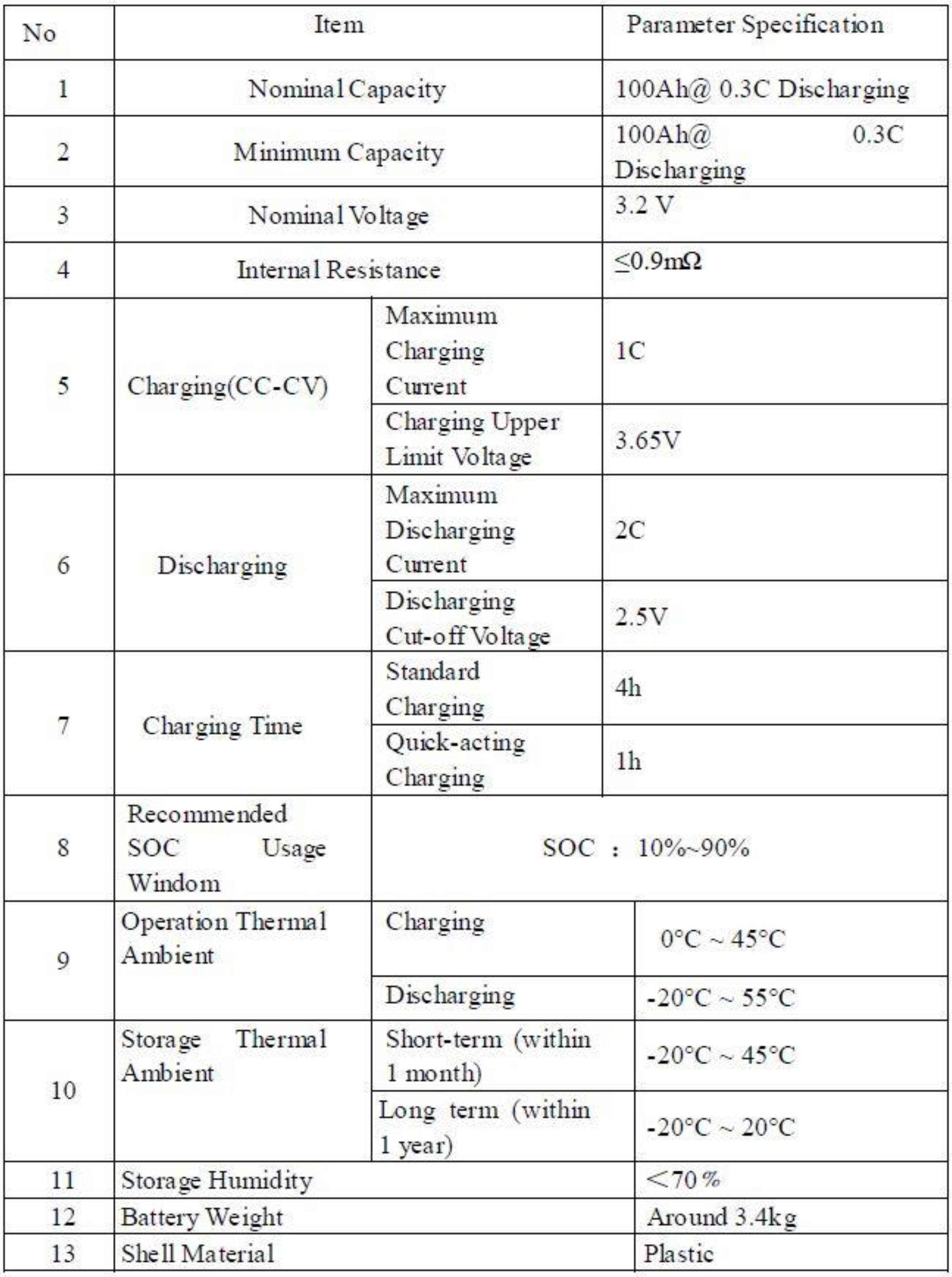
2.2 Terminal post	Standard Option	Taper L type
2.3 Vents cap	Standard Option	Individual pressure relief type With spark arresting and flash back explosion from external ignition source
2.4 Electrolyte	Specific Gravity	Dilute Sulfuric Acid 1.280+0.010 at 20ºC
2.5 Separator	Material Structure	Synthetic pulp with glassmat Three layer structure
2.6 Plate Grid Alloy		Lead + Antimony
2.7 Number of cell per unit		6 cells
2.8 Approx. Weight		35.2 Kg.
3. Characteristic of Life Cycle		
3.1 Discharge/charge condition (80% DOD)	Discharge Charge (120%)	26.7 (A) x 3h. 26.7 (A) x 3.6h.
Temperature		30-40ºC

B2. Lithium-ion Battery

CA100

discharging curve :



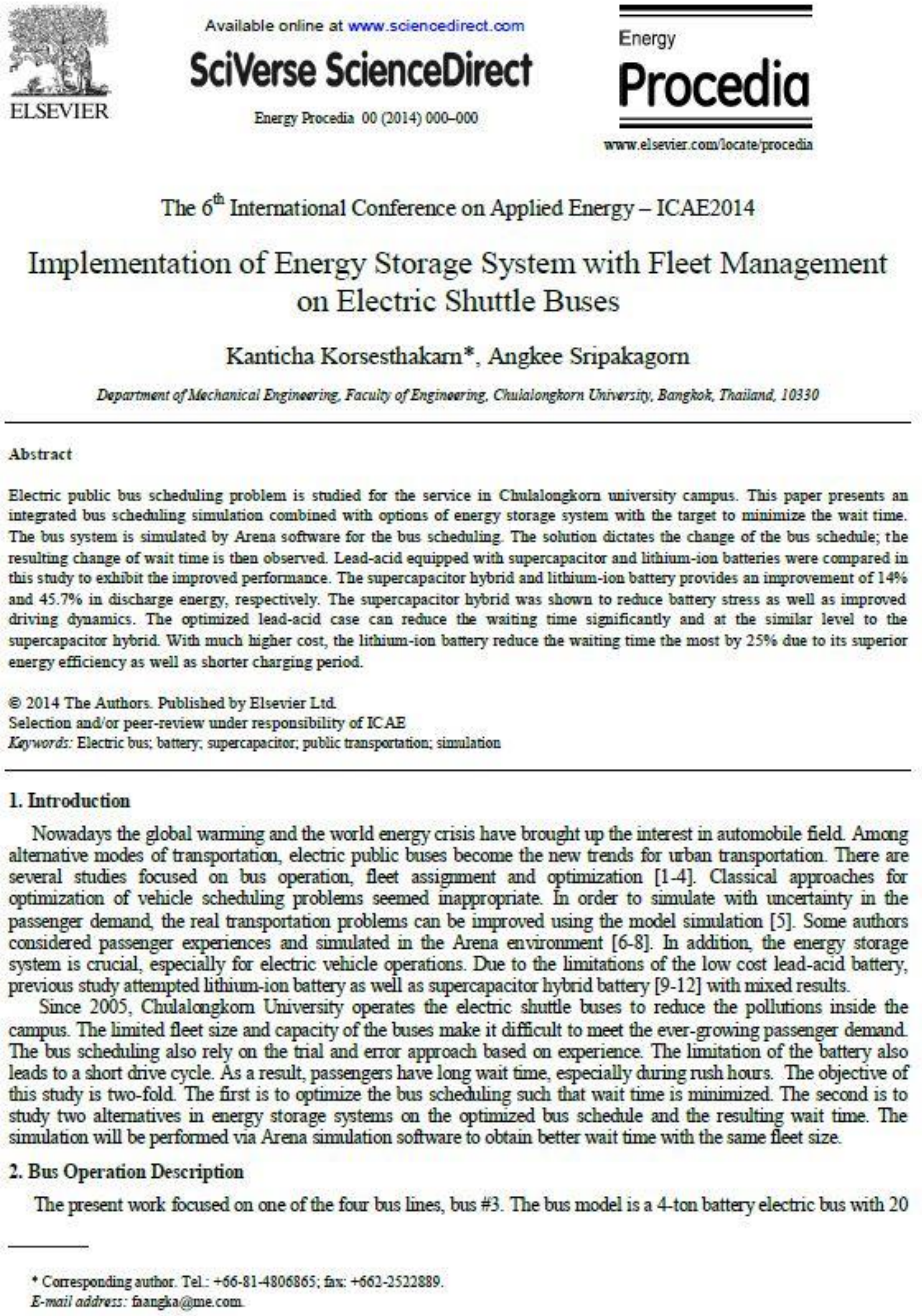


No	Item		Parameter Specification
1	Nominal Capacity		100Ah@ 0.3C Discharging
2	Minimum Capacity		100Ah@ 0.3C Discharging
3	Nominal Voltage		3.2 V
4	Internal Resistance		≤0.9mΩ
5	Charging(CC-CV)	Maximum Charging Current	1C
		Charging Upper Limit Voltage	3.65V
6	Discharging	Maximum Discharging Current	2C
		Discharging Cut-off Voltage	2.5V
7	Charging Time	Standard Charging	4h
		Quick-acting Charging	1h
8	Recommended SOC Usage Windom	SOC ：10%~90%	
9	Operation Thermal Ambient	Charging	0°C ~ 45°C
		Discharging	-20°C ~ 55°C
10	Storage Thermal Ambient	Short-term (within 1 month)	-20°C ~ 45°C
		Long term (within 1 year)	-20°C ~ 20°C
11	Storage Humidity		<70%
12	Battery Weight		Around 3.4kg
13	Shell Material		Plastic

B3. Supercapacitor

Electrical	BCAP1500
Rated Capacitance	1500F
Minimum Capacitance, initial	1500F
Maximum Capacitance, initial	1800F
Rated Voltage	2.70V
Absolute Maximum Voltage	2.85V
Absolute Maximum Current	1150A
Temperature	
Minimum	-40ºC
Maximum	65ºC
Physical	
Mass, typical	280 g
Terminals	Threaded or Weldable
Power & Energy	
Usable Specific Power	6600 W/kg
Specific Energy, E_{max}	5.4 Wh/kg
Stored Energy, E_{stored}	1.52 Wh

APPENDIX C Publication of Dissertation



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Implementation of Energy Storage System with Fleet Management on Electric Shuttle Buses

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Abstract

Electric public bus scheduling problem is studied for the service in Chulalongkorn university campus. This paper presents an integrated bus scheduling simulation combined with options of energy storage system with the target to minimize the wait time. The bus system is simulated by Arena software for the bus scheduling. The solution dictates the change of the bus schedule; the resulting change of wait time is then observed. Lead-acid equipped with supercapacitor and lithium-ion batteries were compared in this study to exhibit the improved performance. The supercapacitor hybrid and lithium-ion battery provides an improvement of 14% and 45.7% in discharge energy, respectively. The supercapacitor hybrid was shown to reduce battery stress as well as improved driving dynamics. The optimized lead-acid case can reduce the waiting time significantly and at the similar level to the supercapacitor hybrid. With much higher cost, the lithium-ion battery reduce the waiting time the most by 25% due to its superior energy efficiency as well as shorter charging period.

Selection and/or peer-review under responsibility of ICAE
Keywords: Electric bus; battery; supercapacitor; public transportation; simulation

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1. Introduction

Nowadays the global warming and the world energy crisis have brought up the interest in automobile field. Among alternative modes of transportation, electric public buses become the new trends for urban transportation. There are several studies focused on bus operation, fleet assignment and optimization [1-4]. Classical approaches for optimization of vehicle scheduling problems seemed inappropriate. In order to simulate with uncertainty in the passenger demand, the real transportation problems can be improved using the model simulation [5]. Some authors considered passenger experiences and simulated in the Arena environment [6-8]. In addition, the energy storage system is crucial, especially for electric vehicle operations. Due to the limitations of the low cost lead-acid battery, previous study attempted lithium-ion battery as well as supercapacitor hybrid battery [9-12] with mixed results.

Since 2005, Chulalongkorn University operates the electric shuttle buses to reduce the pollutions inside the campus. The limited fleet size and capacity of the buses make it difficult to meet the ever-growing passenger demand. The bus scheduling also rely on the trial and error approach based on experience. The limitation of the battery also leads to a short drive cycle. As a result, passengers have long wait time, especially during rush hours. The objective of this study is two-fold. The first is to optimize the bus scheduling such that wait time is minimized. The second is to study two alternatives in energy storage systems on the optimized bus schedule and the resulting wait time. The simulation will be performed via Arena simulation software to obtain better wait time with the same fleet size.

2. Bus Operation Description

The present work focused on one of the four bus lines, bus #3. The bus model is a 4-ton battery electric bus with 20

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seats capacity. The bus operates on a set of 24 deep-cycle lead-acid batteries. Routes and bus scheduling are based on the fleet size of 3 buses set up (Fig.1) to transport the students and university population between departments during the weekdays. An important part of the electric bus schedule is the bus charging period. Once left the depot, during the service, when the battery voltage drops until the cut-off voltage, bus driver must decide and go to the depot to charge the battery until it is full. This process takes 1 hour 25 minutes approximately for lead-acid battery.

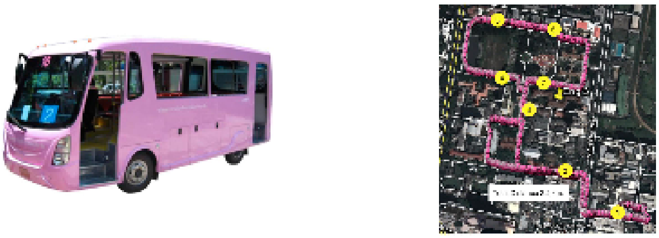


Fig. 1. the appearance of the electric bus and the bus route inside the Chulalongkorn University

3. Simulation Model Description

The simulation model is made up of a series of modules dedicated to: the acquisition of requests to be evaluated and carried out, the movement of bus and passengers, the monitoring of possible delays that actually occur while the simulation runs. During the simulation, a set of performance indicators is calculated to evaluate the robustness of the schedule produced by the Heuristics in response to disturbing elements introduced in the simulation.

3.1 Simulation Modules

- Schedule Module: The bus schedule was gathered from bus carrier. These schedules were inserted in the block diagram with mixed bus schedule each day to calculate passenger arrival rates.
- Queue Module: This module generates the waiting time and passenger arrival rate at each bus stop. For the weight percentage of passenger waiting at each stop, three persons were allocated to collect the number of passengers waiting in queue at the bus stop for two hours daily, one hour of rush hour and one hour of normal hour.
- Bus Movement Module: This module described the movement of the buses through various stops starting from depot to other stations included the bus activities such as pickup, drop off, boarding and waiting for the passenger. In addition, bus charging module is included.

3.2 Simulation and Model Validation

In this simulation model, the average velocity profile and the battery charging duration were obtained from the experiment in Section 4. The following assumptions were made to simplify the simulation process:

- The demand is uniformly distributed within each station and over time on isolated stations.
- Arrival of the bus at the seven stations is sequenced; Bus layover time and external costs are negligible
- Boarding into bus is simplified to take 10 second per one passenger

The model validation was performed by comparing the cumulative numbers of passengers and the waiting time are validated with the real system behavior and show good consistency at high confidence interval.

4. Experiments

The experiment consists of two parts; gathering a representative driving cycle and evaluating alternative energy storage systems. The results will be included in the bus scheduling simulation.

4.1 Driving Cycle Characteristics

The driver operates the bus following the regular route and obtained the data of voltage and current measured from the batteries and velocity profile by using Kayaba® drive-recorder and GPS (Fig.2). The goal of this test is to gather the power provided by batteries and use the profile with electric load to discharge the lab-scaled battery packs. The obtained driving cycles will be scaled down and trimmed to stays within the limitation of the electronic load. The profile will be employed with electric load to discharge the lab-scaled battery packs.

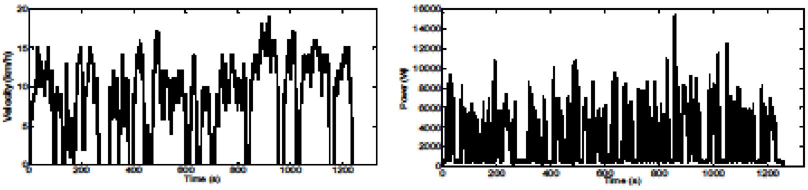


Fig. 2. (a) Velocity trajectory and (b) Power load profile on the representative cycle

4.2 Energy storage systems

For the present study, the lead-acid battery is considered the base-line energy storage system. Two alternatives will be explored namely, lead-acid battery/supercapacitor hybrid and lithium-ion battery. The energy storage system parameters are summarized in Table 1.

Table 1. Parameters of the energy storage options

	Lead-acid Battery	Supercapacitor	Lithium-ion Battery
Battery characteristics	130 Ah, 12.8 V, 35.2 kg.	16.2 VDC, 250 F, 1.68 kg.	100 Ah, 12.8 V (4 cells), 13.6 kg.
Nominal Energy density	40 Wh/kg	5.4 Wh/kg	110 Wh/kg
Stored Energy	1.408 kWh per unit	1.52 kWh per unit	1.496 kWh per unit

For the lab scale, the electronic load on a test-bench draw power from the three set of energy storages (Fig.3) based on a representative driving cycle. A dedicated data acquisition system supplied by National Instrument was employed to monitor the voltage and current signals from energy storage systems.

4.3 Experimental Results

Compared to the base-line lead-acid battery, Table 2 showed that the supercapacitor hybrid provides an improvement of 15.5% in discharge duration and 14% in discharge energy. For the lithium-ion, even with the same nominal energy capacity as the lead-acid battery (see Table 1), the discharge duration is extended by 69.6% with over 45.7% increase in discharge energy. This is due to a lower internal resistance and a slightly lower cut-off voltage. Although with lesser improvement compared to the lithium-ion, the supercapacitor hybrid was shown to reduce battery stress in lead-acid battery as well as improved driving dynamics.

Table 2. Discharge comparison between the three types of energy storage

	Lead-acid Battery	Lead-acid/Supercapacitor hybrid	Lithium-ion Battery
Cut-off voltage	10.52 V	10.52 V	10.10 V.
Discharged duration	4 Hours 30 Minutes	5 Hours 12 Minutes	7 Hours 38 Minutes
Total discharged energy	64.1 Ah	73.2 Ah	93.4 Ah

5. Results

The simulation model was run for 1 day and 5 replications. Started from the base case, as optimized from the simulation, the charging schedule (Figure 3) stays at 6 periods but the periods are shifted to improve the wait time. With the improved energy efficiency of the supercapacitor hybrid and lithium-ion, the charging periods are reduced from 6 to 4 and 3 respectively. This reduction and rearrangement of the charging periods resulted in the improved wait time as suggested in Table 3.

Table 3 shows the results of average passenger waiting time from simulation model during rush hours. The two-sample T-test distribution was used to check the results with the based case model. The optimized lead-acid case can reduce the waiting time significantly and at the similar level to the supercapacitor hybrid but cannot reduce the charging frequency. With much higher cost, the lithium-ion battery reduces the waiting time by almost 25% due to its superior energy efficiency as well as shorter charging period (30 mins). The P-values obtained from statistical test (0.007 and 0.001 for supercapacitor hybrid and lithium-ion) indicate that the waiting time of the based case schedule is significantly longer than the optimized lead-acid battery, lead-acid battery with supercapacitor and lithium-ion battery schedule by using the same fleet size.

Fig. 3. Bus charging time schedules for three types of energy storage

Table 3. Waiting time in the system during rush hour and P-values from paired T-test comparison compared to based case schedule

	Lead-acid (Base case)	Lead-acid (Optimized)	Lead-acid/Supercapacitor	Lithium Battery
Waiting Time	13.52 mins	11.26 mins	11.08 mins	10.18 mins
% Reduction		16.71%	18.05%	24.70%

6. Conclusion

The electric bus transit scheduling was optimized using actual data from the bus service in Chulalongkorn university campus in order to reduce passenger waiting time during rush hours. Energy storage system and fleet management both affect the bus service. The optimized schedule from the simulation can reduce the waiting time significantly. The use of supercapacitor hybrid and lithium-ion battery incrementally improve the waiting time with increased cost factor.

References

[1] S.W. Lam et al. *Multiresponse optimization of dispatch rules for public bus services.* Computers & Industrial Engineering 56; 2009, p. 77–86

[2] A. Fugenschuh. *Solving a school bus scheduling problem with integer programming.* European Journal of Operational Research 193; 2009

[3] J. Euchi, R. Mraihi. *The urban bus routing problem in the Tunisian case by the hybrid artificial ant colony algorithm.* Swarm and Evolutionary Computation 2; 2012, p. 15–24

[4] B.-I. Kim et al. *A school bus scheduling problem.* European Journal of Operational Research 218; 2012, p. 577–585.

[5] Y. Yan et al. *Robust optimization model of schedule design for a fixed bus route.* Transportation Research Part C; 2012, p. 113–121

[6] H.M. Ramadan and O.I. Abduh. *Evaluating the Feasibility of Extending the Shuttle-Bus Pilgrim Transportation System During Nafrah Using Computer Simulation*, Proceedings of the Transportation in Hajj Symposium; 2001

[7] G.M.M. Amrup. *Simulating the Métro and Autobus System in Montréal with Arena.* Discrete System Simulation; 2008

[8] P. Carotenuto et al. *A dynamic simulation model of a flexible transport services for people in congested are.* Energy Efficient Transportation Research Proceedings; 2012

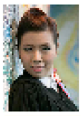
[9] A.J. Fairweather. *Evaluation of UltraBattery™ performance in comparison with a battery-supercapacitor parallel network.* Journal of Power Sources; 2013, p. 191-201

[10] B. Vulturescu et al. *Implementation and test of a hybrid storage system on an electric urban bus.* Transportation Research Part C; 2013, p. 55-56

[11] E. Ferg et al. *The testing of batteries linked to supercapacitors with electrochemical impedance spectroscopy: A comparison between Li-ion and valve regulated lead acid batteries.* Journal of Power Sources; 2013

[12] M. Masih-Tehrani et al. *Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement.* Journal of Power Sources; 2013

Biography



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Paper ID 080

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Improvement of Electric Shuttle Bus Operation using Discrete Event Simulation and Supercapacitor Hybrid

Kanticha Korsesthakarn* and Angkee Sripakakorn

Abstract

Electric shuttle buses are in operation for the past eight years to transport the students and faculty members within Chulalongkorn university campus. Due to limited fleet size and increased passenger demands, passengers have a long wait time at the bus stations during peak hour. The service time also depends on the energy storage system. Lead-acid equipped with supercapacitor were compared in this study to exhibit the improved performance. This paper presents the integrate simulation of energy storage system combined with bus scheduling simulation. The supercapacitor hybrid provides an improvement of 14% in discharge energy. Average wait time and passenger agreed time are observed in this regard. The system is simulated by Arena software for the bus scheduling. The solution dictates the change of the bus schedule; the resulting change of wait time is then observed. The supercapacitor hybrid was shown to reduce battery stress as well as improved driving dynamics and also can reduce the waiting time by 18%. In addition, the feasibility of new shutter-bus schedule and energy storage system can be carried out to obtain the service levels with passenger satisfaction.

Keywords : Electric vehicle, Discrete event simulation, Public transport, Shuttle bus, Supercapacitor

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1. Introduction

At the present time, the energy crisis and global warming phenomenon lead to heightened interest in alternative modes of transportation. Among the options, urban electric public bus has gained much attention. In general, vehicle scheduling problem focused on bus operation, fleet assignment and optimization [1-4] is very complicated. Simulation is an important tool to realistically model the bus network in in discrete events environment. [5-6]. Some studies considered passenger experiences and simulated in the Arena environment [7-9]. The solutions were planned by heuristic approach and also increased the fleet size.

For electric vehicle operations, the energy storage system also plays a crucial role in efficient and satisfactory service. Conventionally, electric public bus relies on the low-cost lead-acid battery. Due to its limitations, many modifications or alternatives are explored. Supercapacitors can be charged and discharged faster as compared to batteries [10]. Previous study attempted to study the performance of lead-acid battery connected with supercapacitor [11] and NiCd battery connected with supercapacitor [12].

Since 2005, Chulalongkorn University campus operates the electric shuttle buses to reduce the exhaust gas and pollutions inside the campus as well as to reduce the operation costs. The limited fleet size and capacity of the buses make it difficult to meet the increased passenger demand. As a result, passengers have long wait time during rush hour. Public transport carrier in the campus has used the trial and error approach for the bus scheduling based on experience. In addition, the limitation of the energy storage system, specific to electric bus, leads to a short drive cycle.

2. Objectives

The objective of this study is to simulate the operation of electric shuttle-bus transportation in discrete events environment such that passenger satisfaction in terms of wait time is improved. In addition, the hybridization of the lead-acid battery with supercapacitor will be attempted for the possible further improvement of the wait time.

3. Bus Operation Description

The present work focused on one of the four bus lines, bus #3. The bus model considered is a 4-ton battery electric bus with 20 seats capacity and now runs on the fleet size of 3 buses (Fig.1). The electric drive operates on a set of 24 deep-cycle lead-acid batteries connected in series. A group of seven bus stations are included in this route.

Fig. 1. The appearance of the electric bus

Routes and bus scheduling are set up to transport the students and faculty members between departments and to the metro station during the weekdays between 6.40 AM and 7.00 PM (Fig.2). There are different schedule for each bus. The route is in the university campus in its entirety; hence the traffic is not influenced by the city traffic outside the campus. An important part of the electric bus schedule is the bus charging period. Once left the depot, during the service, when the battery voltage drops to the cut-off voltage, bus driver must decide and go to the depot to charge the battery until it is full. This process takes 1 hour 25 minutes.

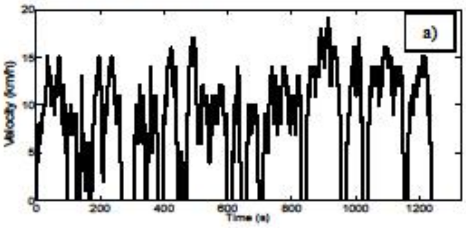
Fig. 2. The bus route inside the Chulalongkorn University

4. Experiments

The experiment consists of two parts. The first part is to gather a driving cycle to be used in energy storage system evaluation. The second part is the evaluation of an alternative types of energy storage systems on the discharge characteristics. The results of this evaluation will be used in the bus operation simulation.

4.1 Driving Cycle Characteristic

The driver followed the usual driving route and obtained the data of voltage and current measured from the batteries and velocity profile by using Kayaba® drive-recorder and GPS (Fig.3). The goal of this test is to gather the power data provided by batteries and use the power profile to run with the electric load to discharge the lab-scaled battery packs. The real driving cycles have been scaled down and trimmed in order to represent the driving cycle yet stays within the limitation of the electronic load.



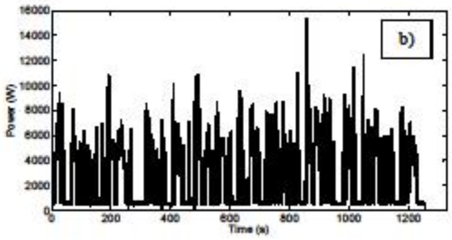


Fig. 3. (a) Velocity trajectory and (b) Power load profile on the representative cycle

4.2 Energy Storage System

For the present study, the lead-acid battery (YUESA Deep cycle EB130) 12.8V and 130Ah capacity is considered the base-line energy storage system. Lead-acid equipped with supercapacitor (Boostcap Maxwell) 250F and 16.2 VDC will be explored for the possible improvement (Fig.4). A direct connection between the supercapacitor and the battery is chosen to assess the improvement without resorting to the intermediate power electronics such as dc-dc converter which is heavy and very expensive.

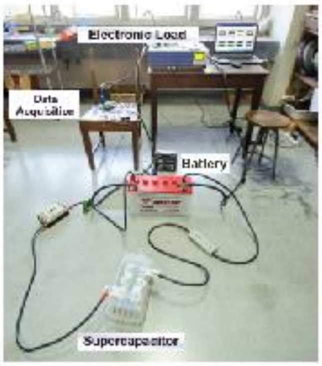


Fig.4. Configuration of electronic load, battery pack and supercapacitor on the test-bench

For the lab-scale tests, the electronic load is connected to the energy storage system to draw the power profile extracted from a set of real driving cycles. A dedicated data acquisition system supplied by National Instrument was employed to monitor the voltage and current signals.

4.3 Experimental Results

Under the representative driving cycle, discharge comparison between the two options of energy storage is summarized in Table 1. Concerning the discharged duration provided by battery packs, the lead-acid battery pack equipped with supercapacitor can help increasing the driving range since the discharge duration was extended by 15%. This value will be input to the simulation in the next section.

When looked into more details, Fig. 5 demonstrated that the coupling with supercapacitor helps lessen the internal losses in the lead-acid battery. Due to rapid changes in current drawn from the realistic driving cycle, the low internal resistance of the supercapacitor help shaving the peak current from the lead-acid hence lower the loss. This allows more energy to be extracted from the same unit of lead-acid battery as well as lower thermal stress level and opportunities of longer life. Under this driving cycle, the discharged energy is increased by 14%. In addition, the bus voltage also shows less variation. This means a better driving dynamic for the electric bus.

Table 1 Discharge comparison between lead-acid battery and Lead-acid battery equipped with supercapacitor

	Lead-acid Battery	Battery with Supercapacitor
Cut-off voltage	10.52V	10.52V
Discharged duration	4 Hr 30 min	5 Hr 12 min
Discharged energy	64.1 Ah	73.2 Ah

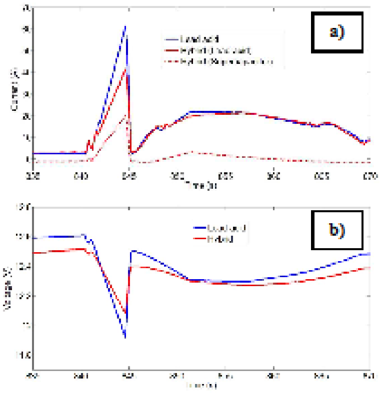


Fig. 5. (a) Current and (b) voltage comparison between the two options of energy storage

5. Simulation Model Description

Real world transit problem is very complicated. Discrete event simulation is a way to attack this vehicle scheduling problem efficiently. For the present study, the simulation proposed bus movements and passenger arrivals developed in Arena environment. Events including passenger arrival, waiting in queue and boarding are considered between bus stations.

5.1 Simulation Modules

The simulation model is made up of a series of modules dedicated respectively to: the acquisition of requests to be evaluated and carried out, the simulation of movement of bus and passengers, the monitoring of possible delays and display of events that actually occur while the simulation runs. During these activities, the model generates unusual demand passengers that the basic heuristic is unable to take into consideration when producing fleet schedules. Finally, a set of performance indicators is calculated to evaluate the robustness of the schedule produced by the

Heuristics in response to disturbed elements introduced in the simulation.

5.1.1 Schedule Module

The bus schedule was gathered from the bus carrier. These schedules were inserted in the block diagram with mixed bus schedule each day to calculate passenger arrival rates.

5.1.2 Queue Module

This module obtained the passenger arrival rates from the schedule module to generate the waiting time and passenger arrival rate at each bus stop. For the weight percentage of passenger waiting at each stop, three persons were allocated to collect the number of passengers waiting in queue at the bus stop for three days focused on one hour of rush hour and one hour of normal hour. They reach the bus stop and await the bus arrival.

5.1.3 Bus Movement Module

This module described the movement of the buses through various stops starting from depot to other stations included the bus activities such as pickup, drop off, boarding and waiting for the passenger. In addition, bus charging module is included.

5.2 Model Validation

The model validation was performed by comparing the simulation model behavior with real system behavior. The comparison is carried out by one-sample T-test distribution. Two parameters were used to validate the model: the number of passengers in the system and the waiting time. The percentage difference value between the real system and the simulation output is 2.76% and significant with P-value 0.331 at 95% confidence interval. For passenger waiting time, the data were validated by direct observation and simulation model output and divided into two intervals, one hour for rush hour and one hour for normal hour. The percentage difference values are 11.47% and 10.63% and also significant with P-value 0.384 and 0.225 respectively at 95 % confidence interval.

6. Results

The simulation model was run for 1 day in schedule time and 5 replications. After running the based case model successfully, the output data was analyzed to make improvement. Two separate results arrived from the base case (Lead-acid battery) and the lead-acid battery equipped with supercapacitor (Table 2). From the base line case with the waiting time of 13.52 mins, the bus schedule has been designed and added the supercapacitor to extend the bus service time with the eventual target to reduce the waiting time. Table 2 shows the results of average passenger waiting time from simulation model during rush hour from 2 options; lead-acid battery and lead-acid battery equipped with supercapacitor.

Table 2 Waiting time in the system during rush hour and P-values from paired T-test comparison compared to based case schedule

	Lead-acid Battery	**Lead-acid Battery with Supercapacitor**
Waiting Time	13.52 mins	11.08 mins
% Reduction		18.0%
P-value		0.007

The two-sample T-test distribution was used to check the results with the base case model. For the new bus schedules, it can reduce the frequency of charging time to 1 time per day and manage to avoid the peak time. The P-values obtained from statistical test indicate that the waiting time of the based case schedule is significantly longer than the optimized lead-acid battery and lead-acid battery with supercapacitor battery schedule by using the same fleet size.

7. Conclusion

The electric bus transit scheduling was designed to improve the bus service using data from the bus service in Chulalongkorn university campus in order to reduce passenger waiting time especially during rush hours. Energy storage system has affected with the bus service time. Lead-acid battery and Lead-acid battery with supercapacitor in the lab scale were compared with realistic load power profile. Adding the supercapacitor bank to the battery increase vehicle dynamics performance and reduce battery stress by assisting with transient currents during acceleration. The simulation model used the discharge duration to simulate the base case bus schedule model compared with the new bus schedules. The new schedule from lead-acid battery equipped with supercapacitor can reduce the frequency of bus charging time since the driving range increased. In terms of cost economy, however, the benefits of supercapacitor are still unclear. Data showed that the supercapacitor addition help to reduce the depth of discharge of the battery pack, potentially resulting in the extended battery life and a decrease in life time battery costs. Higher energy efficiency should also reduce the energy costs per kilometer of travel. This gains may be sufficiently large enough to show every to offset the additional capital cost of the supercapacitor bank although the percent work opted to avoid the expensive power electronics.

8. References

[1] S.-W. Lam et al., “Multiresponse optimization of dispatch rules for public bus services”, Computers & Industrial Engineering 56, 2009, pp. 77–86.

[2] A. Fugenschuh, “Solving a school bus scheduling problem with integer programming”, European Journal of Operational Research 193, 2009, pp. 867–884.

[3] J. Euchi and R. Mraihi, “The urban bus routing problem in the Tunisian case by the hybrid artificial ant colony algorithm, 2012, pp. 15–24.

[4] B.-I. Kim et al., “A school bus scheduling problem”, European Journal of Operational Research 218, 2012, pp. 577–585.

[5] W. D. Kelton et al. *“Simulation with Arena”*, McGraw hill Book Corporation, 2004.

[6] Y. Yan et al., “Robust optimization model of schedule design for a fixed bus route”, Transportation Research Part C, 2012, pp. 113–121.

[7] H.M. Ramadan and O.I. Abduh, “Evaluating the Feasibility of Extending the Shuttle-Bus Pilgrim Transportation System During Nafrah Using Computer Simulation”, 2001.

[8] G.M.M. Aurup, “Simulating the Métro and Autobus System in Montréal with Arena”, 2008.

[9] P. Carotenuto et al., “A dynamic simulation model of a flexible transport services for people in congested arc”, Energy Efficient Transportation Research Proceedings, 2012.

[10] Mairaj ud din Mufti et al., “Super-capacitor based energy storage system for improved load frequency control”, Electric Power Systems Research 79, 2009, pp. 226–233.

[11] A.J. Fairweather, “Evaluation of UltraBattery™ performance in comparison with a battery-supercapacitor parallel network”, Journal of Power Sources, 2013, pp. 191-201.

[12] B. Vulturescu et al., “Implementation and test of a hybrid storage system on an electric urban bus”, Transportation Research Part C, 2013, pp. 55-56.

IMPROVEMENT OF ELECTRIC SHUTTLE BUS OPERATION USING LITHIUM-ION BATTERY*

Kanticha Korsesthakarn [1)] **Angkee Sripakagorn** [2)]

Electric shuttle buses are in operation for the past eight years to transport the students and faculty member within Chulalongkorn university campus. Due to the limited fleet size and energy storage system, passengers have a long wait time at the bus stations during peak hour. Lithium-ion batteries were compared in this study to exhibit the battery performance. This paper presents the battery capacity testing accoarding to Peukert's law and the integrated simulation of energy storage system combined with bus scheduling simulation. The lithium-ion battery provides an improvement of 69.63% in discharge duration and 29.9% in efficiency. Average wait time and passenger agreed time are observed in this regard. The system is simulated by Arena software for the bus scheduling. The solution dictates the change of the bus schedule; the resulting change of wait time is then observed. The lithium-ion battery reduce the waiting time by 25% due to its superior energy efficiency as well as shorter charging period.

KEY WORDS: EV and HV system, lithium ion battery/nickel-metalhydride battery (nickel hydrogenbattery)/lead-acid battery, energy management, Electric Bus, Public Transportation (*A3*)

1. Introduction

At the present time, the energy crisis and global warming phenomenon leads to heightened interest in alternative modes of transportation(1). Among the options, urban electric public bus has gained much attention. In general, vehicle scheduling problem focused on bus operation, fleet assignment and optimization (2-4) is very complicated. Simulation is an important tool to realistically model the bus network in in discrete events environment (5-6). Since 2005, Chulalongkorn University campus operates the electric shuttle buses to reduce the exhaust gas and pollutions inside the campus as well as to reduce the operation costs. The limited fleet size and capacity of the buses make it difficult to meet the increased passenger demand. As a result, passengers have long wait time during rush hour. Public transport carrier in the campus has used the trial and error approach for the bus scheduling based on experience. In addition, the limitation of the energy storage system, specific to electric bus, leads to a short drive cycle. It is thus important to design a feasible bus schedule.

The energy storage system is crucial, especially for electric vehicle operations. Due to the limitations of the low cost lead-acid battery. Among the alternative energy storage systems, lithium-ion batteries are a popular choice due to their high energy densities and cycling durability(7). A number of authors have examined the development and modeling of energy storage systems for vehicle applications as well. Cooper(8) has examined the use of lead-acid battery for hybrid electric vehicles. Liaw and Dubarry(9) proposed a methodology to understand battery performance and life cycle through driving cycle and duty cycle analyses. Hung and Wu(10) developed an integrated optimization strategy in which both the component sizing and control strategies are taken into consideration to maximize the energy capacity stored while minimizing the energy consumed for a given driving cycle. Optimization of combined component sizing and control strategies have been explored by Zou et al.(11) to study the hybridization of a tracked vehicle, and by Kim and Peng(12) for the design of fuel cell/battery hybrid vehicles.

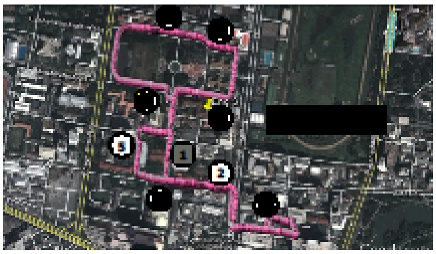
The objective of this work is to access the influence of the alternative energy storage system on the waiting time.

2. Bus Operation Descriptions

The present work focused on one of the four bus lines, bus #3. The bus model considered is a 4-ton battery electric bus with 20 seats capacity and now runs on the fleet size of 3 buses (Fig.1). The electric drive operates on a set of 24 deep-cycle lead-acid batteries connected in series. A group of seven bus stations are included in this route (Fig.2).

Fig. 1 The appearance of the electric bus

Fig. 2 The bus route inside the Chulalongkorn University



3. Experiments

The experiment consists of two parts. The first part is to gather a driving cycle to be used in energy storage system evaluation. The second part is the evaluation of passenger load and power consumption.

3.1. Driving Cycle Characteristics

The driver operates the bus following the regular route and obtained the data of voltage and current measured from the batteries and velocity profile by using Kayaba® drive-recorder and GPS (Fig.3). The goal of this test is to gather the power provided by batteries and use the profile with electric load to discharge the lab-scaled battery packs. The obtained driving cycles will be scaled down and trimmed to stays within the limitation of the electronic load. The profile will be

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employedwith electric load to discharge the lab-scaled battery packs.

3.2. Passenger Load vs. Power Consumption

Since the number of passengers using the bus#3 vary during the day and one trip takes 20 minutes.These data were simplified for the power profile by using average cumulative number of passengers for each trip.

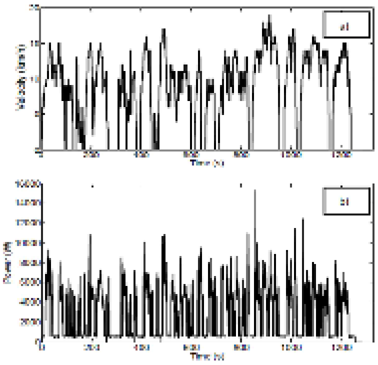

Fig. 3 (a) Velocity trajectory and (b) Power load profile on the representative cycle

Assume one passenger is 57.7 kg. The pack of 15 and 30 lead acid batteries (9 and 18 passengers respectively were loaded into the bus and represented the weight of passengers). The effect of mass and power consumption was determined from the real experiment. The results in Fig.4 indicated the mass is linearly related to the bus energy consumption. Therefore, the power load profile (Fig.3(b)) was gathered from the no load bus. From Fig. 4, the regression equation is:

$$E = 0.1518w + 360.87 \tag{1}$$

where w is total weight of bus including weigh of passengers and E is energy consumption along the entire route.

3.3. Energy Storage System

For the present study, the lead-acid battery (YUASA Deep cycle EB130) 12.8V and 130Ah capacity is considered the base-line energy storage system. Lithuim-ion battery (Calb CA100) 12.8V and 100Ah will be explored for the alternative energy storage ststem (Fig.4).

4. Experimental Results

Under the representative driving cycle, discharge comparison between the two options of energy storage is summarized in Table 1. Concerning the discharged duration provided by battery packs, the lithium-ion battery pack can help increasing the driving range since the discharge duration was extended by 69.63%.

The capacity of lead-acid battery and lithium-ion battery were measured directly using the electronic load (Fig.5). The procedures are repeated three times at each constant current values. The Peukert's equation is written as:

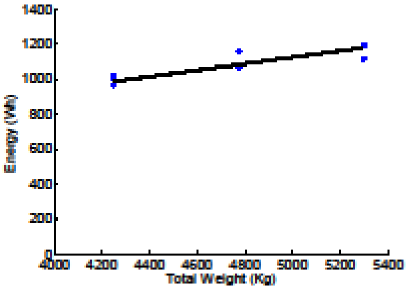

Fig.4 Relation of total weight and energy consumption

$$C = I^k t \tag{2}$$

where C is Peukert's capacity (Ah) for a constant load of I amperes, k is Peukert's constant and t is total time required to discharge battery.

Test results were presented that the battery capacity has relation with the current and discharge time. Lithium-ion battery shows the superior capacity compared to lead-acid battery. For the lead-acid battery. Peukert's constant is 1.33 for lead-acid battery and 1.02 for lithim-ion battery. When k value is 1.00, it means ideal case for the battery. The efficiency of the battery can be determined from discharge energy and capacity. Although the lithium-ion battery has a lower nameplate capacity than lead-acid battery (100Ah vs 130 Ah). The measured capacity of the two is about the same.

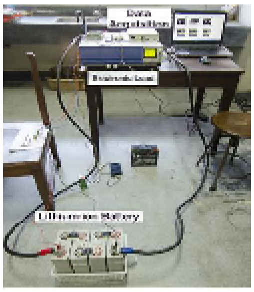

Fig. 5 Configuration of electronic load, lithium-ion battery pack on the test-bench

Table 1 Discharge comparison between lead-acid battery and lithium-ion battery

	Lead-acid Battery	Lithium-ion Battery
Cut-off voltage	10.52V	10.10V
Discharged duration	4 Hours 30 Minutes	7 Hours 38 Minutes
Discharge energy	64.1 Ah	93.4 Ah
Number of trips	13	22
Charging time	1 Hours 25 Minutes	30 Minutes
Capacity	100.77Ah	94.85Ah
Efficiency	63.6%	93.5%

**6.5A at 20 hours for lead-acid battey and 30A at 3.33 hours for lithium-ion battery

Compared to the lead-acid battery, Table 1 showed that the lithium-ion, even with the same nominal energy capacity as the lead-acid battery, the discharge duration is extended by 69.6% with over 45.7% increase in discharge energy and 59.09% increase in the number of trips. This is due to a lower internal resistance and a slightly lower cut-off voltage. Voltage drop of lithium-ion is also lower than lead-acid battery with the same power load profile (Fig.6).

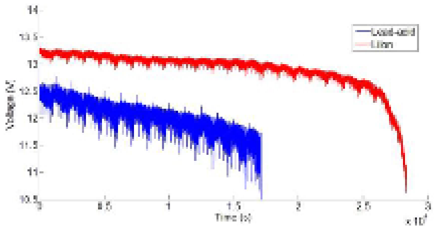

Fig.6 Discharge comparison between lead-acid battery and lithium-ion battery

5. Simulation Model Description

Real world transit problem is very complicated. Discrete event simulation is a way to attack this vehicle scheduling problem efficiently. For the present study, the simulation proposed bus movements and passenger arrivals is developed in Arena environment. Events including passenger arrival, waiting in queue and boarding are considered between bus stations.

5.1 Simulation Modules

The simulation model is made up of a series of modules dedicated respectively to: the acquisition of requests to be evaluated and carried out, the simulation of movement of bus and passengers, the monitoring of possible delays and display of events that actually occur while the simulation runs. During these activities, the model generates unusual demand passengers that the basic heuristic is unable to take into consideration when producing fleet schedules. Finally, a set of performance indicators is calculated to evaluate the robustness of the schedule produced by the Heuristics in response to disturbing elements introduced in the simulation.

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This module obtained the passenger arrival rates from the schedule module to generate the waiting time and passenger arrival rate at each bus stop. For the weight percentage of passenger waiting at each stop, three persons were allocated to collect the number of passengers waiting in queue at the bus stop for three days focused on one hour of rush hour and one hour of normal hour. They reach the bus stop and await the bus arrival.

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This module described the movement of the buses through various stops starting from depot to other stations included the bus activities such as pickup, drop off, boarding and waiting for the passenger. In addition, bus charging module is included.

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The model validation was performed by comparing the simulation model behavior with the real system behavior. The comparison is carried out by one-sample T-test distribution. Two parameters were used to validate the model: number of passengers in the system and waiting time. The percentage difference value between the real system and the simulation output is 2.76% and significant with P-value 0.331 at 95% confidence interval. For passenger waiting time, the data were validated by direct observation and simulation model output and divided into two intervals, one hour for rush hour and one hour for normal hour. The percentage difference values are 11.47% and 10.63% and also significant with P-value 0.384 and 0.225 respectively at 95 % confidence interval.

6. Results

The simulation model was run for 1 day and 5 replications. After running the based case model successfully, the output data was analyzed to design and make the improvement. Three separate results arrived from the base case (Lead-acid battery) and the lithium-ion battery (Table 3). From the base line case with the waiting time of 13.52 mins, the bus schedule has been designed and the energy storage was changed to be lithium-ion battery to extend the bus service time with the eventual target to reduce the waiting time. Table 3 shows the results of average passenger waiting time from simulation model during rush hour from 2 options; lead-acid battery and lithium-ion battery

Table 3 Waiting time in the system during rush hour and P-values from paired T-test comparison compared to based case schedule

	Lead-acid Battery	Lithium-ion Battery
Waiting Time	13.52 mins	10.18 mins
%Reduction		24.7%
P-value		0.001

The two-sample T-test distribution was used to check the results with the based case model. For the new bus schedules, it can reduce the frequency of charging time from twice a day to 1 time per day and manage to avoid the peak time. The P-values obtained from statistical test indicate that the waiting time of the based case schedule is significantly longer than the optimized lead-acid battery and lithium-ion battery schedule by using the same fleet size.

7. Conclusion

Energy storage system play a crucial role to the bus service time. In this study, lead-acid battery and lithium-ion in the lab scale were compared with realistic load power profile. Lithium-ion batteries exhibit the improved performance. The lithium-ion battery provides an improvement of 45.7% in discharge energy, 59.09% in number of trips as well as the shorter charging period. The efficiency of lithium-ion battery is higher than lead-acid battery even the nameplate capacity is lower. The simulation model obtained the discharge duration to simulate the based case bus schedule model compared with the new bus schedules. The new schedules from lithium-ion battery can reduce the frequency of bus charging time since the driving range increased. Lithium-ion can help extend the bus service time with the same fleet size and reduce waiting time by 24.7%.

Acknowledgements

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References

(1) C. Sandy Thomas : Transportation options in a carbon-constrained world: hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles, p. 9279-9296.

(2) W. Lam et al. : Multiresponse optimization of dispatch rules for public bus service: Computer & Industrial Engineering 56, p. 77-86.
(3) A. Fugenschuh : Solving a school bus scheduling problem with integer programming: European Journal of Operational Research 193, p. 867-884.
(4) J. Euchi and R. Mraihi : The urban bus scheduling problem: European Journal of Operational Research 218, p. 577-585.
(5) W.D. Kelton et al. : Simulation with Arena: McGraw hill Book Corporation (2004).
(6) Y. Yan et al. : Robust Optimization Model of Schedule Design for a Fixed Bus Route : Transportation Research Part C, p.113-121.
(7) L. Lu et al. : A review on the key issues for lithium-ion battery management in electric vehicles: Journal of Power Sources, Issue 226, p.272-288 (2013).
(8) A. Cooper : Development of a lead-acid battery for hybrid electric vehicle: Journal of Power Sources, Issue 133, p.116-125 (2004)
(9) Liaw BY and Dubarry : From driving cycle analysis to understanding battery performance in real-life electric hybrid vehicle operation: Journal of Power Sources, Issue 174, p.76-88 (2007).
(10) Hung and Wu : An integrated optimization approach for a hybrid energy system in electric vehicles: Journal of Applied Energies, p.479-490 (2012).
(11) Y. Zou, F. Sun, X. Hu, L. Guzzella and H. Peng : Combined optimal sizing and control for a hybrid tracked vehicle: Journal of Energies, Issue 11, p.4967-4710.
(12) Kim and Peng : Power management and design optimization of fuel cell/battery hybrid vehicles: Journal of Power Sources, Issue 165, p.819-832 (2007).

VITA

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Her main fields of interests are energy storage systems for electric vehicles and optimization