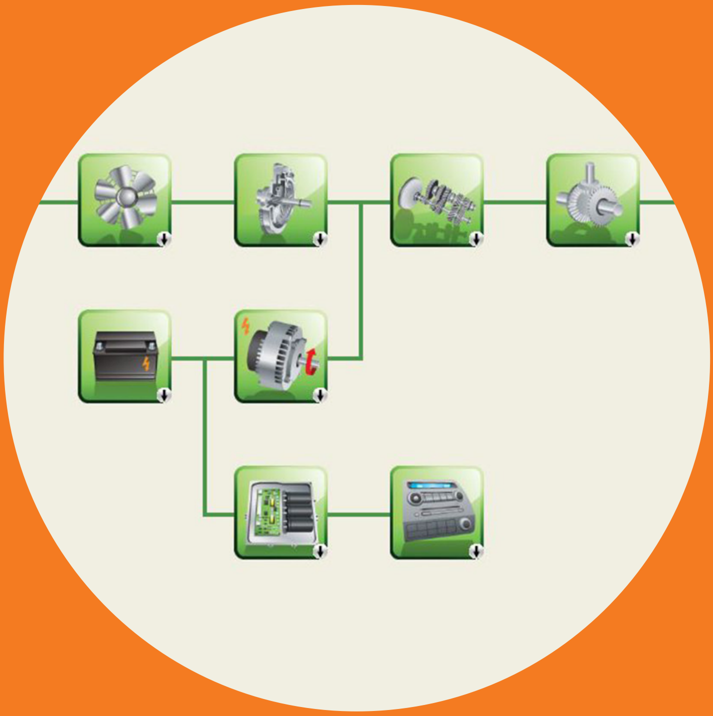
Department of Engineering Design and Production

Improving the Energy Efficiency and Operating Performance of Heavy Vehicles by Powertrain Electrification

Antti Lajunen



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Improving the Energy Efficiency and Operating Performance of Heavy Vehicles by Powertrain Electrification

Antti Lajunen

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Abstract

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Abstract

In this thesis, the potential of hybrid and electric powertrains to improve the energy efficiency and operating performance of heavy vehicles and heavy machinery have been evaluated with scientific research methods. The evaluation was carried out by using representative case applications among on-road heavy vehicles and heavy machinery. These applications are a city bus, an underground mining loader and a heavy vehicle combination. The key objective of this thesis was to analyze the impact of powertrain electrification on the energy efficiency and operating performance. For city buses and underground mining loader, cost effectiveness was also analyzed. The role of the different electrical energy storages in powertrain electrification was evaluated throughout the different phases of this research for each vehicle application.

Many aspects need to be taken into consideration when introducing electric powertrains for heavy vehicles and machinery. Important aspects are the operating environment, strategy and schedule. In this context, this thesis introduces several methods to evaluate these different aspects in terms of energy efficiency and operating performance. These methods are based on vehicle simulation, which was the main research method. Vehicle simulation is a very powerful tool to develop and evaluate different vehicle powertrain technologies. During the research, different vehicle simulation software were used the main tool being the MATLAB/Simulink.

The various simulation results clearly showed that the energy efficiency of the heavy vehicles can be significantly improved by powertrain electrification. It is being underlined that the improvement depends on the powertrain topology, operating cycle, and also energy storage system configuration. According to the cost calculations results, the hybrid and electric city buses have, in most situations, higher life cycle costs than the diesel buses whereas a hybrid underground loader has already potential to be economically more profitable than a diesel loader. The various performance analyses of the energy storages in different heavy vehicle applications showed that the current lithium-ion battery technology provides good performance in terms of power and energy capacity. However, the battery costs and durability are still importance challenges in order to improve the cost effectiveness of heavy vehicles.

Keywords Electric powertrain, Hybrid powertrain, Energy efficiency, Operating performance, Heavy vehicle, Heavy machinery, Energy Storage, Vehicle simulation

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Tiivistelmä

Tekijä
Antti Lajunen

Väitöskirjan nimi
Raskaiden ajoneuvojen energiatehokkuuden ja suorituskyvyn parantaminen voimansiirron sähköistämisellä

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Tiivistelmä

Tässä väitöskirjassa arvioidaan tieteellisillä tutkimusmenetelmillä hybridi- ja sähköisen voimansiirron potentiaalia parantaa raskaiden ajoneuvojen ja työkoneiden energiatehokkuutta ja suorituskykyä. Arviointi suoritettiin keskittymällä kahteen tyypilliseen raskaaseen ajoneuvoon ja yhteen työkoneeseen. Nämä kyseiset ajoneuvot ovat kaupunkilinja-auto ja raskas ajoneuvoyhdistelmä ja työkoneena on kaivoslastaaja. Tämän tutkimuksen keskeisenä tavoitteena oli selvittää voimansiirron sähköistämisen vaikutus raskaiden ajoneuvojen ja työkoneiden energiatehokkuuteen ja suorituskykyyn. Kaupunki linja-auton ja kaivoslastaajan kohdalla tarkasteltiin myös kustannustehokkuutta suhteessa perinteisiin dieselkäyttöisiin ajoneuvoihin. Jokaisen ajoneuvon ja työkoneen kohdalla analysoitiin myös sähköisten energiavarastojen vaikutusta energiatehokkuuteen ja suorituskykyyn.

Raskaiden ajoneuvojen ja työkoneiden voimansiirron sähköistämisessä täytyy ottaa huomioon monia erilaisia tekijöitä kuten toimintaympäristö, ajo- tai työsykli ja operointistrategia. Tämän väitöskirjan tavoitteena olikin luoda mahdollisimman kattavia laskentamenetelmiä, joilla voidaan tasapuolisesti vertailla erilaisia voimansiirron teknologioita ja operointistrategioita. Näiden menetelmien kehityksen keskiössä on ajoneuvosimulointi, jota käytettiin pääasiallisena tutkimusmenetelmänä. Simulointi on tehokas tapa kehittää ja arvioida erilaisia voimansiirron teknologioita varsinkin kun kyseessä on raskaat ajoneuvot ja työkoneet. Tutkimuksessa käytettiin ajoneuvosimulointiin kehitettyjä ohjelmistoja ja MATLAB/Simulink ohjelmistoa.

Kokonaisuudessaan tutkimuksen tulokset osoittivat, että raskaiden ajoneuvojen ja työkoneiden energiatehokkuutta voidaan merkittävästi parantaa voimansiirron sähköistämisellä. Tulokset osoittivat myös, että mahdollinen energiatehokkuuden parantuminen on kuitenkin usein vahvasti riippuvainen voimansiirron topologiasta, operointisyklistä ja myös energiavarastosta. Kustannustehokkuusanalyysien mukaan hybridi- ja sähkölinja-autoilla on vielä useimmiten korkeammat elinkaarikustannukset kuin perinteisillä diesel linja-autoilla. Hybridikaivoslastaajalla on sen sijaan jo potentiaalia olla taloudellisesti kannattavampi kuin dieselkäyttöinen lastaaja. Energiavarastojen suorituskyvyn analyysit osoittivat, että nykyinen litium-ioni akkuteknologia tarjoaa hyvän suorituskyvyn teho- ja energiakapasiteetin suhteen. Näiden akkujen kustannukset ja kestoikä ovat kuitenkin vielä tärkeitä haasteita kun halutaan parantaa raskaiden ajoneuvojen ja työkoneiden kustannustehokkuutta.

Avainsanat Sähköinen voimansiirto, Hybridivoimansiirto, Energiatehokkuus, Suorituskyky, Raskas ajoneuvo, Raskas työkone, Energiavarasto, Ajoneuvosimulointi

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Preface

This research was carried out in the Vehicle Engineering Research Group of the Department of Engineering Design and Production, School of Engineering, Aalto University. The research was funded by several TEKES (Finnish Funding Agency for Technology and Innovations) research projects, Multidisciplinary Institute of Digitalisation and Energy (MIDE) of Aalto University, and individual grants from Walter Ahlström Foundation, Aalto University, Fortum Foundation, and Helsinki University of Technology.

I would like to thank Professor Matti Juhala for giving me the opportunity to do my thesis in such an interesting field of study. I wish to thank all my research colleagues at the Vehicle Engineering Laboratory. Special thanks to Ari Tuononen and Panu Sainio who both have inspired me on their own professional way in my research over the years. I would also like to thank Jussi Suomela for his valuable contribution in our research projects.

Espoo, 19 August 2014

Antti Lajunen

Contents

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their Roman numerals

I. Lajunen, Antti. Energy consumption and cost-benefit analysis of hybrid and electric city buses. *International Journal of Transportation Research: Part C*, vol. 38, pp 1–15, Jan 2014.

II. Lajunen, Antti. Powertrain Design Alternatives for Electric City Bus. In *Proc. IEEE Vehicle Power and Propulsion Conference*, Seoul, Korea, pp. 1112–1117, Sep 2012.

III. Lajunen, Antti. Energy-Optimal Velocity Profiles for Electric City Buses. In *Proc. IEEE International Conference on Automation Science and Engineering*, Madison, WI, USA, pp. 886–891, Aug 2013.

IV. Lajunen, Antti. Development of Energy Management Strategy for Plug-in Hybrid City Bus. In *Proc. IEEE Transportation Electrification Conference and Expo*, Dearborn, MI, USA, pp. 1–6, Jun 2012.

V. Lajunen, Antti and Suomela, Jussi. Evaluation of Energy Storage System Requirements for Hybrid Mining Loader. *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3387-3393, Oct 2012.

VI. Lajunen, Antti. Development of Energy Management Strategies for Heavy Mobile Machinery. In *Proc. ASME Dynamic Systems and Control Conference*, Palo Alto, CA, USA, pp. 1–8, Oct 2013.

VII. Lajunen, Antti. Fuel economy analysis of conventional and hybrid heavy vehicle combinations over real-world operating routes. *Journal of Transportation Research: Part D,* vol. 31, pp. 70–84, Aug 2014.

Author’s Contribution

The Publications I-IV and VI-VII are entirely based on the contributions of the Author. The Author has contributed also the major part of the Publication V. The second author of the Publication V, Jussi Suomela, provided valuable feedback and support during the work and publishing phases of the paper.

Publication 1: Energy consumption and cost-benefit analysis of hybrid and electric city buses

Publication I has a major contribution for the evaluation of the energy efficiency and cost effectiveness of conventional, hybrid and electric city buses. This publication introduces a method to compare the lifecycle costs of city buses with different powertrain technology in fleet operation. The fleet operation is especially important when the comparison includes buses that have rechargeable electrical energy storages such as plug-in electric and full electric buses. Vehicle simulation was used to define the energy efficiency of the different technologies in several different types of operating routes. The energy consumption simulation results served as input data for the cost-benefit analysis, which was carried out as a lifecycle cost analysis. Overall, the results show that the energy efficiency can be significantly improved by hybridization and even more with full electric powertrain. The alternative powertrains could also significantly reduce the pollutant emissions when comparing to the conventional diesel buses. The lifecycle costs analysis results indicated that the cost effectiveness of the hybrid and electric buses depends heavily on the bus configuration, and the operation route and schedule. In certain type of operation, hybrid buses can already be economically more profitable than diesel buses. The capital cost is the most critical factor to make the buses with alternative powertrain economically sustainable. The results also show that the energy storage costs and durability are other critical factors for the plug-in hybrid and electric buses.

Publication 2: Powertrain Design Alternatives for Electric City Bus

Publication II presents an analysis of different powertrain design alternatives for electric city bus. Six different powertrain alternatives with different component configurations were defined in terms of energy storage, electric motor(s) and transmission. Two types of electric motors were used; permanent magnet and induction electric motors. The powertrain components were dimensioned based on the requirements in a typical city bus operation. In addition, also the advantages and disadvantages of dual-source energy storage with a battery pack and ultracapacitors were evaluated. The comparison between the powertrain options is based on energy consumption simulations in different operating routes. Even if the energy efficiency of the full electric powertrain is generally high, there are still considerable differences between the different powertrain alternatives; the largest difference was a little over 10%. The advantages of the dual-source energy storage included a drastic decrease in the battery charging current and required cooling power of the battery. Also the discharge current and energy throughput of the battery can be significantly decreased by using ultracapacitors in parallel with a battery.

Publication 3: Energy-Optimal Velocity Profiles for Electric City Buses

Publication III evaluates the energy efficiency of diesel and electric city buses with energy-optimal velocity profiles. The paper presents an optimization method, which can be used for defining an energy-optimal velocity trajectory between the stops on the operating route. The paper also evaluates the differences between the operation of diesel and electric city buses. According to the results, the main difference in the energy consumption is that a diesel bus consumes a lot more energy during the acceleration phase, and the braking energy can be stored in the battery in the case of the electric bus. The energy consumption of an electric bus is less impacted by the driving pattern characteristics, e.g. by the the sub-cycle average speed and duration, than in the case of a diesel bus. Overall, the results clearly show that the energy efficiency could be significantly improved being around 18% by optimizing the operating speed of a city bus. The improvement is about the same for the diesel and electric buses.

Publication 4: Development of Energy Management Strategy for Plug-in Hybrid City Bus

This publication introduces a simulation based development process of energy management strategy (EMS) for plug-in hybrid city bus. Based on a given driving cycle and operating schedule, theoretical control parameters are developed depending on the optimization target. The process is based on dynamic programming and vehicle simulation. The fuel consumption and battery aging minimization are used as optimization targets. In the control problem, the battery life was taken into account as equivalent fuel consumption. The simulation results show that the fuel consumption and battery aging of a plug-in hybrid city bus are strongly dependent on the driving cycle. By optimizing the fuel consumption alone, already a significant increase in battery useful life was observed. The battery useful life can be further improved by a compromise solution between the fuel economy and battery aging.

Publication 5: Evaluation of Energy Storage System Requirements for Hybrid Mining Loader

In this publication, an evaluation of technical requirements for electrochemical energy storage systems in hybrid underground mining loaders is presented. These requirements take into account the power and energy capacity, costs, life cycle, and safety-related requirements. The evaluation of the requirements is based on the characteristics of the current energy storage technology and vehicle simulation results. The evaluation shows that lithium-based batteries offer sufficient power and energy capacity; meanwhile, the requirements for cost and cycle life durability are dependent on the operating strategy and configuration of the loader. In particular, the power-intensive duty cycle of a mining loader can be challenging for batteries in terms of cycle life and thermal management. Based on the simulation results, the energy and work efficiency of different hybrid loader configurations were analyzed. According to the analysis, the energy efficiency and productivity could be significantly improved by hybridization. The paper also presents a calculation for the payback time for the hybrid electric underground mining loaders. The calculation indicates that a hybrid underground loader could already be economically more profitable than a diesel powered loader.

Publication 6: Development of Energy Management Strategies for Heavy Mobile Machinery

This publication introduces a method for developing energy management strategies for heavy mobile machinery. The method is based on dynamic programming algorithm, which can be used for solving optimization problems. In the case of heavy machinery, not only the energy consumption but also the operating efficiency can be a target of the energy management strategy optimization. The case application is a hybrid electric underground mining loader but the strategies were also developed for diesel-electric and full electric loaders. The paper also evaluates and compares the energy and work efficiency of the loaders with different powertrain topologies. The results showed that the energy management strategy of the hybrid electric loader is a compromise between energy and operating efficiency. With the electric loader, the results in terms of energy and operating efficiency were practically the same with both optimization targets. This is because the power consumption of the auxiliary devices is quite important in heavy loader operation. A faster operation decreases the total amount of energy consumed in auxiliary devices.

Publication 7: Fuel economy analysis of conventional and hybrid heavy vehicle combinations over real-world operating routes

The publication VII evaluates the fuel economy of the diesel and hybrid electric heavy vehicle combinations. The fuel economy analysis is based on simulation results, which were carried out in the Autonomie vehicle simulation software. Simulation models of conventional and parallel hybrid heavy vehicle combinations were developed in the software. Simulations were carried out in real-world operating routes, which were measured in the popular truck routes in southern part of Finland. As the simulations were conducted with four different total weights of the combinations, the impact of payload capacity on the load specific fuel consumption was also analyzed. The simulation results show that with hybridization the fuel economy can be improved but the impact of the operating route can be significant. Higher total weights of the heavy vehicle combinations increase the fuel consumption almost linearly but also decrease significantly the payload specific fuel consumption.

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List of Abbreviations and Symbols

Abbreviations

550	Helsinki region bus driving cycle
AC/DC	AC to DC rectifier
AUX	Auxiliary devices
BATT	Battery
BR	Braunschweig driving cycle or Brake resistor
CD	Charge-Depleting (a hybrid vehicle operating strategy)
CO	Carbon oxide (pollutant emissions)
CO2	Carbon dioxide
CONV	Conventional vehicle
CS	Charge-Sustaining (a hybrid vehicle operating strategy)
DC/DC	DC to DC converter
DFP	Diesel Particulate Filter
DP	Dynamic Programming
ED	Electric drive
EGR	Exhaust Gas Recirculation
EMS	Energy Management Strategy
ESS	Energy Storage System
EV	Electric Vehicle
FD	Final drive (Differential gear)
GEN-SET	Engine-generator
H3	Helsinki region bus driving cycle
HC	Hydrocarbon (pollutant emissions)
HM	Hydraulic motor

HP	Hydraulic pump
HVC	Heavy Vehicle Combination
ICE	Internal Combustion Engine
Li-ion	Lithium-ion (a battery type)
NiCd	Nickel Cadmium (a battery type)
NiMH	Nickel Metal Hydride (a battery type)
NiZn	Nickel Zinc (a battery type)
NOx	Nitric oxide and nitrogen dioxide (pollutant emissions)
NRMM	Non-Road Mobile Machinery
NYC	New York City Bus driving cycle
OCC	Orange County City bus driving cycle
PAR	Parallel (a hybrid powertrain topology)
PM	Particulate matter (pollutant emissions)
RG	Reduction gear
ROI	Return of Investment
SCR	Selective Catalytic Reduction
SER	Series (a hybrid powertrain topology)
SOC	State-of-Charge
SORT	Standardised On-Road Test Cycles
TX	Transmission
UC	Ultracapacitor
UCAP	Ultracapacitor module
UITP	The International Association of Public Transport

Symbols

C_{batt_he}	High-energy battery cost
C_{batt_hp}	High-power battery cost
C_{cap}	Capital cost of a conventional diesel bus
C_{chg}	Cost of the external charging equipment
C_{CONV}	Conventional loader initial costs
C_{elec}	Electricity cost

C_{ess}	Energy storage cost
C_{fuel}	Diesel fuel cost
C_{mc}	Maintenance cost
C_{op}	Yearly operating cost
C_{op_conv}	Operating costs of a conventional loader
C_{op_hyb}	Operating costs of a hybrid loader
C_{ucap}	Ultracapacitor system cost
D_{km}	Yearly driven distance
D_a	Yearly driven distance in operation
d_{rate}	Discount rate
E_{batt}	Battery usable energy
E_{km}	Battery energy throughput
E_{route}	Energy consumed for a single route
f_C	Capital cost factor
f_{HYB}	Hybrid loader initial cost factor
I	Battery current
L	Battery life in years
$\dot{m}_{batt}$	Equivalent fuel consumption of the battery
$\dot{m}_{fuel}$	Fuel consumption
$\dot{m}_{rbatt}$	Equivalent fuel consumption to compensate the regenerated braking energy
N_C	Number of conventional buses
N_{cycle}	Battery cycle life
N_E	Number of rechargeable buses
N_{init}	Initial number of buses in a fleet
N_t	Number of energy storage replacements
P_{batt}	Battery power
P_{chg}	Charging power
P_{fuel}	Fuel power
P_t	Total power demand
t	Time

t_a	Maximum available time for charging
t_{chg}	Charging time
T_d	Time elapsed at one distance step
T_{op}	Operation time in a year
t_{rtot}	Duration of a route including a minimum waiting time between the operations
T_s	Service life
u	Control variable
u_k	Power split factor
v_k	Speed
v_{max}	Maximum speed
v_{min}	Minimum speed
w_k	Control variable
w_{HYB}	Amount of work
X_{chg}	Charging factor
α	Weighting factor
θ	Battery temperature

1. Introduction

1.1 Background and motivation

The limited energy resources and the increasing demand for transportation have continuously raised the interest towards alternative powertrain technologies to provide sustainable energy saving solutions in many sectors of transportation as well as in the field of heavy machinery (Mol et al., 2009; Thomas, 2009). The increasing energy use of the diesel powered heavy vehicles and machinery also increases the amount of pollutant and CO_2 emissions. Hybridization and electrification of vehicle powertrains has a lot of potential to decrease the fuel consumption and emissions (van Vliet et al., 2010; Hellgren, 2007; Åhman, 2001). There are increasing amount of hybrid and electric vehicles being used every day. However, there are still challenges to overcome for the large scale adoption of alternative powertrain technologies, and work needs to be done in the development of economically sustainable solutions for on-road heavy vehicles and heavy machinery (Feng and Figliozzi, 2013; Croft McKenzie and Durango-Cohen, 2012). In this context, powertrain electrification is considered as an effective solution to use electrical energy to move or to operate a vehicle or a machine, and increase the energy and operating efficiency. The powertrain electrification includes the use of hybrid and electric powertrains with electrical energy storages (Ehsani et al., 2010; Khaligh and Li, 2010). Electrical batteries and ultracapacitors are the typical electrical energy storages for on-road vehicles and mobile machinery (Burke and Miller, 2011; Rotenberg et al., 2011).

Electric powered vehicles have been in use for more than 100 years but large-scale market adoption by using the modern electrical energy storage technology has not yet happened (Feng and Figliozzi, 2013; Weiss et al., 2012). The technological development of power electronics and the battery technology, especially the lithium-ion batteries, has given a lot of promise for the large scale electrification of vehicles (Haizhong et al., 2012; Lukic et al., 2008). In difference to light duty passenger vehicles, heavy vehicles such as city buses and delivery trucks are interesting applications for electrification due to their operating characteristics. For instance, city buses operate in predefined routes, which usually include frequent accelerations and decelerations. In this type of driving, the conventional diesel powered city buses do not have high energy efficiency whereas hybrid and electric buses are better suited for stop-and-go driving, and they can regenerate braking energy into the energy storage.

Non-road mobile machinery (NRMM) include machines from variety of applications areas e.g. form construction to material handling equipment and from agricultural tractors to underground mining machines. Typical heavy mobile machines are, among others, wheel loaders, excavators, forklifts, and straddle carriers. Because of the small production series of heavy machines, only recently the powertrain electrification has been considered to be economically viable for mobile machinery (Kunze, 2010). The component durability in the electric powertrains has been sometimes questioned as the heavy machinery usually operate intensively in harsh conditions. Nevertheless, the electrification of heavy machinery offers not only a way to improve energy efficiency and decrease emissions but also a possibility to enhance the operating efficiency (Jo and Kwak, 2011; Lin et al., 2010; Wang et al., 2009). In some cases, the inherent properties of electric motors and actuators provide better controllability and drivability of the machines when comparing to the mechanical powertrain or hydraulic systems.

Because heavy vehicle combinations (HVC) consume a lot of fossils fuels in their operation, and because their share of the total transportation energy consumption is significant, improving the energy efficiency of these vehicles has been a research focus for a long time. Several non-electrification technologies have been studied over the years to increase the fuel economy of heavy-duty trucks and HVCs e.g. (NAS, 2010; Hill et al., 2009a; Ogburn et al., 2008). One way to decrease the energy consumption and the energy intensity, which corresponds to the load specific fuel consumption, is to adopt higher weights for the vehicle combinations (Vierth and Haraldsson, 2012; Ruzzenenti and Basosi, 2009). In recent years, there has been more and more interest for longer and heavier vehicles in Europe in order to increase the energy and operating efficiency of the road transport sector (Bark et al., 2012; Rijkswaterstaat, 2011; Christidis and Leduc, 2009). Hybridization and electrification have not often been considered as a solution to improve the energy efficiency of HVCs. Even if the operation of HVCs is typically over a long-distance and consists mostly of constant speed driving, a significant amount of braking energy can be regenerated because of the road elevation changes.

The motivation for this thesis came from the fact that despite the energy efficient electrical powertrain technology already exists but it is not yet being used in large scale, and the potential for energy savings and reduction of the pollutant emissions is not being fully exploited. Another source of motivation was the lack in the scientific literature of the detailed analyses about the use of electric powertrains in heavy vehicles. A successful powertrain electrification of heavy vehicles and machinery requires a detail evaluation of the potential energy savings in the dedicated operating environment as well as a lifecycle cost analysis to demonstrate the economically sustainable solutions. This thesis is considered to have an important contribution to the before mentioned topics. It is also considered that the large scale adoption of the electric powertrains facilitates to introduce other advanced technologies, among others, the autonomous operation of vehicles.

1.2 Research objectives and questions

There are numerous different choices for powertrain electrification, which are usually called as powertrain topologies or architectures. Depending on the application, it can be a complex task to choose the most suitable solution in terms of energy efficiency, operating performance and cost effectiveness. In this context, the operating performance refers to the technical performance in terms of operating productivity, and also to the economic performance in terms of operating costs. The main research objective of this thesis is to demonstrate the potential of electric powertrains in selected heavy vehicle and machinery applications to improve energy efficiency and operating performance as well as cost effectiveness. The selected applications include a city bus, an underground mining loader and a heavy vehicle combination. The specific characteristics of the vehicle or machine operation have been taken into account because they may have significant impacts on the energy and operating efficiency as well as cost effectiveness. These types of specific characteristics are, among others, the operating cycle and schedule for city buses, and duty work cycle for a mining loader.

The energy management strategy (EMS) and energy storage system (ESS) analysis were the secondary objectives of this thesis. The EMS has a central role for the effective and robust operation of the hybrid and electric powertrains. In this thesis, the aim was to introduce simulation based methods for the EMS development, and methods to fairly compare different powertrain topologies to each other also by eliminating the impact of the EMS. Almost in every phase of this thesis, the importance of the ESS was evaluated because it can have a major impact on the operating performance and especially on the cost effectiveness of heavy vehicles and machinery.

In the context of this thesis, the following research questions were defined:

1) What is the potential of electric powertrains in heavy vehicles and machinery to increase the energy and operating efficiency?
2) What are the impacts of operating environment and conditions on the benefits of the powertrain electrification?
3) What kinds of challenges/requirements relate to the use of electrical energy storages in electric and hybrid powertrains of heavy vehicles?
4) Which are the main challenges in cost effectiveness with electric powertrains in heavy vehicles?

1.3 Research method

The main research method of this thesis was vehicle simulation. Because practical testing of heavy vehicles and machinery can be time consuming and expensive, most of the research results were generated by mathematical modeling and simulation. Different vehicle simulation software were used, and also some simulation models were developed entirely during the research. The main tool was MATLAB/Simulink, which is widely used as a simulation model development environment also by commercial vehicle simulation software like ADVISOR (Markel et al., 2002) and Autonomie (Vijayagopal and Rousseau, 2011). MATLAB/Simulink is a versatile modeling and simulation environment, which itself does not include any ready models for entire vehicles but offers a powerful platform to develop and simulate different types of models. The main simulation software was ADVISOR, which has been widely used both for light duty and heavy duty vehicles e.g. (Ribau et al., 2014; Suh et al., 2012; Same et al., 2010; Baisden and Emadi, 2004). ADVISOR has quite extensive model and component data library, which facilitates the development of new powertrain topologies and configurations. Nowadays, modeling and simulation is very powerful tool to investigate and analyze different vehicle powertrain technologies without consuming a lot of monetary resources and time. The simulation environment also facilitates to create different operating environments for the vehicular applications to analyze the impact of e.g. driving and climate conditions. Vehicle modeling and simulation have been widely used by the industry and academia in scientific research to evaluate the performance and energy efficiency of different types of powertrain technologies.

1.4 Contributions of the Thesis

This thesis has several types of contributions in different levels in the evaluation of the energy and operating efficiency of heavy vehicles and machinery. The research findings in this thesis are considered to be a valuable complement to the existing research knowledge about the impacts of the powertrain electrification in heavy vehicles. The contributions to the development of methods to evaluate and compare different types of powertrain topologies and configurations as well as to design energy management strategies are also considered as important contributions.

The major contribution of this research is the process of evaluating the energy efficiency of alternative powertrains in city buses. In this process, a fleet operation and operating schedule are integrated to the traditional evaluation process of the energy consumption. This way the differences in the operation of alternative powertrains can be fully taken into account. Similarly, the operating cycle has been considered for the underground mining loader not just as a power demand but as a working operation in which different tasks are carried out. These approaches enable to fairly compare the energy consumption of different powertrain technologies, and also to evaluate the impact of the operating cycle and tasks on the energy and operating efficiency. As the existing literature has been focused mostly on the improvement of energy efficiency, the possibility of improving the operating efficiency or productivity with the powertrain electrification has been emphasized in this thesis in the case of heavy mobile machinery. This thesis also contributes to the analysis of life cycle costs of city buses and hybrid underground mining loaders. The cost calculations are presented from the operator point of view because these types of vehicles and machines are often operated by professionals in business operations.

In the case of heavy vehicle combinations, a technically and also politically sensitive topic of using higher weights for vehicle combinations was evaluated in terms of the energy and operating efficiency. This particular subject has not been given a lot of research attention even if the payload specific fuel consumption can be significantly improved by adopting higher weights. In the evaluation, the vehicle combinations were based on real tractor-trailer combinations and real-world operating cycles were used in simulations. In this case, also the importance of taking into account the real operating conditions was illustrated by the differences in the energy efficiency of different parallel hybrid vehicle combinations.

Because the electrical energy storages are the key components in the powertrain electrification, the role of these energy storages in heavy vehicles and machinery was evaluated throughout the different phases of this research. In the evaluations, the focus was on the energy storage durability, and especially on the useful life of lithium based batteries. The battery useful life estimations were calculated for each case application, and the impacts of the energy storage costs were analyzed for the city buses and underground mining loader. There are not many scientific publications in the existing literature that present the energy storage life estimations for hybrid and electric heavy vehicle applications.

The developed mathematical methods enable a fair comparison of energy efficiency potential of different powertrain topologies and configurations, and serve for the development of energy management strategies in particular applications. With the aid of these methods, the energy-optimal velocity profiles were defined for a diesel and an electric city bus and different types of mining loaders. The focus of these methods is not only to investigate or optimize the energy efficiency but also illustrate the potential how much the operating efficiency could be increased. The use of the developed methods and research processes are not limited to the selected heavy vehicle applications but they may be used for other types of vehicles as long as their particularities are taken into account in the process.

1.5 Outline of the Thesis

This thesis has six different sections. This first chapter introduces the background of the research, presents the research objectives and methods, and summarizes the author's contribution. The second chapter focuses on the state-of-the-art by presenting the underlying technology of the selected heavy vehicle and machinery applications. In chapters 3-5, the contributions of the published scientific papers are summarized. The chapter six includes discussion and conclusions.

2. Technology overview

Electric powertrains have been used for on-road heavy vehicles since the invention of the automobile. In fact, in the early years of automobiles, a large portion of the vehicles were powered by electricity. Due to the development of internal combustion engines and technical challenges in electrical energy storage technology, the vehicles equipped with an electric powertrain became less interesting applications. For some time, the electrification of on-road vehicles has been seen as a solution to overcome the challenges of energy efficiency, pollutant emissions, crude oil dependency, and greenhouse gas emissions.

2.1 City bus

A city bus has been an application, which has had several powertrain layouts and degrees of electrification throughout the history. The oldest widely used bus application is the trolleybus, which uses overhead wires to electrically power the bus often without any on-board energy storage in the bus (Brunton, 2000; Sinclair, 1940). Different powertrain solutions for hybrid and electric buses had been designed already a long time ago (Parsegian, 1969; Hoffman, 1972). Batteries have usually been the energy storage solution in alternative powertrains but the technical development of ultracapacitors has made them as a viable choice also as a single storage of energy (Burke and Miller, 2011; Kühne, 2010). Even though the technical solutions have been recognized a long time ago, the main challenge has been the performance of the electrical energy storage and the related component and development costs of the electric powertrain. Figure 2.1 shows a modern, lightweight electric city bus (eBus, 2014).

The energy efficiency of city buses has been widely studied in literature, and recently a lot of focus has been given for the different types of hybrid and electric buses (Croft McKenzie and Durango-Cohen, 2012; Nylund and Koponen, 2012; Zaetta and Madden, 2011). Over the years, the different hybrid and electric powertrain solutions for city buses have been studied, and their potential to increase energy efficiency has been clearly illustrated (Banjac et al., 2009; Katrašnik et al., 2007; Åhman, 2001). Depending on the differences in climate conditions and driving cycles, the energy efficiency of a city bus can have significant variations. Usually, the low average operating speed is produced by the high number of stops in the operating route, which is typical in inner city driving cycles. There are several choices for the hybrid and electric powertrain configuration and the differences in the energy efficiency between the different configurations can be considerable depending on the operating conditions.

Figure 2.1. An electric city bus (eBus, 2014).

2.1.1 Powertrain technologies

The powertrain of a modern, diesel-powered city bus typically consist of an engine, a hydraulic torque converter, an automatic gearbox and a final drive (a differential gear) at the rear axle. City buses are usually rear wheel driven although some special buses, such as airport shuttle buses, are sometimes front wheel driven. Even though the diesel engine technology has been developed over the years, the efficiency of a typical diesel engine in a city bus operation is relatively low due to the stop and go type of driving. The amount of pollutant emissions of diesel engines have been decreased due to the advanced engine control and additional exhaust gas treatment systems such as EGR, SCR and DFP. The pollutant emission regulations are gradually becoming stricter and stricter (Regulation, 2009). Because of the typical characteristics of the city bus operation, a hydraulic torque converter with an automatic gearbox is being used in conventional city buses to ensure a smooth deliver of torque from the engine to wheels especially in take-off and acceleration phases. The major part, between 65-75%, of the energy losses in the powertrain of a diesel bus originate from the engine and its mechanical accessory (Delorme et al., 2009).

The hybrid powertrains in city buses are somewhat similar to those in passenger vehicles. However, the different driving patterns in combination with high driving torque requirements, when comparing to passenger vehicles, generates different requirements for the powertrain. The most typical topologies for the hybrid powertrain have been parallel and series configurations. From the structural point of view, the parallel topology usually has two variations; pre-transmission and post-transmission parallel hybrid. Depending on the hybrid system control and the component technology, the parallel hybrid powertrain can be operated differently such as a power-assist or a full hybrid. Series hybrid topology is the most common in city buses

(Barnitt, 2008). It has flexible structure as there is no mechanical link between the engine and the wheels. As the engine control is not dependent on the vehicle's speed, it facilitates the development of the engine and emission control. Figures 2.2 and 2.3 present the powertrain layouts for a pre-transmission parallel hybrid and series hybrid topologies. The complex Toyota Prius-type, power-split hybrid powertrain has also been used in city buses even though the high level of complexity increases the costs. An example of this type of powertrain is the two-mode, input and compound split transmission by Allison transmission (Allison, 2014). The hybrid powertrain is well suited for the city bus operation having frequent acceleration and deceleration phases, and average speed being relatively low.

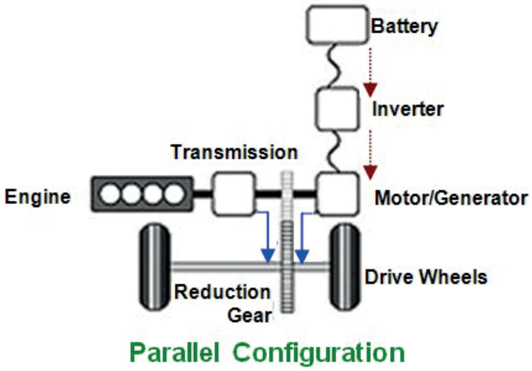


Figure 2.2. Parallel hybrid powertrain topology.

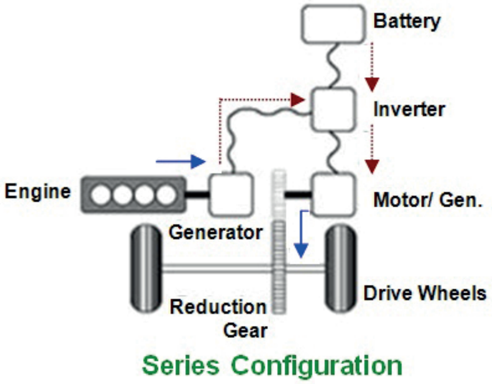


Figure 2.3. Series hybrid powertrain topology.

A full electric powertrain has far more simpler structure than any other automotive powertrain. It typically consists of energy storage, a traction motor and a gear reduction. The most common energy storage is an electrical battery, which powers one or more electric traction motors. Nowadays, the electric motors are often permanent magnet or induction motors, which are equipped with a liquid cooling system. Similar to series hybrid topology, full electric powertrain has a great flexibility in the powertrain structure. The need for reduction gears in the powertrain depends on the electric motor technology. By using in-wheel motors inside the wheels, no reduction gears are needed whereas by using induction motors, typically at least a two-speed gearbox is being used (Ehsani et al., 2010). The challenge in the full electric powertrain is the limited energy capacity of electrical batteries. Even if lithium-ion battery technology offers a good performance in terms of power and energy capacity, the operation needs to be well organized for being economically competitive against diesel and hybrid buses because of the battery recharging requirements.

Fuel cell hybrid buses have also a full electric powertrain, and the main energy and power source is a fuel cell stack. Because of the dynamical characteristic of fuel cells, electrical energy storage is being used as an energy buffer for rapid power discharge and braking energy regeneration (Bubna et al., 2010). Figures 2.4 and 2.5 present the powertrain layouts for a power-split and fuel cell hybrid topologies.

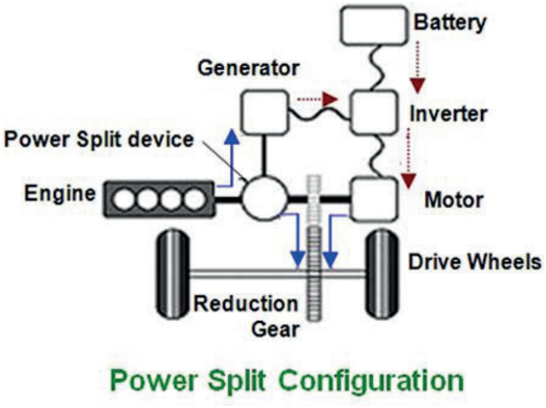


Figure 2.4. Power-split hybrid powertrain topology.

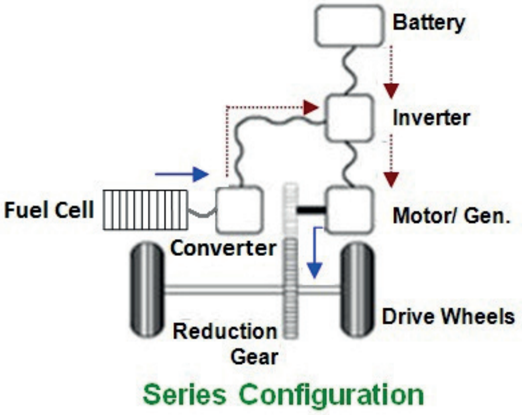


Figure 2.5. Fuel cell hybrid powertrain topology.

Because of the limited energy capacity of the electrical energy storages, trolleybuses are still the most commonly used electric bus application in the world (Kühne, 2010; Brunton, 2000). The trolleybuses get their operating energy from the overhead transmission system via a current collector. These types of buses have a full electric powertrain, and are usually equipped only with a small energy storage for driving short distances (Kühne, 2010; Sinclair, 1940).

2.1.2 Operation cycles and conditions

City buses are being operated as a fleet to provide a service for the people. The buses are operated in predefined bus routes, and there are several bus stops along the route. Depending on the route location and the time of the day, different time schedules are being generated. Because the ultimate target is to provide a service, the operation boundary values come from the needs of the service. A city bus operation is usually characterized by an operating cycle or a driving profile, which includes several consecutive stops to the bus stops, and often also in the traffic lights. Due to the driving pattern characteristics, the average speed remains relatively low and not a lot of constant speed driving is usually done. This type of driving profile is not very well suited for diesel engines in order to have high energy efficiency and low emissions. There are some commonly used test cycles for city buses such as Braunschweig and New York Bus, which are presented in Figure 2.6. Braunschweig cycle is a transient driving schedule simulating an urban bus driving with frequent stops. The New York Bus cycle is a representative of actual driving patterns of transit buses in New York City (Dieselnet, 2014).

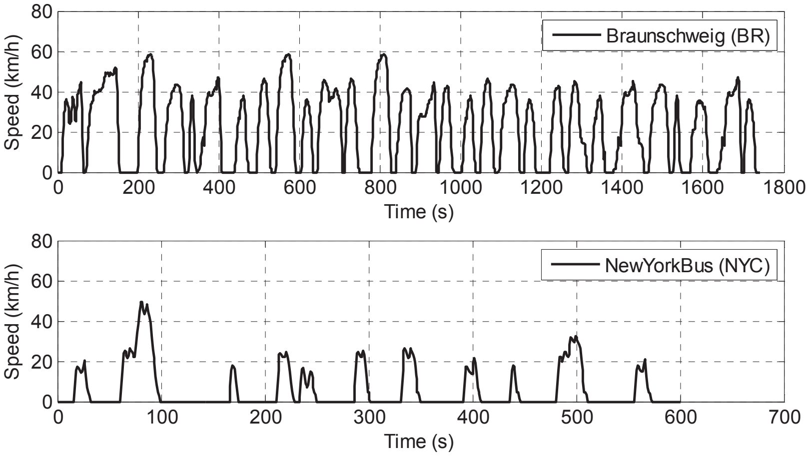


Figure 2.6. Speed profile of the bus test cycles Braunschweig and New York Bus (Dieselnet, 2014).

There are no official test cycle procedures for city buses because the fuel consumption is not defined for heavy vehicles by any official procedures as it is the case for passenger vehicles. Therefore, sometimes it is not easy to compare different research and measurements results, because the results are often strongly dependent on the operation cycle. Especially the lack of elevation profiles in the typical test cycles impacts on the results. The different types of driving cycles are needed for taking into account the different driving environments in terms of the driving speed and the stop frequency. The different types of driving cycles also serve for the development of the energy management and control strategies of the hybrid and electric buses. The fuel consumption for a typical diesel powered city bus can be between 30 and 100 liters/100km (Nylund and Koponen, 2012). The low-end representing a steady arterial road driving, and the high-end a very slow speed inner city operation e.g. New York Bus cycle (Dieselnet, 2014).

Table 2.1 presents the characteristics of the driving cycles that were used in the different simulations for city buses in this thesis. These cycles represent the different types of driving that city buses are used for. The Helsinki3 (H3) cycle corresponds to extra urban driving being comparable a city bus operation in an arterial road around a city center. The Jokeri cycle is a measured driving cycle which corresponds to a bus line 550 in Helsinki region in Finland. It is especially interesting because it has sub-urban driving patterns mixed with typical urban driving, and it includes the elevation changes. The Lahti 03 (a bus line in the city of Lahti in Finland) is similar to 550 but it has more inner city driving so the average driving speed is lower and there is more idling at stops. The road elevation is also taken into account in the L03 cycle. This intensifies the total power demand because there are quite steep uphill periods along the cycle. The other driving cycles presented in Table 2.1 (Braunschweig, Manhattan, New York Bus and Orange County) are commonly used for the city bus energy efficiency and emission evaluations (Dieselnet, 2014; Nylund and Koponen, 2012).

Table 2.1. Characteristics of bus driving cycles.

	Braunschweig	**Helsinki3**	**Jokeri**	**Lahti 03**	**Manhattan**	**New York Bus**	**Orange County**
Abbreviation	BR	H3	550	L03	MAN	NYC	OCC
Max speed (km/h)	58.2	71.7	83.3	64.0	40.7	49.6	65.4
Average total speed (km/h)	22.5	41.2	31.5	26.5	11.0	5.9	19.8
Average speed (km/h)	30.1	48.4	35.9	35.1	17.2	18.1	25.2
Distance (km)	10.9	10.3	28.6	22.9	3.3	1.0	10.5
Average stop time (s)	16.0	17.1	10.9	28.6	20.1	36.9	13.2
Stop time percentage	26 %	15 %	13 %	25 %	35 %	62 %	21 %
Stops per km	2.6	0.8	1.4	1.2	5.7	10.1	2.9
Duration (s)	1740	903	3276	3115	1090	601	1910

In 2001, The International Association of Public Transport (UITP) introduced as a result from a project the Standardised On-Road Test Cycles

(SORT) for the evaluation of the urban bus fuel economy (UITP, 2001). The purpose of the SORT cycles is to be able to easily compare fuel consumption of different buses from different manufacturers based on real driving tests. Unfortunately, these cycles have not yet been widely used in the academic research or in the industry.

2.2 Underground mining loader

Non-road mobile machinery (NRMM) or more commonly called as mobile work machines define a miscellaneous group of different machines. The common features among these machines are that the most of them are powered by a traditional diesel engine, and they are used intensively in task-oriented operating cycles. Probably the largest group is the construction machines such as excavators, wheel loaders and dumpers. Figure 2.7 presents some typical mobile work machines. The following list describes the machines (the source of the figures is in the parenthesis):

- Bobcat S300 small loader (http://www.bobcat.com),
- Sandvik LH514 underground mining loader (http://mediabase.sandvik.com),
- John Deere 75D excavator (http://www.deere.com), and
- Ponsse Harvester Bear 8W (http://www.ponsse.com).

Figure 2.7. Typical mobile work machines.

Same way as city buses and heavy vehicle combinations, also NRMM are mostly used by professionals in commercial, private or public operations. This means that the productivity or operating efficiency and the return of investment (ROI) is important when choosing the machine. It is typical for heavy NRMM that their operation needs a high peak power capacity, and that the same duty cycle is repeated continuously. These kinds of requirements are extremely well suited for the powertrain electrification because by hybridization the peak power demand can be easily met without oversizing the engine. The energy management of the hybrid system can be optimized as there are not a lot of changes in operation and it is well known beforehand. In addition, an electric powertrain can improve the controllability over the typically used hydrostatic or hydrodynamic drive systems. An underground mining loader is comparable to a wheel loader as these both usually have an articulated steering, a four-wheel drive and a bucket to transport material. Because of the specific characteristics of mine environment, the underground mining loader has as low height as possible, which in turns increases the length of the machine as it can be seen in Figure 2.7.

Very few research studies have been published in the area of mobile work machines and their energy efficiency. Recently, due to the growing interest of the powertrain hybridization, more research focus has been given also for machinery (Kunze, 2010). Most of the published research work about heavy hybrid work machines has been focused on the hybrid powertrain development (Jo and Kwak, 2011; Lin et al., 2010), control strategy development (Kim et al., 2010; Xiao et al., 2008), or powertrain simulation (Grammatico et al., 2010; Hui and Junqing, 2010). In (Wang et al., 2009), a comprehensive performance analysis was performed for a hydraulic excavator with different hybrid topologies.

2.2.1 Powertrain technologies

The powertrain of a loader is traditionally mechanical and powered by a diesel engine. Smaller wheel loaders and underground mining loaders have sometimes hydrostatic powertrain, in which the mechanical power is transformed into hydraulic power by a pump, which in turn powers the hydraulic motors closer to the wheels. Figure 2.8 presents a layout of an underground mining loader with a hydrostatic powertrain (Lajunen et al., 2010). The components are: ICE = engine, AUX = auxiliary devices, HP = hydraulic pump, HM = hydraulic motor, RG = reduction gear, FD = final drive.

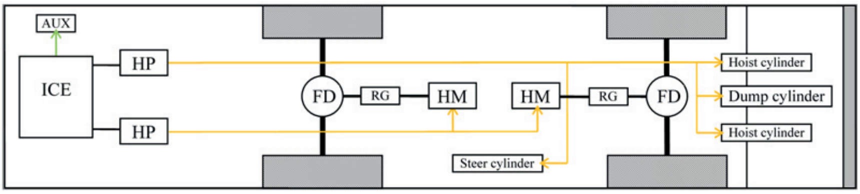


Figure 2.8. Component-level layout of a diesel powered underground mining loader.

Because the operating speed of mining loaders is very low and a high torque capability is demanded, especially in the loading phase, multiple stages of reduction gears are needed between the motor and the wheels. Besides traditional gearbox and differential gears, reduction gears are also used in the wheel hub.

Due to the operational characteristics of a loader, an electric powertrain offers a lot of advantages in comparison to a mechanical and a hydraulic powertrain. In large-size heavy machinery it is actually more practical to have an engine-generator (gen-set) as a power source delivering power to electric traction motors (Mol et al., 2009). Diesel-electric powertrains have been used for a long time e.g. in mining dumpers. As the hybridization type, the series hybrid topology is well suitable for a heavy mobile work machine due to its flexibility. Especially with underground mining loader, where there is not a lot of available space, the series hybrid offers a practical solution. In most of the powertrain electrification cases among the heavy machinery, there have been either series hybrid or full electric solutions. In small machines, full electric powertrains have been used for a long time. For instance, small inside operated forklifts have been often powered by a lead-acid batteries because the heavy weight of the batteries has not been a problem, and the operation is done in a limited area, which facilitates the charging (Gaines et al., 2008). For mining machines, such as mining loaders, the full electrification solution typically includes the electrical energy supply by a power cable. The length of the mining tunnels is still in the scope that the cables are somewhat practical and maneuverable.

An important part of the mobile work machine is its capability to transport and manipulate different materials. This capability requires specific systems such as the boom, arm and bucket in excavators and loaders. These systems are powered by hydraulics because typical hydraulic system has high power to weight and power to volume ratio, which is very important in an application where high power is needed in very limited space. On the other hand, hydraulic systems are not necessarily very energy efficient due to the some of their inherent properties e.g. continuous circulation of the hydraulic fluid while idling. With electrification, also the energy efficiency of hydraulic systems can be improved by controlling the hydraulic power production with electric actuators. Electrohydraulic systems can also improve the controllability of machines.

2.2.2 Operating cycles and conditions

Underground mining loaders are designed to transport materials, typically crushed rock material, from a loading place to a collecting area. The operation environment in underground mines includes narrow tunnels, high humidity and air impurities. These harsh operating conditions impose specific design requirements for the machines that operate in underground mines. Even though the NRMM are operated in various environments and used for different purposes, there are a lot of similarities between different machines in their operating cycles. The operation of a work machine is usually described by a duty-cycle which includes the power requirement for the power source, which is typically a diesel engine or engine-generator. Because these machines often operate in environments that have rough surfaces, specific requirements in terms of moving capability need to be taken into account. For instance, mine tunnels surfaces are usually rough and wet, which can make the driving of heavy machine quite challenging so that an accurate control of the machine is desirable.

Figure 2.9 illustrates the distinct phases of a typical duty cycle of an underground mining loader. The duty cycle includes the empty bucket cycle, which basically corresponds to a driving in a downhill to get to the loading place. The full bucket cycle corresponds to the driving uphill with a full load of material in the bucket. The maximum payload or tramming capacity for underground mining loaders is usually around 30-40% of the operating weight (weight without payload). There is a substantial amount of elevation in a relatively short distance in the duty cycle.

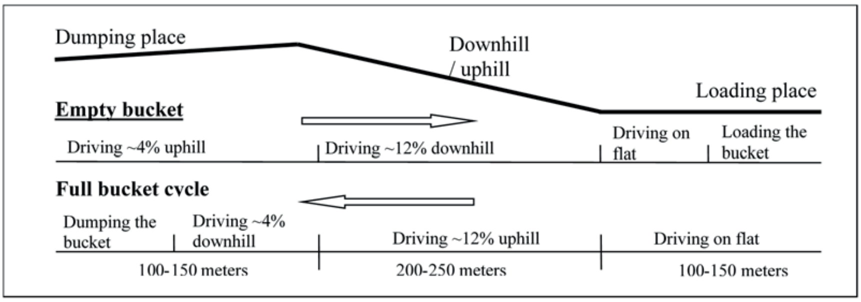


Figure 2.9. Typical duty cycle of an underground mining loader (Lajunen et al., 2010).

2.3 Heavy vehicle combinations

Because the demand for the road freight transportation is increasing and heavy vehicle combinations (HVC) are responsible of a large part of the total transportation energy consumption, there is a growing interest to improve the energy efficiency of these vehicles (Grenzeback et al., 2013; Davis et al., 2012). The total number of HVCs is relatively small in comparison to passenger vehicles but their fuel and energy consumption per vehicle is very high, which indicates that even small improvements in the energy efficiency of an individual vehicle can have a significant impact on the total energy consumption. In this case, the heavy vehicle combination refers to a combination of a tractor and one or more trailers, and these vehicles are operated over a long distance in freight transportation. There are numerous different combinations for trailers, the most common being the tractor and semi-trailer in world-wide. The full trailer is also widely used but often in very long distance operation. Figure 2.10 presents typical heavy vehicle combinations based on the European Modular System (Bark et al., 2012; Åkerman and Jonsson, 2007). In the United States, the regulations and traditions in on-road freight transportation are different than in Europe (Ogburn et al., 2008).

The maximum weight of a heavy vehicle combination is limited to 40t in many European countries (Hill et al., 2009a). In Finland and Sweden, the maximum weight has been for a long time 60t, and in October 2013, even higher combination weights were accepted in Finland up to 76t (LVM, 2013). In Sweden, a 90t combination has been tested for timber transportation (Skogforsk, 2014). The heavier and longer vehicle combinations are believed to increase the energy and operating efficiency of road transport sector (Bark et al., 2012; Vierth and Haraldsson, 2012; Leduc, 2009). Despite the fuel consumption increases along with higher weights, the load specific fuel consumption can be decreased because of the higher payload capacity. Figure 2.11 presents an example of a 76t HVC.

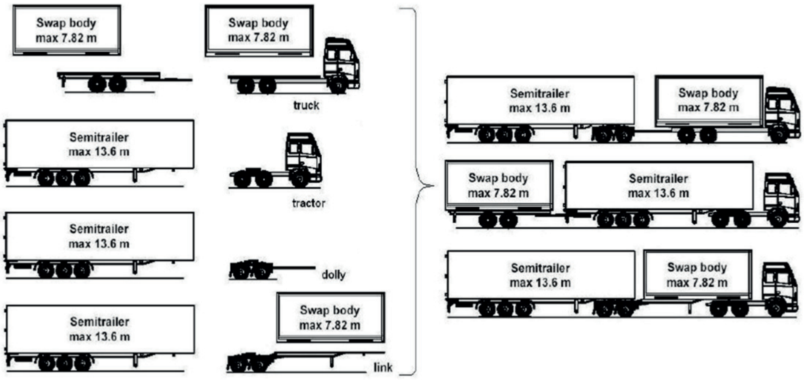


Figure 2.10. Commonly used load carrier combinations for HVCs (Bark et al., 2012).

Figure 2.11. A 76t heavy vehicle combination: tractor + swap body + link + semitrailer.

Over the years, several research studies and development projects have been carried out to assess the best technologies to improve the energy efficiency of HVCs (NAS, 2010; Hill et al., 2009a; Ogburn et al., 2008). Most of these studies have been concentrated on the non-electrification technologies. Even though the major part of the energy losses originate from the diesel engine, the electrification of powertrain has not often seen as a solution to improve the energy efficiency. This is because of the type of operation of vehicle combinations and expensive electrical systems. It has to be acknowledged that the potential to improve the energy efficiency of a HVC by a powertrain electrification is much less than for e.g. passenger vehicles and city buses (Zhao et al., 2013a; NAS, 2010; Cooper et al., 2009; Delorme et al., 2009). This is mostly due to their operation, which is often constant speed driving without any distinctive acceleration and braking phases in the speed profile. But when the road elevation is taken into account, there is actually considerably amount of braking energy that can be regenerated and stored in an on-board storage. The stored energy can be used not only as driving power but also to deliver the power for the auxiliary devices even during the driving pauses.

2.3.1 Powertrain technologies

The powertrain of a traditional heavy-duty truck or tractor has a diesel engine, a clutch or a torque converter, an automatic or a manual gearbox, and a final drive (differential gear) at the rear wheels. The tractor of a HVC have usually two tractive rear axles for heavy load transportation. In long distance operation, the tractor usually has a large size diesel engine (cylinder displacement varies from 10 to 16 liters) attached via a clutch to a manual gearbox. Nowadays, the gearboxes have at least 10 gears but a typical number of gears is 12 in European trucks. In difference to city buses, the average efficiency of the engine in typical operation is higher due to the constant speed operation (Zhao et al., 2013a; Delorme et al., 2009).

As the powertrain electrification of heavy vehicle combinations has not necessarily been considered an effective way to reduce the fuel consumption, only few applications has been developed directly for heavy trucks e.g. (Arts, 2012; Walkowicz et al., 2012). In research, hybridization has been studied in parallel with non-electrification technologies. Because of the constant speed type of operation, a parallel hybrid has been often seen as the best suitable powertrain topology for heavy-duty trucks and tractors (Zhao et al., 2013a; Delorme et al., 2009). In long distance driving, it is not necessary to have the possibility to drive purely on electric power, which can simplify the hybrid powertrain construction and control. The amount of braking energy, which can be regenerated to an on-board electrical energy storage, is heavily dependent on the power capacity of the electric motor and the energy storage. This is because the braking power is easily high even with light braking due to the high total weight of the vehicle combination. For increasing the potential to regenerate braking energy, it is possible to equip also the trailer axles with electric motors or other types of energy regeneration systems (Midgley and Cebon, 2012). This solution requires that the tractor and trailer are being used together, which in fact is quite typical with HVCs operated by small business operators. As the hybridization of the powertrain is done by using a high voltage battery system, it enables the use of high voltage auxiliary devices, which in turn can increase the operation efficiency of those devices (Frey and Kuo, 2007). Even if HVCs have powerful auxiliary devices, unlike in city buses, these devices' usage is much less frequent. The disadvantage of the auxiliary devices that are directly attached to the engine is that there is a significant amount of idling losses, which cannot be avoided. Fully electric auxiliary devices could be used only when needed, and the use of smart control algorithms could further improve the energy efficiency.

2.3.2 Operating routes

Heavy vehicle combinations are designed for a long distance operation mainly to transport and deliver different kinds of goods and materials. In our organized society, the freight transportation is a part of a larger logistical network. This means that the operation routes of HVCs are more or less well established. There are some material transport, such as timber, that is collected from varying locations. But also in timber transportation, there have been certain logistics put in place to be able to efficiently organize the transport of timber from the forest to its final destination, which is usually a factory site. Often, the transportation of goods and materials includes some sort of centralized delivery locations such as distribution centers e.g. for food or parcel transportation. Overall, the operation of HVCs is mostly concentrated on multilane highways but also on one lane national roads in smaller countries.

2.4 Energy storage technology

A key component in the powertrain electrification is an on-board electrical energy storage, which is either a battery or ultracapacitors (also called supercapacitors) or a combination of them (Burke and Miller, 2011; Khaligh and Li, 2010). The energy storage functions as an energy buffer in hybrid vehicles, and as a single energy source in full electric vehicles. In the past, the hybrid and electric vehicles had often a lead-acid type battery as energy storage. These types of batteries have been and are still popular in automotive applications but their performance as an energy buffer for a hybrid powertrain or as an energy storage for full electric powertrain is not good enough in terms of specific energy (kWh/kg). Other types of batteries for vehicular application are nickel (NiCd, NiMH, NiZn) and lithium based batteries, and molten salt batteries, which are high-temperature electric batteries that use molten salts as an electrolyte (Lodi et al., 2010; Lukic et al., 2008; Karden et al., 2007). The last decade has shown that the lithium based batteries have superior performance than any other commercially mature, secondary battery technology developed for vehicular applications (Burke and Miller, 2011; Scrosati and Garche, 2010). Lithium based batteries have been widely used in consumer electronics since early 90's but the more demanding technical requirements in automotive field have taken a lot of time for the development of suitable lithium based batteries for vehicles. Figure 2.12 present a comparison of technical characteristics for different battery technologies (Ibrahim et al., 2008).

Several different chemistries have been developed for lithium based batteries, and their technical performance is nowadays adequate for the vehicular applications. The biggest challenge of the lithium based batteries in the use of heavy on-road vehicles is the cost and durability (Roscher et al., 2011; Wood et al., 2011). The major part of the costs is material and manufacturing costs, which are estimated to be substantially decreased by a high volume production (Pillot, 2014; Anderman, 2010). In recent years, the lithium-ion battery production volumes have been rising and the costs are predicted to decrease already in the near future (Pillot, 2014; Santini et al., 2010). If the relatively short life is acceptable for batteries in consumer electronic applications, it is quite the opposite in vehicular applications. Passenger vehicles are often being used more than 10 years and the service life of commercial vehicles can be up to 20 years. In many vehicle markets the second hand, used vehicles and machinery are important part of the vehicle sales. This has been problematic for hybrid and electric vehicles, and machinery because it is difficult to estimate the future retail value of a vehicle with expensive energy storage. Because heavy vehicles are usually operated by professionals, the costs of a vehicle need to be competitive, and technology has to be reliable.

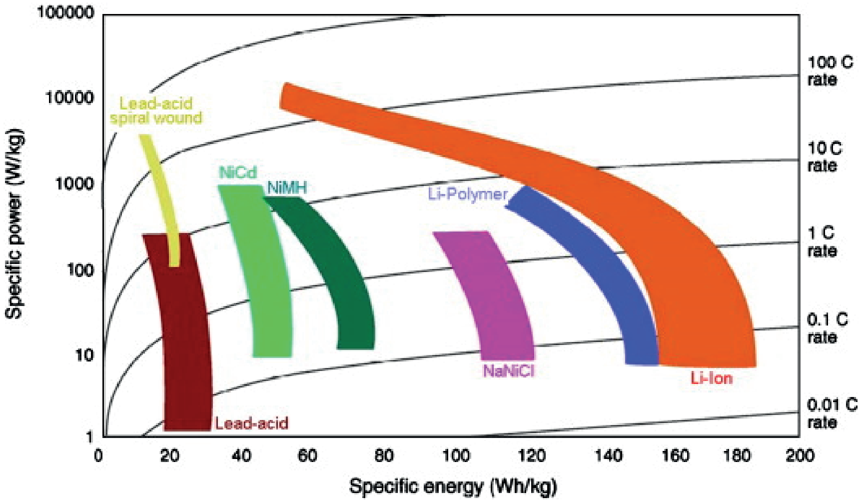
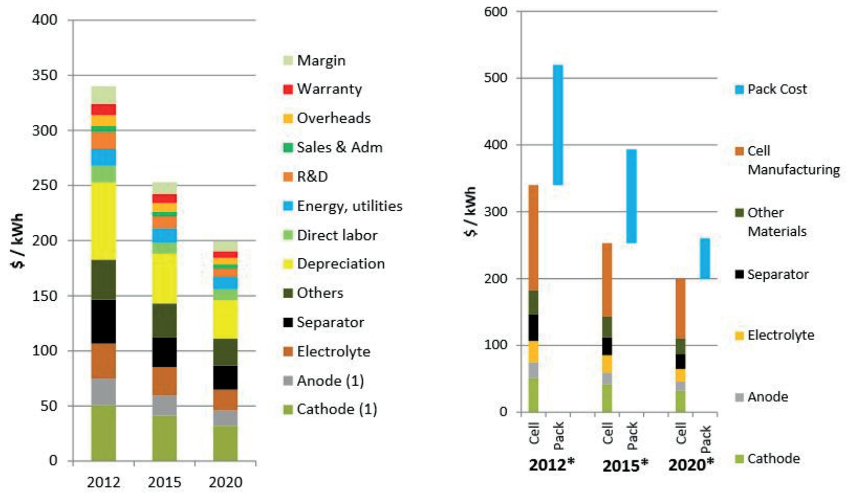


Figure 2.12. Performance comparison of battery technologies (Ibrahim et al., 2008).

The lithium based batteries are being used increasingly in vehicular application, and more and more effort and resources is being put on their development. No immediate replacement or serious competitor is foreseen for lithium based batteries in automotive field in the next decade. However, the future battery technologies are under a rapid development, and it is believed that cheaper and higher performance batteries will be available in the future (Pillot, 2014; Anderman, 2010). Figure 2.13 presents the recent cost estimations for a 36 Ah lithium-ion pouch cell, and for a battery pack of an electric vehicle. In the left side of the figure, the cell costs are divided into different areas. The battery pack costs in the right side of the figure are divided into material and manufacturing costs. In this scenario, in five years, from 2015 to 2020, the cell costs are estimated to decrease about 20%, and the pack cost almost 35% (Pillot, 2014).

Ultracapacitors (UC) are electrochemical capacitors, which offer high power density but relatively low energy density (Burke and Miller, 2011; Khaligh and Li, 2010). Ultarcapacitors have low internal resistance, which gives high efficiency. As batteries are usually sufficient energy storage for vehicles, the use of ultracapacitors has not been considered such an interesting solution because of the lack of energy capacity. Recently, ultracapacitors have been studied more and more in vehicular applications, for instance (Rotenberg et al., 2011; Burke, 2010; Bauman and Kazerani, 2008). Because in vehicle accelerations a high peak of power is often needed, and the braking energy is usually recovered by high peaks of power, the power limitations of batteries can easily be exceeded. For these reasons, by combining two different types of energy storages, which have complementary characteristics, such as a battery and ultracapacitor module, creates a superior energy storage system having high power and energy capacity. It is called as dual-source energy storage and not only the performance is better than with a single storage but also the durability can be improved (Bubna et al., 2012; An et al. 2008; Lukic et al., 2008).



(1) Active materials only

* For Production > 100 000 packs/year

Figure 2.13. Estimated li-ion cell and battery pack costs for electric vehicles (Pillot, 2014).

3. City bus (Publications I-IV)

3.1 Energy consumption and powertrain topology

In the context of hybrid city buses, most of the research has been probably done for comparing the different powertrain topologies e.g. (Muncrief et al., 2012; Hellgren, 2007; Williamson et al., 2006). Depending on the operating cycle, the hybrid city buses have been evaluated to have from 10% to 40% lower fuel consumption than the conventional diesel powered buses. Recently, some measurement studies have clearly confirmed the potential of hybrid buses in terms of energy efficiency (Hallmark et al., 2012; Nylund and Koponen, 2012; Williamson, 2012). The major deficiency in the literature is the weak connection between the operating conditions and the powertrain topologies. The correlation between the average operating speed and fuel consumption of diesel, and also hybrid electric buses, has been recognized (Clark et al., 2009). Nevertheless, it has been hard to draw definitive conclusions about the energy efficiency of different powertrain topologies of city buses in relation to their operating conditions in terms of driving cycle and schedule. A dedicated process for evaluating the energy consumption in a fleet operation of city buses was developed in Publication I. The evaluation included six different powertrain topologies, which were simulated as a bus fleet in six different operating routes. The routes represent different types of driving in urban and city center environments having also different driving schedules. The following topologies were considered in the evaluation:

- **CONV:** A lightweight diesel city bus.
- **PAR_1:** A parallel hybrid bus with ultracapacitors as energy storage.
- **PAR_2:** A parallel hybrid bus with a high-power lithium-ion battery as energy storage.
- **SER_1:** A series hybrid bus with a high-power lithium-ion battery as energy storage.
- **SER_2:** A plug-in hybrid bus with a series hybrid powertrain and a high-energy lithium-ion battery as energy storage.
- **EV:** A full electric city bus with a high-energy lithium-ion battery as energy storage.

Tables 3.1–3.3 describe the technical specifications of the different bus simulations models. The total weight of a bus in simulations consisted of curb weight of 10,000 kg, about 20 passengers (1500 kg) and the weight of the energy storage system. All simulations were conducted in 20 °C of ambient temperature. The energy storage system temperature was kept in between 20 and 25 °C with the aid of active cooling.

Table 3.1. General characteristics of the simulation models.

Parameter	Value
Curb weight (kg)	10000
Vehicle frontal area (m^2)	6.2
Drag coefficient	0.6
Rolling resistance	0.01
Wheelbase (m)	6.5
Front weight fraction	0.34
Centre of gravity, height (m)	1.0

Table 3.2. Conventional and parallel hybrid bus powertrain configurations.

	CONV	PAR_1	PAR_2
Engine power (kW)	202	162	140
Electric motor power (kW)	---	75	100
Battery configuration	---	---	Saft 6Ah cell, 2 packs in parallel, 144 cells in series in a pack
Battery system voltage (V)	---	---	518
Ultracapacitors	---	Maxwell BCAP3000, 280 capacitors in series	---
Energy storage weight (kg)	---	300	225
Transmission	6-speed Allison T280R gear ratios [3.49; 1.86; 1.41; 1.00; 0.75; 0.65]		

Table 3.3. Series hybrid and electric bus powertrain configurations.

	SER_1	SER_2	EV
Gen-set power (kW)	110	63	---
Electric motor power (kW)	150	150	150
Battery configuration	Saft 6Ah cell, 3 packs in parallel, 144 cells in series in a pack	Kokam 40Ah, 2 packs in parallel, 168 cells in series in a pack	Kokam 40Ah, 6 packs in parallel, 168 cells in series in a pack
Battery system voltage (V)	518	622	622
Battery nominal power (kW)	131	373	373
Battery capacity (kWh)	9.3	49.7	149
Energy storage weight (kg)	338	505	1514
Battery cycle life (cycles)	10000	3000	3000

Charge sustaining (CS) energy management strategies were developed for the parallel and series hybrid bus simulation models. The focus was on the development of robust and adaptive rule-based strategies which could be used in different bus driving cycles and in different operation conditions. The details of the energy management strategies are described in Lajunen (2012).

Figure 3.1 summarizes the energy consumption results for the different bus topologies. The presented bars corresponds the energy consumption variation caused by the different operating cycles. In comparison to diesel bus, the average decrease in the energy consumption is around 20% for the parallel hybrid bus with ultracapcitors, and more than 30% for the parallel and series hybrid buses with a high-power lithium-ion battery. The plug-in hybrid and full electric buses have the potential to increase the energy efficiency more than 70%. An important outcome of these results lies in the fact that how much the operating cycle has impact on the energy consumption. It can be seen that it has a major impact on the conventional diesel bus and a very little impact on the full electric bus. The hybrid buses are impacted depending on their degree of electrification. The parallel hybrid buses usually have lower degree of electrification than the series hybrid buses. In this case, the higher degree of electrification provides better energy efficiency. Figure 3.1 also shows the results in two driving cycles; Braunschweig (BR) and New York Bus (NYC). The very low average speed (~6 km/h) and a high portion of idling (~60% of time at stop) in NYC increases the energy consumption of the diesel engine operation dominant bus topologies (CONV and PAR_1). In the Braunschweig cycle, the differences in the energy consumption for the diesel, and parallel and series hybrid buses are much less dramatic. This can be explained by the high demanding driving cycle where the diesel engine operates in relatively high efficiency region. The plug-in hybrid (SER_2) bus has much higher energy efficiency than the other hybrid buses. In this case, the plug-in hybrid was operated 75% of time in pure electric mode and the rest of the operation as a series hybrid bus.

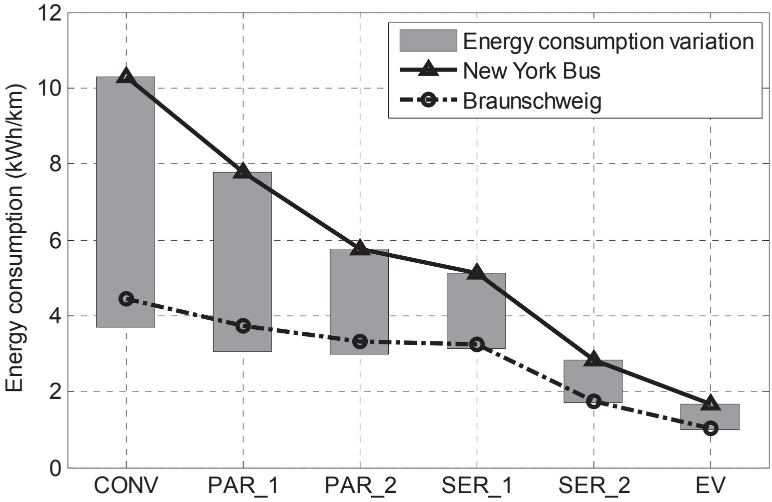


Figure 3.1. Energy consumption of different city bus technologies.

Figure 3.2 presents the potential for the reduction of regulated emissions. The presented bars corresponds the emission variation caused by the different operating cycles. As the engine operation in the hybrid buses was not optimized in terms of the regulated emissions, it is even possible to have more emissions in some cycles with the parallel hybrid bus (PAR_1).

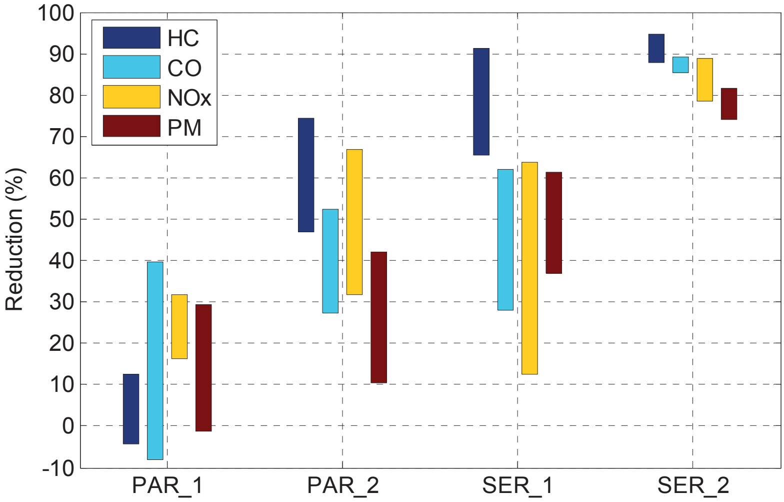


Figure 3.2. The potential to reduce the regulated emissions with hybrid city buses.

The results show that with the hybrid technology the potential is higher to reduce the regulated emissions than the energy consumption. The small size diesel engine and high portion of electric operation of the plug-in hybrid bus provide a significant potential to reduce the emissions, and it is less limited by the charging than the full electric bus as it has the possibility to operate also as a hybrid bus.

For inherent reasons, the full electric powertrain topology has the best energy efficiency among the different topologies. Not having a traditional mechanical powertrain allows several different powertrain topologies for an electric city bus. Six different electric powertrain alternatives were evaluated in terms of energy and powertrain efficiency by simulation in Publication II. The following design alternatives in terms of an energy storage system, a traction motor, and a transmission were considered:

A) Battery and a single traction motor
B) Battery, a single traction motor and a multi-gear transmission
    B1) Permanent magnet motor
    B2) Induction motor
C) Battery and two traction motors with a single-gear transmission
    C1) Permanent magnet motors
    C2) Induction motors
D) Battery with ultracapacitors and a single traction motor

Figure 3.3 shows the efficiency maps and torque curves for the baseline permanent magnet and induction motors. The specifications of the powertrains of each design alternative are presented in Table 3.4.

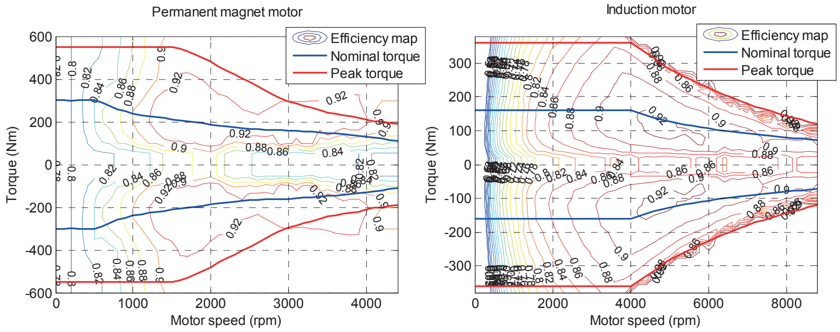


Figure 3.3. Efficiency comparison of different electric motors.

Table 3.4. Drivetrain specifications.

Parameters	Design alternatives				
	A / D	B1	B2	C1	C2
Motor rated power (kW)	138	109	88	69	64
Motor peak torque (Nm)	1380	1091	471	690	344
Transmission gear ratios	--	[1.75 1.0]	[3.5 2.0]	[1.0]*	[2.0]*
Final drive gear ratio	7.5	7.5	7.5	7.5	7.5

The powertrain alternatives were simulated in four different driving cycles. The differences in the energy consumption between the powertrain design alternatives are shown in Figure 3.4. The alternative A is chosen here as the reference case. The presented differences in the energy consumption are then in comparison to the alternative A.

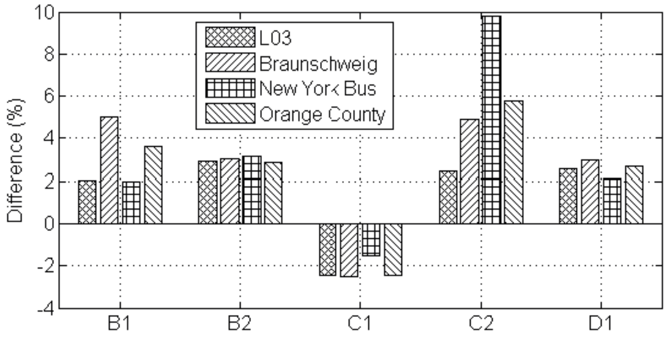


Figure 3.4. Difference in the energy consumption of different electric powertrains.

Overall, the differences are relatively significant considering that the different powertrain designs are quite similar. The largest difference (more than 10%) is between the configurations C1 and C2 in the New York Bus cycle. In general, the performance of the configuration C2 is the weakest, and it does not seem to adapt to the New York Bus cycle type of driving. Alternatively, C1 outperforms all the other powertrain options in all driving cycles. The results between the two types of electric motors illustrate the differences in their technical characteristics. The results of configurations B1 and B2 are quite similar whereas the results of configurations C1 and C2 are very different. Due to the larger speed range of the induction motors, the operating efficiency without a multi-gear transmission is much worse than with the permanent magnet motors. Except the alternative C2, which would be generally a poor choice for a full electric bus, the impact of the driving cycle is almost negligible.

3.2 City bus operation

As the operation of city buses can be different depending on the operating route and schedule, it is important to take these factors into account when comparing different powertrain technologies. The plug-in hybrid and electric city buses, also called as rechargeable electric buses, impose additional challenges for their efficient and economic operation due to the need of recharging the energy storage. To be able to fairly compare different types of city buses in a fleet operation, and especially the rechargeable buses, a specific method for determining the number of buses was developed in Publication I. The method calculates the number of required rechargeable buses based on the energy consumption, charging power and operating schedule. Equation 3.1 presents the final form of the calculation which is used to determine the amount of rechargeable buses. The full development of Equation 3.1 is presented in Publication I.

$$N_E = N_C + \frac{t_{chg}}{t_a} = N_C\left(1 + \frac{E_{route}}{P_{chg}t_{rtot}}\right), \tag{3.1}$$

where N_C is the required number of conventional buses (integer), t_{chg} is the charging time, t_a is the maximum available time for charging, E_{route} is the energy consumed for a single route, P_{chg} is the charging power, and t_{rtot} is the duration of the route including a minimum waiting time between the operations in the starting station. In this case, it is assumed that the charging of the buses is done during the operation at the end of the route. This way, the size of the battery and charging power are reasonable, and no special requirements are generated for the charging infrastructure. Other solutions for the charging are overnight and opportunity charging, which were not considered in this research. The charging of the buses during the night would need a very large battery pack and a substantial amount of total charging power at the depot. Opportunity charging refers to charging along the route typically at the bus stops, and it requires high power charging stations with a temporary energy buffer to avoid overloading the electrical grid (TOSA, 2013).

The fleet operation was taken into account in Publication I by creating specific operating routes based on the commonly used bus driving cycles. Table 3.5 presents the descriptions for the generated operating routes. These routes were used in the simulations to define the energy efficiency, and the impacts of the different operation were this way taken into account also for the life cycle cost calculation.

Table 3.5. Descriptions of the generated bus routes.

	550	BR	H3	MAN	NYC	OCC
Number of cycles	1	2	4	3	6	2
Duration (min)	54.6	58.0	60.2	54.5	60.1	63.7
Total distance (km)	28.6	21.7	41.3	10.0	5.9	21.0
Operation interval (min)	10	10	20	5	5	15

In addition to increase the energy efficiency of city buses by alternative powertrain technologies, further energy savings can be foreseen by optimizing the operation speed in relation to the powertrain efficiency. As mentioned before, the commonly used driving cycles e.g. Braunschweig, Orange County, and Manhattan are often used to evaluate the energy consumption of city buses. Because the speed in these cycles is fixed with time, the energy-optimal velocity in relation to the powertrain efficiency is not achieved. The energy-optimal velocity profiles were defined for electric and diesel city buses in Publication III. The method for defining the energy-optimal velocity is based on the use of a dynamic programming algorithm (Sundström and Guzella, 2009). The driving profile is defined as speed versus distance because in the optimization of the velocity profile the distance is a fixed parameter and there is a target time to be reached. The typical city bus driving pattern usually consists of an acceleration, constant speed driving and deceleration phase. One pattern or a sub-cycle can be characterized by a distance (e.g. between the bus stops), a duration based on the operation time schedule, and a speed limit. The bus operation schedule in a route is known beforehand, which allows to define the characteristics for the driving patterns between the stops in the route. A well-known city bus test driving cycle, Braunschweig, was used here as the reference cycle for the simulations. Equation 3.2 present the cost function to minimize the total energy consumption thus to optimize the driving speed for the electric bus.

$$J = \sum_{k=0}^{N-1} P_{batt}(\, w_k, k) \cdot T_d(\, w_k, k), \tag{3.2}$$

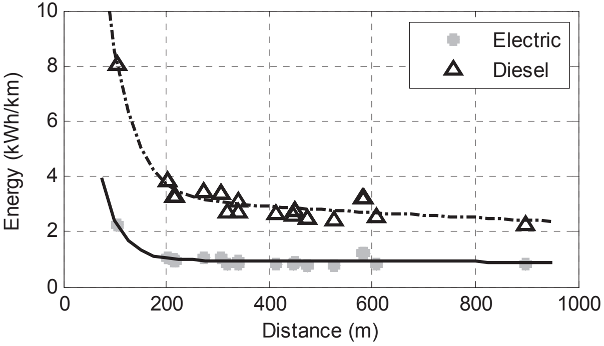
where P_{batt} is the battery power including the output power and power losses in the battery, T_d is the time elapsed at one distance step, and w_k is the control variable which is used for the determination of the speed (v_k) as in

$$v_k = w_k(v_{max} - v_{min}) + v_{min}, \tag{3.3}$$

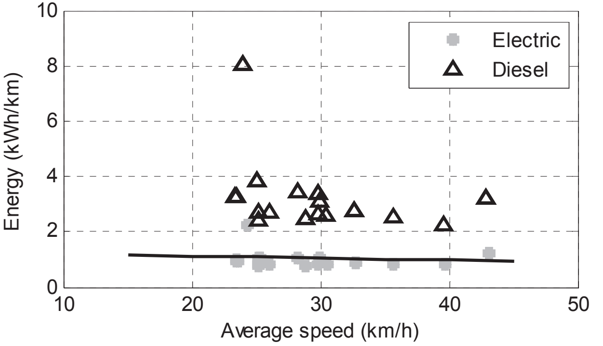
where v_{max} is the maximum speed and v_{min} is the minimum speed. The results of the energy-optimal velocity simulations in terms of the specific energy consumption are presented in Figure 3.5. The results show the specific energy consumption in each Braunschweig sub-cycle for the electric and diesel bus.

The results are divided into three different result figures to show the impact of sub-cycle distance, averages speed and duration on the energy consumption.

a) Sub-cycle distance



b) Average speed of sub-cycles



c) Sub-cycle duration

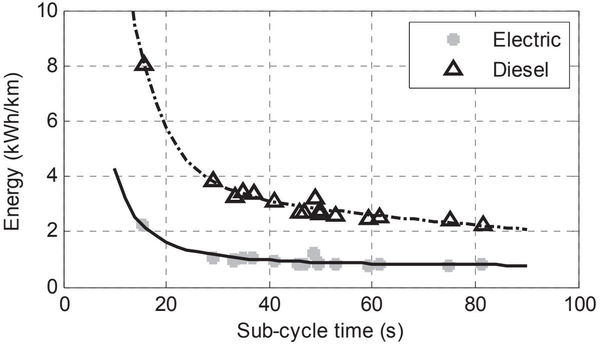


Figure 3.5. Energy consumption with the energy-optimal velocity profiles.

It can be concluded that the impact of the different sub-cycle characteristics on the energy consumption of the electric bus is almost negligible. Only when approaching very short cycle distances and durations (Figures 3.5a and3.5c), the energy consumption tends to increase rapidly. This is because a sub-cycle has then only fast acceleration and deceleration phases, which results in lower efficiency operation of the engine, and in the fast deceleration the efficiency of the braking energy regeneration is lower due to the high peaks of power. With the diesel bus, there is a stronger impact of the distance and the duration of the sub-cycle on the energy consumption. In short sub-cycles, the energy consumption is almost two times higher (200 meters vs. 800 meters) than the longer sub-cycles.

The corresponding energy efficiency increase with the optimal-velocity profiles for the electric and diesel bus was calculated in comparison to the results with the original Braunschweig cycle. Figure 3.6 presents the energy efficiency increase in the cases of the distance, average speed and duration of the sub-cycle.

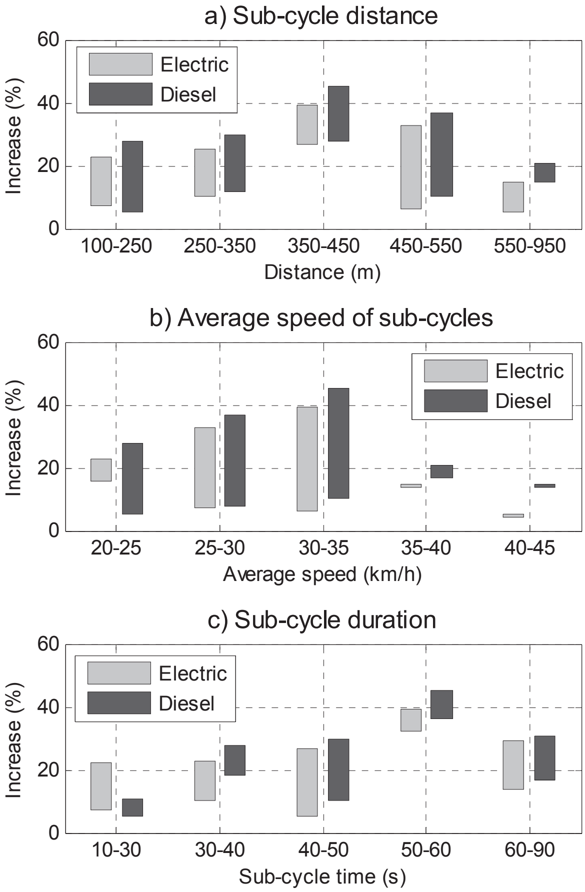


Figure 3.6. Energy efficiency increase in the Braunschweig cycle.

The increase is shown as a bar because there is quite a lot of variation in the energy consumption due to the different forms of the original driving patterns, which correspond to the sub-cycles in the Braunschweig cycle. The Braunschweig cycle is measured from city bus operation so that the speed profiles of sub-cycles can be quite different even if the duration and distance are same. According to these results, it seems that there is a lot of potential to increase the energy efficiency of the electric buses, and also diesel buses. The results indicate that the potential is weakly dependent on the sub-cycle distance, duration and average speed. By taking into account all the sub-cycles, the energy efficiency increase is about 17% for the electric bus and 19% for the diesel bus.

3.3 Energy storage

The energy storage has the central role in the powertrain electrification of city buses. Batteries has been often the choice for the energy storage but sometimes ultracapacitors are being used in hybrid buses. The operation of the energy storage system in the different bus applications was evaluated in Publication I, and the benefits of a dual-source energy storage were analyzed in Publication II. The energy management strategy impact on the battery useful life and energy consumption in plug-in hybrid bus was evaluated in Publication IV. The impact of the electrical energy storage can be illustrated with a specific metric called the energy throughput per driven distance (kWh/km), which can be used for the estimation of battery useful life. Based on the simulation results in Publication I, the energy throughput of the ESS were calculated for each operating route. Figure 3.7 shows the total energy consumption as function of the energy throughput of the ESS for each bus configuration and operating route (the markers correspond to the routes). These results clearly show that with a higher degree of electrification, the energy throughput is higher and the energy consumption is lower. In this case, the degree of electrification refers to the ratio of electric power vs. diesel power. With the low level of electrification (PAR_1 and PAR_2), the energy throughput remains 2 to 3 times less than with full electrification (EV), and the energy consumption variation is quite high between the operating routes. The high energy throughput of the battery in the configuration SER1 is not necessarily good for the battery life. The amount of the energy used through the battery can be affected by the design of the energy management strategy.

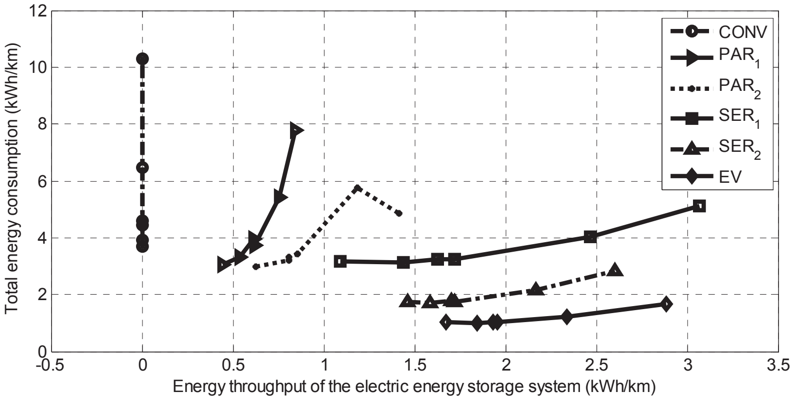


Figure 3.7. Total energy consumption vs. the energy throughput of the ESS.

Because the lithium-ion batteries and ultracapacitors have different performance characteristics, they can be used together as a dual-source energy storage system also called a hybrid ESS. The technical benefits of a hybrid ESS in an electric bus were evaluated in Publication II. Based on the simulation results, the impacts on the battery operation were analyzed in different driving cycles. The analyzed results are shown in Figure 3.8. By using the ultracapacitor unit for peak power shaving and peak power regeneration in braking, it can decrease drastically the charging current and the required cooling power of the battery. In this case, the average reduction of the charging current is around 65%, and the reduction of the cooling power is around 60% except in the driving cycle L03 where it is 45%. Also the discharge current and the energy throughput of the battery are significantly decreased, 25% on average. With these reductions, it is reasonable to believe that the battery useful life could be significantly increased. The downside of a hybrid ESS is the high costs and relatively complex control system.

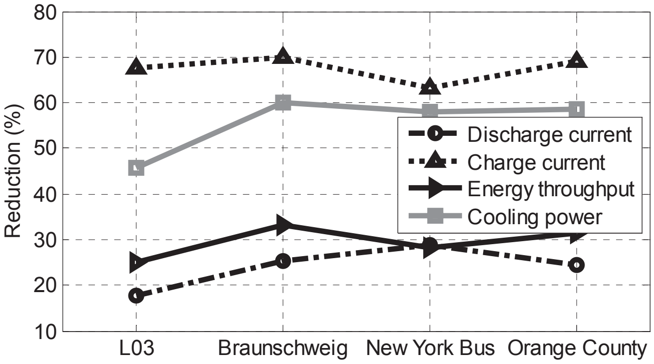


Figure 3.8. Impact of hybrid ESS on the current, energy throughput and cooling power of the battery.

The durability has been a concern with lithium-ion batteries for a long time. In vehicular applications, the powertrain component life is desired to be quite long, which is not necessarily the case with lithium-ion batteries because their life is strongly dependent on operating cycle and conditions. Especially in hybrid vehicles, the battery life can be influenced by advanced control methods as there is another power source on-board. The impact of an energy management strategy on the battery useful life in a series plug-in hybrid city bus was evaluated in Publication IV. The battery life was taken into account in the development process of energy management strategies. In this case, the battery aging was modelled based on the charging and discharging current and battery temperature. The process is based on dynamic programming and vehicle simulation. The full description of the process is presented in Publication IV. In the control problem, the battery life was taken into account as equivalent fuel consumption. The battery useful life was estimated based on a severity factor, which was defined in terms of the battery temperature and current. The cost function for the control problem is shown in Equation 3.4.

$$J = \int_0^{t_f} (1-\alpha)\dot{m}_{fuel}\big(u(t), P_t(t)\big) + \alpha\left(\dot{m}_{batt}\Big(I\big(u(t)\big), \theta(t)\Big) + \dot{m}_{rbatt}\Big(I\big(u(t)\big)\Big)\right) dt, \quad (3.4)$$

where $\dot{m}_{fuel}$ is the fuel consumption, u is the control variable, P_t is the total power demand, $\dot{m}_{batt}$ is the equivalent fuel consumption of the battery, $\dot{m}_{rbatt}$ is the equivalent fuel consumption to compensate the regenerated braking energy, I is the battery current, θ is the battery temperature, and α is a weighting factor to adjust the relative importance of the fuel consumption and battery aging. The control variable for the problem here is u, which corresponds to the power split between the engine-generator and the battery pack.

The optimal control parameters for a rule-based control were defined with a dynamic programming algorithm with different weightings of α. Then the plug-in hybrid bus model was simulated in different driving cycles with the optimized control parameters. A typical rule-based control strategy was used for the reference simulations without any specific parameter optimization. In this strategy, the battery capacity is first used in to its lowest acceptable level of state of charge, and then operated as charge-sustaining hybrid. This strategy is also called as the CD-CS strategy. The battery state of charge (SOC) in the simulations of the reference case and the optimization cases (α = 0, α = 0.25 and α = 0.5) is presented in Figure 3.9. It can be seen that in the control parameter optimized simulations the battery SOC trajectories are somewhat identical. This is because in the optimization simulations the target final SOC was between 15-20%. In the operation of a plug-in hybrid bus, it is desirable to have low level of energy in the battery at the end of the cycle. This also enables an equal comparison of the different control strategies.

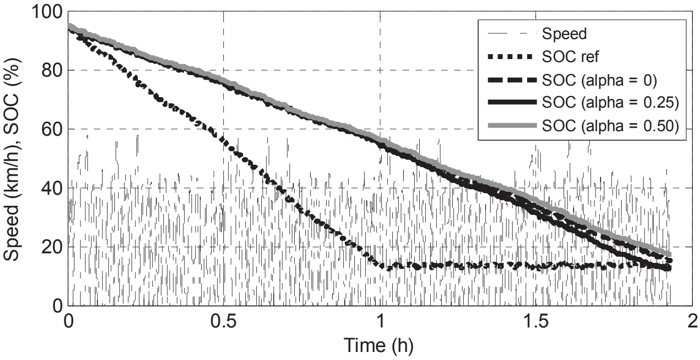


Figure 3.9. Comparison of the battery state of charge.

Figure 3.10 presents a comparison of the engine operation data in Braunschweig cycle in the cases of α = 0 and α = 0.5. It can be seen that in the first scenario, the engine is operating mostly in its high efficiency region by following the optimal operation line and in the case of α = 0.5, the engine needs to operate also in the lower efficiency regions.

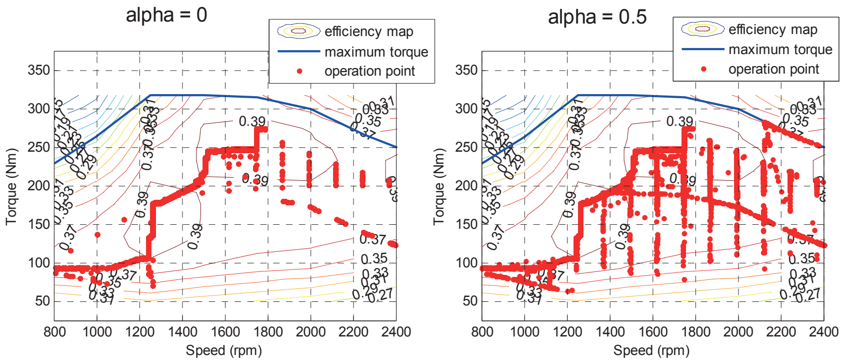


Figure 3.10. Engine operation data in Braunschweig cycle.

From the simulation results, the fuel consumption and battery useful life were analyzed. The corresponding results are presented in Figure 3.11 and 3.12. The results show the fuel consumption difference in relation to the reference case when using the CD-CS strategy. In the case of α = 0 when the fuel economy is being optimized, the fuel consumption decreases 5-10%. If the battery aging and the fuel economy are equally important (α = 0.5), the fuel consumption increases quite dramatically, especially in Braunschweig and New York Bus cycles. This increase is heavily dependent on the driving cycle.

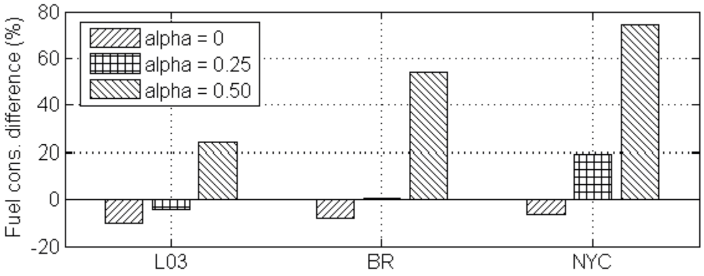


Figure 3.11. Fuel consumption difference.

Figure 3.12 presents the impact of the optimized control parameters on the battery life. According to these results, by minimizing partly the battery aging (α = 0.25 and 0.5), it does not seem to have a significant advantage over the case where only the fuel consumption is minimized (α = 0). Overall, the battery life can be increased essentially in the more demanding and higher speed driving cycles. The particular difference of the L03 cycle is that it includes the road elevation and it has substantial amount of hill climbing. The other cycles represent driving on a level road. Hill climbing usually increases the battery current levels e.g. acceleration in uphill and deceleration in downhill.

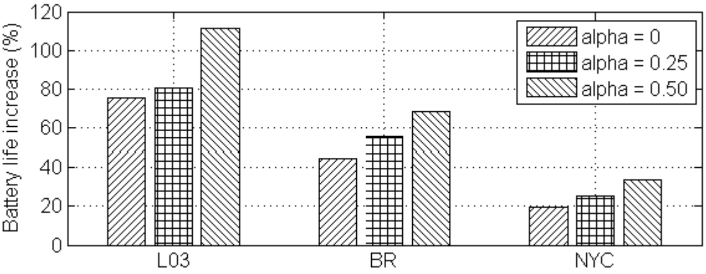


Figure 3.12. Battery life increase.

3.4 Costs

Because city buses are usually operated by transit agencies, which have limited budgets, the capital and operating costs of the buses are important selection criteria in the investment decision making. For many reasons, alternative powertrain technologies are still considerably more expensive than the traditional diesel city buses. In terms of costs, the main advantages of the hybrid and electric buses are the lower operating costs, and lower pollutant and CO2 emissions. The emissions are sometimes taken into account as evaluation criteria in public transport bidding procedures. The reduction of the costs remains as the major factor in order to increase the investments in alternative powertrains in city buses.

A life cycle cost analysis was carried out in Publication I for diesel, parallel and series hybrid, and electric buses. The analysis was based on a fleet operation of buses in different types of operating cycles, and with different operating schedules (Table 3.5). The following variables were taken into account in the life cycle cost calculation; capital costs, operating costs, and costs of the energy storage system replacements. The capital costs consist of the purchase costs of the buses and the charging equipment if needed. The operating costs include diesel and electricity consumption, and maintenance costs. The maintenance costs include general repairs and spare parts. The key assumptions and cost parameters are presented in Table 3.6.

Table 3.6. Parameters for the cost-benefit analysis.

Parameter	abbr	Value
Diesel city bus capital cost (€)	C_{cap}	225000
Diesel fuel cost, EU average 12/2012 without VAT (€/l)	C_{fuel}	1.185
Electricity cost without VAT (€/kWh)	C_{elec}	0.10
Maintenance cost for diesel bus (€/km)	C_{mc}	0.14
High power battery cost (€/kWh)	C_{batt_hp}	1000
High energy battery cost (€/kWh)	C_{batt_he}	750
Ultracapacitor system cost (€)	C_{ucap}	15000
External charging equipment cost (€)	C_{chg}	200000
External charging power for electric bus (kW)	P_{chg}	100
Operation time in a year (h)	T_{op}	4000
Service life in years	T_s	12
Discount rate (%)	d_{rate}	7

The life cycle costs (C_{LC}) for a bus fleet was calculated with Equation 3.5.

$$C_{LC} = N_{init} f_C C_{cap} + X_{chg} C_{chg} + \sum_{t=0}^{T} \left(N_{init} C_{op} D_a + N_t C_{ess} \right) \cdot (1 + d_{rate})^{-t}, \quad (3.5)$$

where N_{init} is the initial number of buses in a fleet, f_C is the capital cost factor of a hybrid or electric bus (for diesel bus f_C = 1), C_{cap} is the capital cost of a conventional diesel bus, X_{chg} is 1 for rechargeable buses and 0 for the other types of buses, and C_{chg} is the cost of the external charging equipment, C_{op} is the operating cost (€/km), D_a is the yearly driven distance in operation, N_t is the number of the energy storage replacement at year t, C_{ess} is the energy storage cost, d_{rate} is the discount rate, and t is the time in years. The capital cost factor indicates how much higher the bus purchase costs are for the hybrid and electric buses e.g. 1.5 correspond to 50% higher costs.

Based on the bus fleet simulations, the life cycle costs were calculated for each bus topology and for each operating route. Figure 3.13 presents the breakeven variation of the capital cost factor for the hybrid and electric buses in relation to the diesel bus. The bars show the variation caused by the operating routes. The results show, that the reference capital cost factors are not in the scope of the variations except for the parallel hybrid bus with ultracapacitors as energy storage (PAR_1). The reference cost factors correspond to the estimated present value bus purchase costs of the hybrid and electric buses as presented in Publication I.

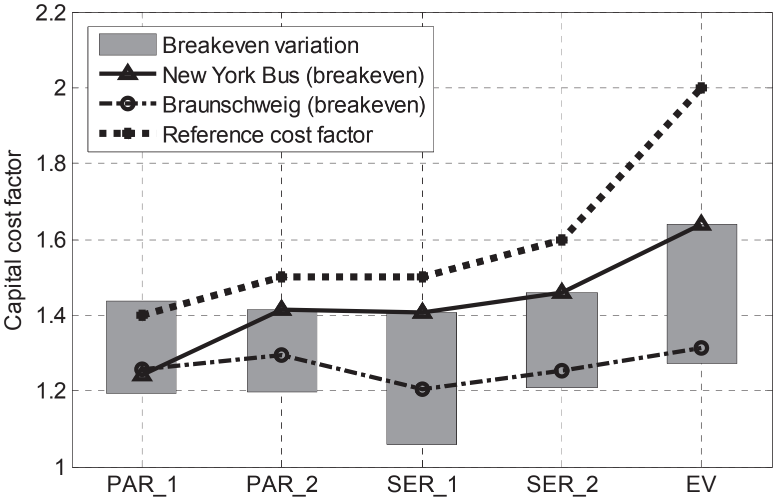


Figure 3.13. Variation of the cost factors for breakeven in life cycle costs.

The results indicate that the capital costs of the hybrid and electric buses needs to be reduced to make them economically sustainable with currently used diesel city buses. For the hybrid buses, an average of 30% (capital cost factor 1.3) higher capital costs would make them even with diesel buses. For the full electric bus, the breakeven capital cost factor has a lot of variation caused by the different operating routes, and the average is little less than 1.5.

This variation is mainly due to the increased amount of buses and the ESS replacements in certain operating routes.

Figure 3.14 presents the variation of operating costs for all the different bus topologies. The operating route has less impact on the operation costs of the hybrid and electric buses. In the case of electric bus, a major part of the operating costs comes from the energy storage replacement costs.

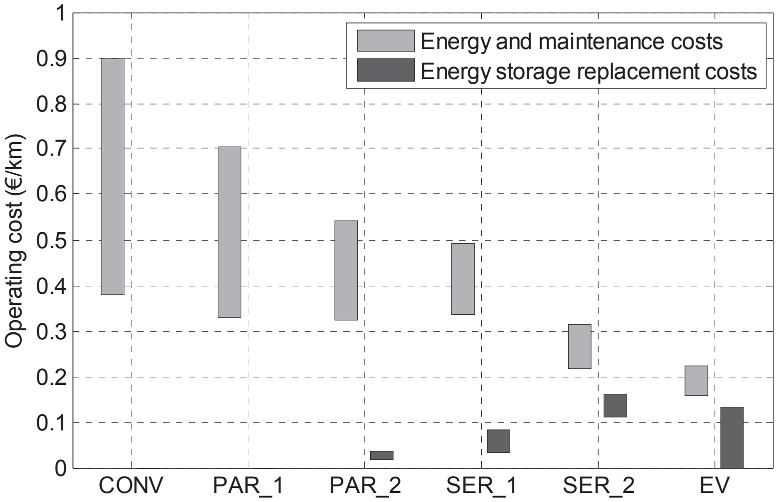


Figure 3.14. Variation of the life cycle operating costs.

Figure 3.15 presents a sensitivity analysis for the life cycle costs by showing the effect of certain key parameters on the life cycle costs. The effect of each parameter was calculated individually in relation to the reference case which was shown in Figure 3.13. According to these results, the hybrid buses have on average 5-10% higher life cycle costs than the diesel buses. The electric bus life cycle costs are about 20% higher. The lower cost and longer life of the ESS do not have a significant impact on the life cycle costs of the charge-sustaining parallel and series hybrid buses (PAR_1, PAR2 and SER_1) whereas the 50% lower ESS costs have a notable impact on the life cycle costs of the plug-in hybrid and electric bus. Also, the higher fuel costs reduce the life cycle costs of the plug-in hybrid and electric bus. The 25% reduction to the capital costs reduces significantly the life cycle costs of each bus configuration, and would make them more profitable in terms of life cycle cost than the conventional diesel buses. Based on these results, it can be concluded that the most efficient way to increase the cost effectiveness of the hybrid and electric city buses is to reduce the initial purchase costs and the ESS costs.

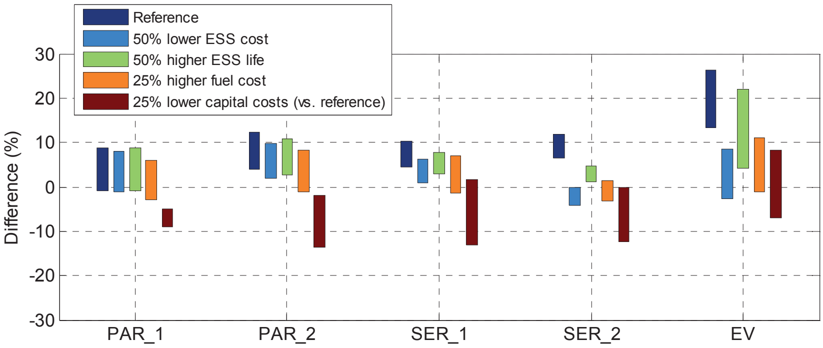


Figure 3.15. Life cycle cost sensitivity to various parameters.

4. Underground mining loader (Publications V and VI)

4.1 Energy and operating efficiency

Due to the increasing fuel prices and stricter pollutant emission limits, hybridization and electrification are becoming sustainable solution also for powertrains of heavy mobile machinery. There are not many research studies published about heavy mobile machinery, and only recently there has been a growing interest to the alternative powertrain solutions, which have increased the research activities e.g. (Liukkonen, 2013; Hui and Junqing, 2010; Lajunen et al., 2010; Lin et al., 2010). The energy and operating efficiency of a hybrid underground mining loader was analyzed in Publication V. Also, the energy storage system requirements were evaluated. The research was carried out by simulation with a dedicated model, which schematic component-level layout is presented in Figure 4.1. The components are: GEN-SET = engine-generator, AUX = auxiliary devices, AC/DC = AC/DC converter, DC/DC = DC/DC converter, BR = brake resistor, UCAP = ultracapacitor module, BATT = battery, FD = final drive, ED = electric drive, TX = transmission, HP = hydraulic pump. The simulation model was developed in MATLAB/Simulink environment. The conventional, diesel powered loader was measured in a real mine environment, which allow to verify the correct model operation (Hentunen et al., 2010; Liukkonen et al., 2010). The simulations were carried out in a typical duty cycle, which is about 700 meters long and has eight distinct phases of operation as was illustrated in Figure 2.9. (Lajunen et al., 2010)

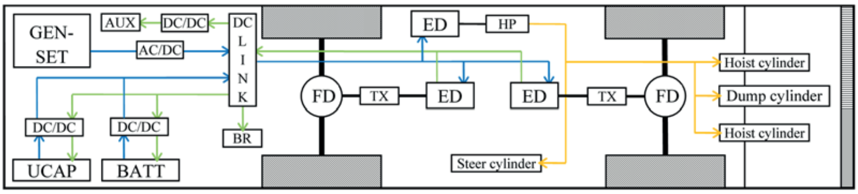


Figure 4.1. Component-level layout of the hybrid loader simulation model.

Different configurations of a hybrid loader were defined in terms of the ESS and operating strategy. The configurations included two different types of battery chemistries, and a dual-source energy storage system with a battery back and an ultracapacitor module. The operating strategies included charge-sustaining (CS) hybrid and charge-depleting (CD) plug-in hybrid strategies. The reference simulations were carried out with the conventional (CONV), diesel powered loader, which was presented earlier in Figure 2.8. All the hybrid loader configurations are powered by a 50 kW engine generator. Four of the hybrid configurations operate CS strategy (CS1-CS4), and another four with CD strategy (CD1-CD4). Each hybrid configuration has different ESS configuration. Table 4.1 presents the general characteristics of the loader models, and Tables 4.2 and 4.3 the details of the battery and ESS configurations.

Table 4.1. General characteristics of the mining loader models.

Description	Diesel	Hybrid
Engine or gen-set power	90 kW	50 kW
Driving motor type and nominal power	hydraulic 158 kW	electric 45 kW
Work hydraulic power	hydraulic motor 67 kW	electric motor 67 kW
Average power of auxiliary devices	10 kW	10 kW
Driveline total gear ratio	1:75	1:75
Operating weight	14.5 t	14.5 t
Simulated payload	3 t	3t

Table 4.2. Battery pack configuration data (K=Kokam, A=Altairnano).

Specifications	K40_1	K40_2	K100_1	A50_1	A50_2
Modules	12	20	20	10	20
Voltage (V)	311	518	518	230	460
Weight (kg)	144	200	491	213	426
Volume (l)	118	196	470	214	428
Max discharge power (kW)	62	104	207	69	138
Max charge power (kW)	25	41	104	69	138
Energy (kWh)	12.4	20.7	51.8	11.5	23.0

Table 4.3. Energy storage configurations for hybrid loader models.

Configuration	Energy storage configuration	Max discharge power (kW)	Max charge power (kW)
CS1	K40_1+Ucap	62+(59)	25+(59)
CS2	K40_1	62	25
CS3	A50_1	69	69
CS4	K40_2	104	41
CD1	K40_2+Ucap	104+(59)	41+(59)
CD2	K40_2	104	41
CD3	A50_2	138	138
CD4	K100_1	207	104

The work or operating efficiency is defined here as tons of material moved in an hour, and the energy efficiency as energy consumed for moving 1 t of material. The increase in the work efficiency of the hybrid loader and the decrease in its fuel consumption were calculated in relation to the conventional loader. The increased work performance of the hybrid loader comes mainly from the fact that it can operate faster, thus it drives at higher speeds.

Figures 4.2a and 4.2b present the main operating data of the loader configuration CS1, which has a battery pack and an ultracapacitor module as energy storages. During the long downhill drive (the period from 40s to 85s), both storages store braking energy and the gen-set is shut down. The ultracapacitor module is basically fully recharged after the downhill drive (around t = 85s, voltage = 390V). During the peak power demands, e.g., t = 10s, t = 30s, and t = 135s, all the power sources are used together to provide maximum performance.

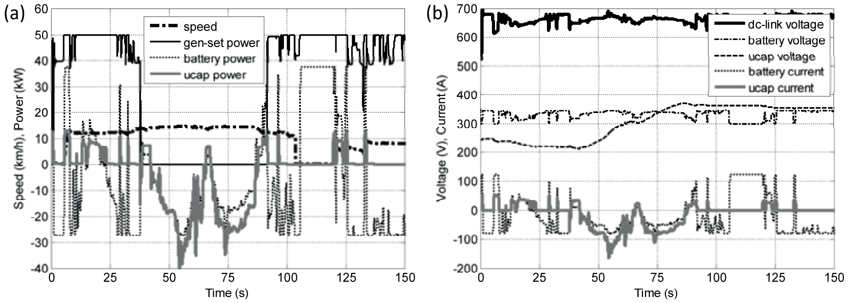


Figure 4.2. Operating data of the loader configuration CS1 at the beginning of the duty cycle.

Figure 4.3a shows the impact of the battery energy capacity on the increase in the work efficiency of the hybrid loader, and the decrease in its fuel consumption. With both operating strategies, CS and CD, the work efficiency is increased in a similar way. Depending on the energy capacity of the ESS, the increase varies from 20% up to 35%.The CD strategy allows inherently more effective reduction of fuel consumption. On average, the fuel consumption decrease is around 40% for the CS hybrid loader and 55% for the CD hybrid loader. Figure 4.3b presents the influence of the battery power capacity on the work efficiency. The higher battery current limits have a little impact whereas the fast charging can increase significantly the work efficiency. The reference charging current was 1C and the fast charging was defined as 4C or a maximum power of 200 kW.

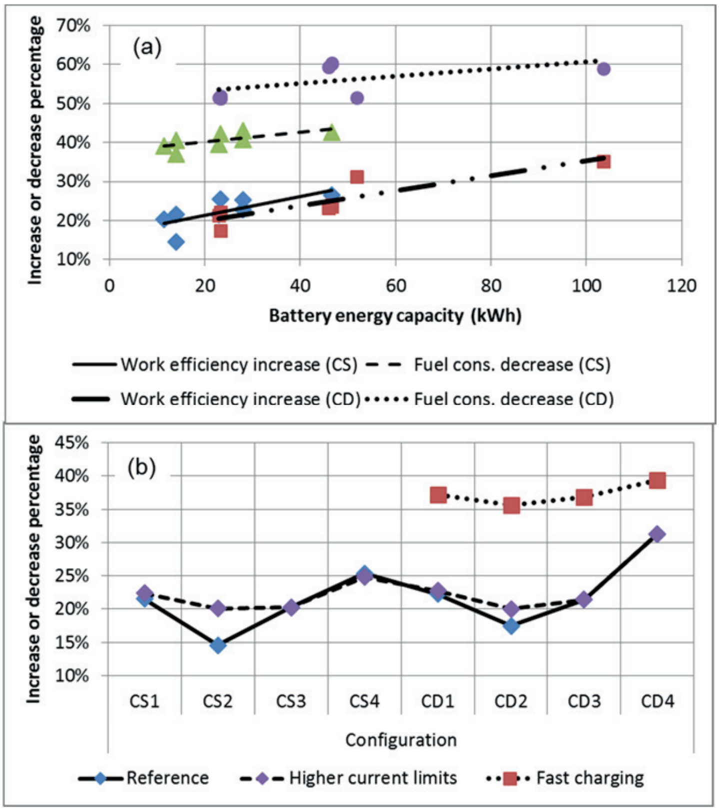


Figure 4.3. (a) Impact of the battery energy capacity on the loader performance, (b) Impact of the elevated battery power capacity on the work efficiency.

4.2 Operating strategy

A method for the development of energy management strategies (EMS) based on the duty cycle characteristics for underground mining loaders was presented in Publication VI. The method is based on a dynamic programming algorithm and vehicle simulation. The method was used to define the optimal power-split between an engine-generator (gen-set) and a battery of the hybrid loader. The method was also used to evaluate the energy efficiency and operating efficiency of a diesel-electric, a hybrid, and an electric loader.

Figure 4.4 presents the context for the EMS development in the case of an underground mining loader. The presented duty cycle includes the empty and full bucket cycles, which were illustrated earlier in Figure 2.9. The maximum operating speed is limited by the environment, typically less than 15 km/h. The minimum speed in this case was chosen to be 1 m/s for ensuring the controllability of the machine. The maximum speed 4 m/s was based on the limitations of the underground conditions. The possible velocity trajectories are then between these two speed limits.

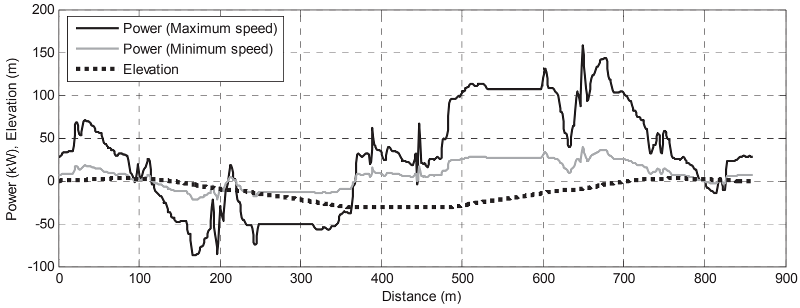


Figure 4.4. Mining loader driving power at the wheel for the minimum and maximum speed.

The optimal control sequence for the EMS was calculated by dynamic programming simulations. In difference to the common time-based simulations, which is typical to on-road vehicles, in this study the DP simulations were carried out in distance-based. This is because the duty cycles of the mobile work machines are usually defined by the distance and are related to a certain environment e.g. a mine or a construction site. The cost function for minimizing the total consumed energy or maximizing the operating efficiency is formulated as

$$J = \sum_{k=0}^{N-1} \alpha \left(\mathrm{P}_{fuel}(u_k, w_k, k) \cdot T_d(w_k, k) \right) + (1-\alpha) \cdot T_d(w_k, k), \qquad (4.1)$$

where P_{fuel} is the fuel power, T_d is the time elapsed at one distance step, u_k is the power split factor (between the gen-set and battery), w_k is the control variable which is used for the determination of the speed (v_k), and α is a weighting factor for choosing the optimization target, either the energy efficiency or operating efficiency. Therefore, in this case the alpha can be either 0 or 1.The speed is determined here the same way as it was for the city buses in Equation 3.3. $P_{fuel} \cdot T_d$ is the energy consumption at each distance step, and in the case of the operating efficiency (t/h), the optimization problem is to maximize the driving speed, thus minimize the consumed time, which is very straightforward. The optimization targets, energy consumption and elapsed time, could be made comparable e.g. by taking into account the overall cost of the operation.

Figures 4.5 and 4.6 present the dynamic programming simulation results for the hybrid loader with two different optimization targets. The optimization target in Figure 4.5 is to maximize the operating efficiency (α = 0), and in Figure 4.6 to minimize the energy consumption (α = 1). In the first case, the corresponding operating time for the cycle is 244 s and for the latter case 264 s, thus the operating efficiency is 8% higher in the first case. On the contrary, the energy efficiency is around 8% higher in the latter case. The most visible difference between these two optimization targets can be seen in the battery power signal. In the uphill part of the cycle (distance = 480 m ... 720 m), much more power is drawn from the battery when the operating efficiency is optimized (α = 0). This can be achieved by recharging the battery more during the first part of the cycle as it can be seen in the difference of the battery power and the battery state of charge between Figures 4.5 and 4.6.

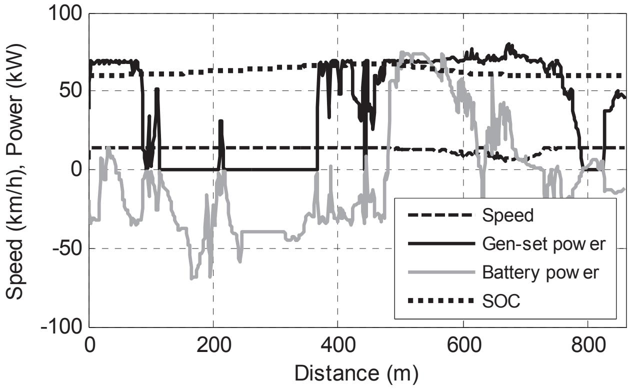


Figure 4.5. Hybrid loader simulation results (α = 0).

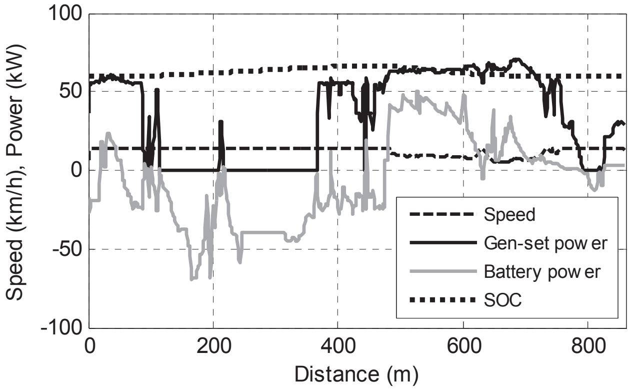
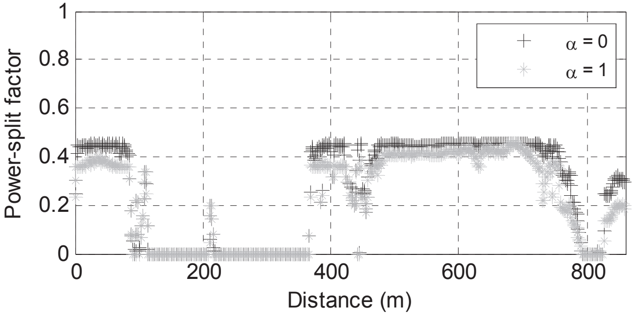


Figure 4.6. Hybrid loader simulation results (α = 1).

Figure 4.7a presents the comparison of the optimal power-split factors for the engine-generator, and Figure 4.7b shows the battery recharging factor. In this case, the power-split factor corresponds to the portion of the gen-set power from the total available power, which is the sum of the gen-set and the battery maximum available power. The maximum power-split factor for the gen-set is then 0.45. It can be seen in Figure 4.7a that the major difference between the two optimization cases is that the gen-set power is often close to the maximum power when the operating efficiency is being maximized (α = 0). The power-split factor of the energy efficiency optimized case (α = 1) corresponds to the optimal efficiency operation of the gen-set. The recharging factor describes the portion of the gen-set power used for recharging the battery. The rest of the gen-set power is used for driving and auxiliary devices. In the operating efficiency optimized case (α = 0), the battery is charged a lot more than in the other case.

a) Power-split factor



b) Battery recharging

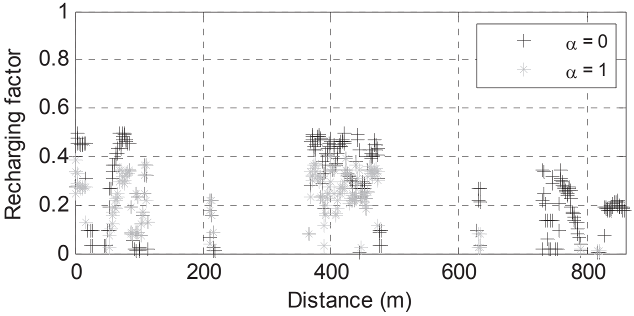


Figure 4.7. Hybrid loader control comparison.

4.3 Energy storage

The operation of an underground mining loader is very energy intensive, which leads to high requirements for the energy storage. The energy storage requirements were evaluated for the underground mining loader in Publication V. One of the important requirements for the energy storage is the durability under operation. The battery life is often defined as the amount of charging and discharging cycles. For the charge-sustaining hybrid, these cycles are shallow cycles because the battery is never fully depleted. A deep cycle corresponds to a full discharge-charge cycle. The amount of occurring battery shallow and deep cycles was defined based on the simulation results for the different hybrid loader configurations. The battery cycles impact on the work and energy efficiency is shown in Figure 4.8. The amount of cycles is calculated for 1000 hours of operation. It can be seen in Figure 4.8a that with higher number of shallow cycles, both the work efficiency and energy efficiency is higher. In the reference simulations, the shallow cycles were between 3–8% of the total energy of the battery pack. The amount of deep cycles has no impact on fuel consumption, but work efficiency is increased by smaller numbers of deep cycles, as shown in Figure 4.8b. The amount of deep cycles is diminished by increasing the size of the battery hence reducing the need for recharge.

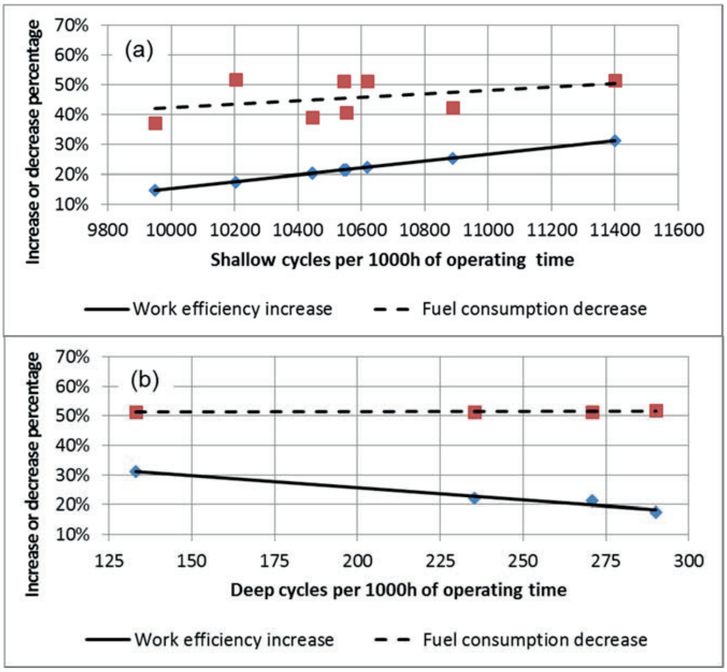


Figure 4.8. Impact of battery cycles on the loader performance: (a) Shallow cycles, (b) Deep cycles.

The effective current can be used as a measure of the level of stress for batteries. In Publication V, the battery effective current and cooling power were calculated for each loader configuration. Figure 4.9a shows the effective current of the battery pack as the C-rate for each loader configuration. Usually, the higher the effective current is, the greater the demands on the battery will be, and at the same time, the battery will probably need to operate at higher temperatures. This demand is a lot less with the higher capacity batteries than with the smaller capacity batteries e.g. the battery of the configuration CD4 is 2.5 times higher than the capacity in configuration CD2. There are considerable differences between the different battery chemistries. This can be seen when comparing the configurations CS2 and CS3 to each other. In the first of these configurations the battery chemistry is lithium NCM (Nickel-Cobalt-Manganese) and the latter one has lithium titanate chemistry, which nominal cell voltage is lot lower than in the former chemistry. This leads much higher currents in the configuration CS3 with the same size battery.

The battery cooling requirement in three different scenarios is shown in Figure 4.9b. In the case of higher current limits, the continuous recharge current limit was increased to 4C for the Kokam battery. The case of two battery packs correspond a case where two battery packs were used instead of one. The cooling power is expressed as a percentage of the nominal discharge power of the battery. There is a positive correlation with the effective current; the cooling power is higher when the effective current is higher. However, the increase in the cooling power is lot less than it was in the case of the effective current.

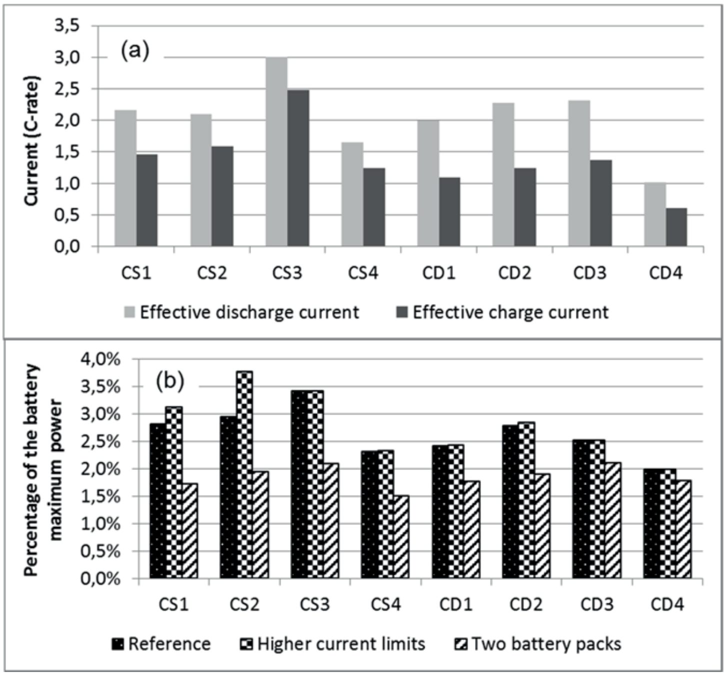


Figure 4.9. (a) Battery effective discharge and charge current. (b) Battery cooling power as percentage of its maximum power.

4.4 Costs

The initial cost is one of the most important factors that can make a hybrid loader economically more profitable than a conventional loader. Based on the simulation results in Publication V, the payback time was calculated for each hybrid loader configuration in relation to the conventional loader. Equation 4.2 was used to define the work that is needed to be done with a hybrid loader to amortize the higher costs. The amount of work (w_{HYB}) was defined in terms of tons of material moved in the duty cycle.

$$w_{HYB} = \frac{C_{ESS} + C_{CONV}(f_{HYB} - 1)}{C_{op\_CONV} - C_{op\_HYB}}, \tag{4.2}$$

where C_{ESS} is the initial costs of the energy storage system, C_{CONV} is the conventional loader initial costs, f_{HYB} is the cost factor for hybrid loaders, and C_{op_CONV} and C_{op_HYB} are the operating costs for moving one ton of material for a conventional and hybrid loader, respectively. In this evaluation, the operating costs are only based on the diesel and electricity consumption.

The payback time for the hybrid loader configurations and the impact of the battery costs on payback time is shown in Figure 4.10 with three different battery cost scenarios: $1500, $1000, and $500 per kilowatt-hour. Even though the battery costs are usually important, in the case of the hybrid loader it has minor impact on the cost effectiveness. The differences in the payback time between the different hybrid loaders are more important than the differences between the battery cost scenarios, especially in terms of the battery cycle life. The battery cycle life is presented here also as amount of work. Except the configuration CD4, the charge-depleting hybrid loaders have shorter payback time but the battery life is quite close to their breakeven payback time. This means that the total service life of the loader should be taken into account when calculating the cost effectiveness. With the CS hybrid loaders, the battery cycle life is far from the breakeven payback limit, which indicates that there would be lot less battery replacements during the service life. By doubling the energy storage capacity (Figure 4.10b), it only slightly shortens the amortizing time, and at the same time, the cycle life of the battery is then also shorter. This is because the battery cycle life is calculated based on the deep cycles in the operation. The double battery pack provides more power, which improves the work performance but increases the amount of deep cycles at the same time. If work were to be done 20 hours per day during 300 days in a year with the conventional loader, the yearly amount of work would then be around 156,000 tons. If the same amount of work were done with the hybrid loaders (less operating hours), the payback time for these hybrid loaders would be then between 3-4 years.

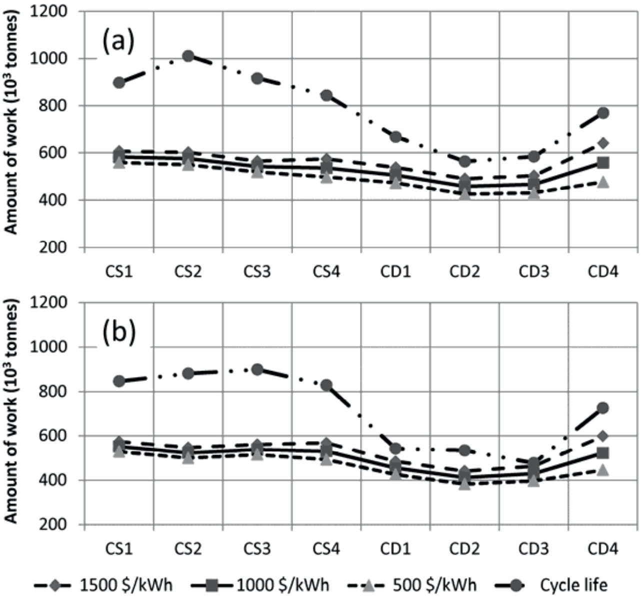


Figure 4.10. Amount of work required to amortize the elevated costs of the hybrid loader with different battery costs: (a) Reference simulations, (b) Double battery pack.

The impact of the higher initial costs of the hybrid loaders is shown in Figure 4.11 where the payback time of the hybrid loader is shown with four different initial cost scenarios. The battery cost is fixed to $1000/kWh. The 50% higher initial cost scenario corresponds to the reference scenario presented in Figure 4.10. The differences between the different loader configurations are relatively small whereas an increase in the capital cost significantly increases the amount of work to be done for the breakeven in payback time with the hybrid loader. For instance, increase from 30% higher initial costs to 60% practically doubles the required work to be done. Based on these results, it can be concluded that the initial costs are one of the most important factors in the cost effectiveness of the hybrid underground mining loaders as this was also the case with city buses. However, the energy storage and especially the battery costs were not as significant as they were for the city buses.

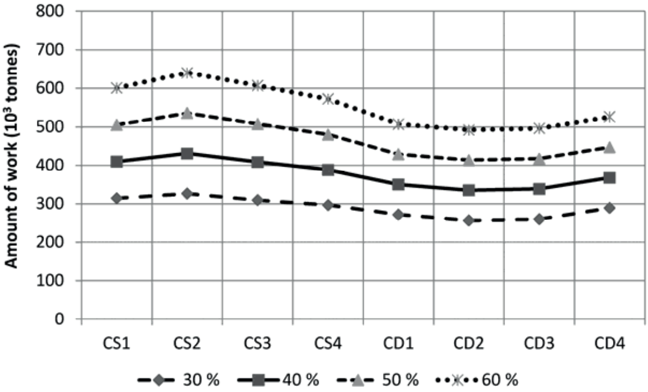


Figure 4.11. Impact of the initial costs of the hybrid loader on payback time.

5. Heavy vehicle combinations (Publication VII)

5.1 Energy and operating efficiency

Because the energy efficiency of heavy vehicle combinations is dependent on their payload capacity, one interesting way to improve their energy efficiency is to adopt higher total weights to increase the payload capacity. Some studies have been previously done in this field, and the results have been somewhat positive in terms of energy efficiency (Vierth and Haraldsson, 2012; Rijkswaterstaat, 2011). The fuel economy of different heavy vehicle combinations was evaluated in Publication VII. This evaluation was done by simulation in the Autonomie vehicle simulation software (Autonomie, 2014). The vehicle combinations considered in this research are based on the European combinations, and specifically on the vehicle combinations that are used in Finland. Table 5.1 describes the structures of four different HVCs with general technical data.

Table 5.1. Descriptions and general technical data of the heavy vehicle combinations.

Maximum weight	40t	60t	76t	90t
Axles	3+3 = 6	3+4 = 7	3+3+3 = 9	3+3+2+3 = 11
Trailer(s) description	one semitrailer	full trailer	swap body + link + semitrailer	semitrailer + dolly + semitrailer
Frontal area (m^2)	10	10	10	10
Drag coefficient	0.6	0.64	0.67	0.7
Rolling resistance coefficient	0.008	0.008	0.008	0.008
Engine max. power (kW)	337	466	522	560
Transmission [gear ratios]	12-speed [0, 11.32, 9.16, 7.19, 5.82, 4.63, 3.75, 3.02, 2.44, 1.92, 1.55, 1.24, 1.00]			
Final drive ratio	2.5			
Trailer(s) empty weight (kg)*	8460	12560	16100	18740

* Includes trailers, dollies and links

Because the operating route can have a significant impact on the fuel economy of a heavy vehicle combination, several different types of operation routes were defined for the simulations. The operating routes were measured from popular truck routes in southern Finland. Table 5.2 presents the specifications of the operating routes. The simulations were carried out with a target speed of 80 km/h. For HVCs, the typical speed limit is often 80 km/h in Europe. The possible speed limits lower than 80 km/h were not applied.

Table 5.2. Description of the simulated operating cycles.

Route	M01E	M03S	H06N	H14W	H26N
Distance (km)	145	163	257	61	51
Target time (h)*	1,9	2,1	3,3	0,8	0,7
Cumulative elevation (m)	-1,3	-97,1	31,0	19,2	83,0
Climbing (m)	880	696	1259	413	443
Descend (m)	-882	-793	-1228	-394	-360
Climbing gradient (m/km)	6,1	4,3	4,9	6,8	8,8

* target speed is set to 80 km/h

Figure 5.1 summarizes the fuel consumption results for the conventional HVCs. The results illustrate the increase of the fuel consumption and the decrease of the payload specific fuel consumption in function of the increased total weight. When comparing HVCs in the same operation, it is actually more useful to use the payload specific fuel consumption (the amount of fuel consumed per payload ton-kilometer) as the comparison criteria rather than the fuel consumption. The bars in Figure 5.1 include the consumption variation due to the differences in fuel consumption between the operating cycles. These results clearly show that by increasing the total weight, the fuel consumption increases almost linearly. Despite the increase of the fuel consumption, the payload specific fuel consumption decreases. In the first case (40t → 60t), the total weight of the combination is increased by 50% and the payload is increased by 60%, which leads to 18% decrease in the payload specific fuel consumption.

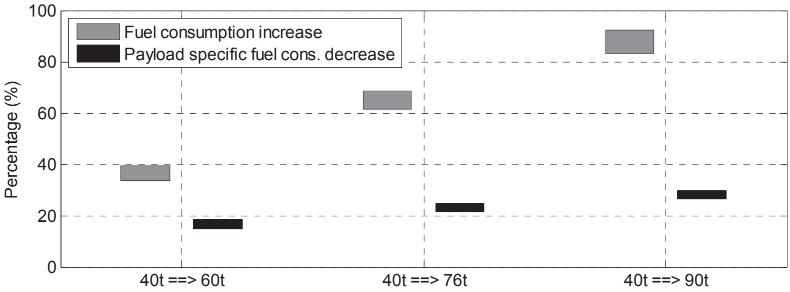


Figure 5.1. Fuel consumption increase and payload specific fuel consumption decrease.

The impact of the powertrain hybridization on energy efficiency of HVCs was also evaluated in Publication VII. The pre-transmission parallel hybrid was chosen as the hybrid configuration. For evaluating the impact of the hybrid system configuration on the fuel economy, three different parallel hybrid powertrain configurations were defined based on a battery and an electric motor. The detailed technical specifications of the different configurations are presented in Publication VII. The following list describes briefly the different configurations:

- **HYB1:** Small size high-power type battery and small size electric motor
- **HYB2:** Medium size high-power type battery and medium size electric motor
- **HYB3:** Large size high-energy battery and medium size electric motor

Table 5.3 presents the specifications of the battery systems in the hybrid combinations.

Table 5.3. Specifications of the battery options.

Description	Battery1	Battery2	Battery3
Battery type and cell nominal capacity	Saft 6Ah	Saft 6Ah	Kokam 40Ah
Cell configuration	One pack with 180 cells in series	Two packs in parallel, 180 cells in series in a pack	One pack with 168 cells in series
Total / usable energy capacity (kWh)	3.8 / 2.7	7.6 / 5.3	25 / 20
Continuous discharge / charge (C-rate)	20 / 20	20 / 20	5 / 3
Peak discharge / charge (C-rate)	40 / 40	40 / 40	10 / 5
Nominal system voltage (V)	648	648	622
Full cycle life estimate (cycles)	10,000	10,000	5000
Battery system weight (kg)	90	180	378

Figure 5.2 presents some operating signals of the 60t parallel hybrid HYB2 configuration in the H26N cycle. It can be seen that the braking energy is usually regenerated in the downhill phases with relatively high power levels e.g. t = 1190 s and t = 1375 s. The electric motor assists the engine during uphill phases e.g. between 1500-1520 s and between 1640-1660 s. The charge sustaining strategy keeps the battery state of charge (SOC) within its predefined limits and therefore the energy available for the engine assist can sometimes be limited (e.g. 1650 s).

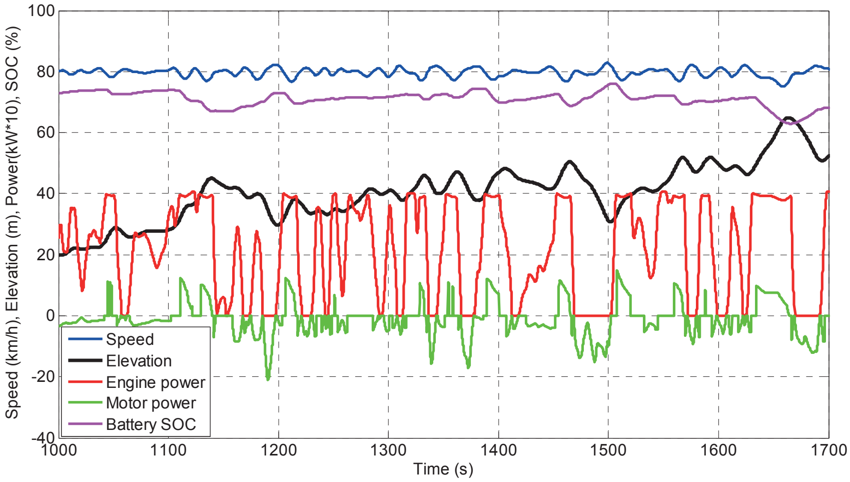


Figure 5.2. Operating signals of 60t parallel hybrid combination (HYB2) in part of the cycle H26_N.

Figure 5.3 presents the fuel consumption decrease with the hybrid vehicle combinations in comparison to the corresponding conventional combinations. For each hybrid configuration and operating cycle, the fuel consumption is shown in the bar where the variation represents the fuel consumption differences with different total weights (40t–90t) of the combination. These results indicate that the hybridization is more advantageous in the M01S, H14W and H26N operating cycles. All these cycles have substantial amount of hill climbing. On average, the fuel consumption decrease is between 3.6–4.2% depending on the combination.

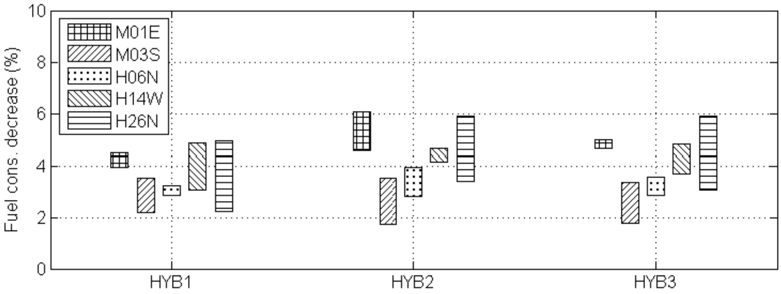


Figure 5.3. Comparison of fuel consumption decrease between hybrid configurations and operation cycles.

As the empty weight of the parallel hybrid tractor is increased due to the additional mass of the hybrid system components, the comparison to the conventional combination was also made by using the payload specific fuel consumption in Figure 5.4. The bars show the variation of the fuel consumption decrease between the operating cycles. The average saving percentage drops down to 3%. Because of the heavier system mass of the HYB2 and HYB3 configurations, the HYB1 configuration outperforms the others in the case of 40t combination. With the 60t combination, there are no significant differences between the three hybrid configurations whereas with higher weights, the configuration HYB2 outperforms the other configurations.

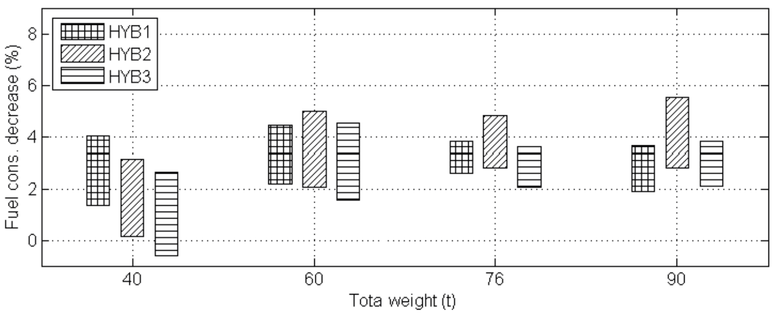


Figure 5.4. Payload specific fuel consumption decrease.

5.2 Energy storage

The energy storage, in this case a battery, is often the most critical part of the hybrid system in terms of performance, durability and costs. To evaluate the cyclic durability of the battery, the energy throughput (kWh/km) can be used as an estimate for the battery degradation during its lifetime. Figure 5.5 presents the energy throughput of the battery for each hybrid vehicle combination. The bars describe the variation caused by the operating cycle. There is a great deal of variation between the operating cycles, which is partly because of the differences in braking energy regeneration, and partly because of the energy management strategy. The amount of the regenerated breaking energy is higher with higher total weights but it seems to almost saturate between the 76t and 90t combinations because the energy throughput of the battery does not practically increase between these two combinations. This can be explained by the hybrid system component power limits in regeneration. Even if 90t has more available braking power than 76t, most of the extra energy is not recovered mainly because of the motor and battery current limits.

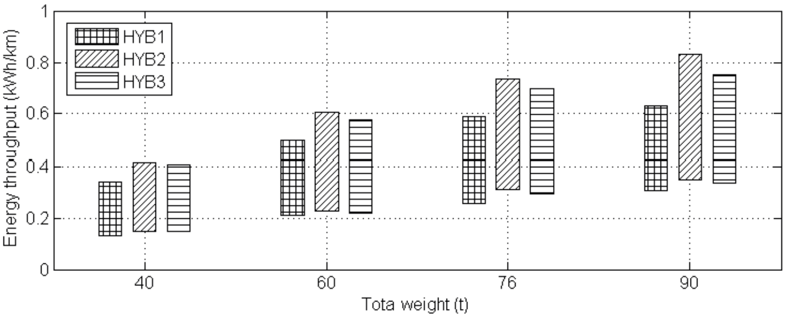


Figure 5.5. Battery total energy throughput.

Considering the yearly driven distance to be 100,000 kilometers (~62,150 miles), the corresponding battery life in years can be calculated with Equation 5.1.

$$L = \frac{N_{cycle} E_{batt}}{E_{km} D_{km}}, \tag{5.1}$$

where N_{cycle} is the battery cycle life as the amount of deep cycles, E_{batt} is the battery usable energy capacity, E_{km} is the battery energy throughput, and D_{km} is the yearly driven distance. Figure 5.6 shows the calculated results for the battery life in years. The bars describe the variation similarly as in Figure 5.5. Because of the different types of operating routes and different performance of the hybrid configurations, there is a vast amount of variation in the battery life between the routes. It is important to notice the differences between the hybrid configurations. As the configuration HYB1 could be considered as a cost effective solution for the 40t combination, it would not be a very long lasting solution for the heavier combinations. Because the energy capacity of the battery in the configuration HYB3 is many times larger than in HYB1 and HYB2, it has a significantly longer estimated life.

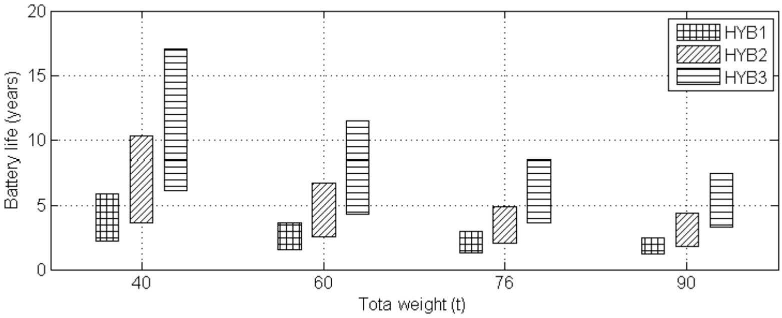


Figure 5.6. Estimated battery life variation in years.

6. Conclusions and discussion

Powertrain electrification brings along new challenges for both the vehicle manufacturers and the vehicle users. Because the use of electrical energy in a vehicle enables vast varieties in the design of the powertrain, it requires a dedicated approach to be able to exploit the benefits of this technology. In this context, the scientific research has an important role to introduce and develop new multidisciplinary methods and approaches to manage the integration of different technologies. One descriptive example of this is the energy storage integration in the vehicle environment. For instance, lithium based batteries offer a good performance and are technologically mature enough for vehicular applications but the battery systems are complex and need robust, well developed management system. The development of these types of systems requires experience and specific knowledge as well as dedicated methods to evaluate different technologies. At the same time, the research can provide valuable understanding of the new technology for the vehicle users. The correct and robust system operation has a significant impact on getting the maximum benefit from the use of heavy hybrid and electric vehicles and machinery in terms of energy efficiency and operating performance. It is important to choose the suitable powertrain alternative based on the needs of the operation. A lot of consideration should be also given for the operation planning especially when there are several vehicles or machines in a fleet. This thesis introduces specific methods to fairly compare different powertrain technologies in heavy vehicles. These methods take into account the specific characteristics of the heavy vehicles and machinery as well as the operating conditions. The results show that there are many factors that impact on the energy efficiency of hybrid and electric heavy vehicles. One important factor is the operating cycle, which impact on the energy efficiency was analyzed for the different heavy vehicle applications. In addition to the energy and operating efficiency, also life cycle costs were evaluated for city buses and underground mining loader. Often, the aspect of costs has been neglected when evaluating new powertrain technologies. In the case of heavy vehicles, which are typically used as the means of production, the operating and life cycle costs are one of the most important factors when choosing the vehicles.

Probably the most common application equipped with an electric or hybrid powertrain among the heavy vehicles is the city bus. This is understandable as the diesel engine powered powertrain of a city bus is far from the ideal solution for the inner city and urban area public transportation. Not only is the energy efficiency low but also the pollutant emissions and noise levels are harmful in the areas where the population density is high. At the moment, the technological and other advantages of hybrid and electric buses are still not enough to make them fully economically sustainable for transit agencies as it was presents in this thesis. Because of this, many of the city bus fleets with alternative powertrains have been, at least, partly financially supported by the governments or other entities. Obviously the financial support is also a positive development in the early adoption of the electric powertrains. However, the economical sustainability of hybrid and electric buses is more complicated than just the expensive initial investment. As an important contribution of this thesis, it was illustrated that there are many factors that impacts on the cost-benefit of these vehicles. For instance, it was shown that there is an important dependence between the cost parameters, the operating conditions, and the life cycle costs of city buses. In addition, it was shown in this thesis that the energy efficiency of city buses could be also improved by optimizing the driving speed profile.

It was illustrated in this thesis that the powertrain hybridization could significantly improve the energy efficiency and operating efficiency of an underground mining loader. It was also shown that the economical savings in the energy costs and the improvement in productivity can substantially reduce the payback time of a hybrid powertrain. The simulation results indicated that the operation of an underground mining loader is well suitable for using hybrid and electric powertrains. The operation is often done in the same types of duty cycles including the same work phases e.g. loading, transport and dumping. The energy storage system analysis showed that the configuration of the ESS has an important impact on the energy efficiency and work performance. In difference to on-road vehicles, the powertrain electrification of heavy mobile machinery can generate so called secondary savings in energy consumption in addition to the savings in the machine operation. For instance, this is the case in the underground mining where the use of diesel engines in underground mine tunnels requires to have powerful ventilation systems because the toxic emissions from diesel powered equipment have to be constantly evacuated. The use of large scale ventilation systems requires significant amounts of energy, which represent an important part of a mine’s total running costs. Therefore, by hybridization and electrification of underground mining machines, important energy saving are also foreseen by reducing the ventilation needs.

As the energy resources are scarcer and energy costs are increasing, all the technological ways of improving energy efficiency are needed. It was shown in this thesis that not only the powertrain electrification but also the operation optimization in its different forms can significantly improve the energy efficiency of heavy vehicles. It was calculated that the energy-optimal velocity profiles of city buses can improve the energy efficiency close to 20%. This could be already implemented in some extent with city buses if dedicated bus lanes were to be used. Another form of the operation optimization is the higher weights of heavy vehicle combinations. By increasing the commonly used total weight 40t of a vehicle combination by 50% to 60t, a decrease in the payload specific fuel consumption almost 20% was calculated based on the simulation results.

Even though electrical energy has been stored successfully for a long time, it is still one of the major challenges in the development of the electric and hybrid powertrains. Nowadays, the batteries are the most common electrical energy storages in vehicles, and the development and commercialization of new battery technologies has been increasing. However, it seems that the energy and power capacity of batteries will not be increased significantly in the near future. This means that the current lithium based batteries are being used for some time, which requires that the possible technical lacks of these batteries needs to be somehow compensated e.g. with advanced methods in the battery system design and control. One technical challenge is the battery useful life, thus durability. In the case of heavy vehicles and machinery, it was shown in this thesis that the operation characteristics generate great demands on the battery durability. To ensure a satisfactory life for the battery, advanced methods needs to be developed in terms of battery management because only keeping the battery within the predefined temperature levels can be challenging. Sometimes it is reasonable to consider sacrificing a part of the energy efficiency or performance to make sure that the battery life is not being diminished. In the powertrain electrification where the role of the energy storage is important, a special attention should be given for the choice of the battery chemistry because different battery chemistries have quite different performance characteristics. The results of the different energy storage analyses in this thesis showed that e.g. battery sizing, current acceptance and operating cycle have significant impacts on the battery life and the energy and operating efficiency of the heavy vehicles.

It was illustrated in this thesis that not always the powertrain electrification or hybridization of heavy vehicles offers high potential for energy savings. This was the case with the heavy vehicle combination where the fuel consumption reduction was evaluated to be no more than six percent and with some combinations and operating routes as low as two percent. However, it should be remembered in this case that a cost calculation should be carried out to be able to evaluate the economical profitability of the hybridization. It is possible that even small savings in the fuel consumption could be enough for an acceptable payback time of the hybridization.

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