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Auxiliary Model Review for Design Analysis of Hybrid Electric Heavy-Duty Long-Haul Vehicles.

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Abstract

The upcoming of CO2 emission legislations for heavy-duty long-haul vehicles, causes a shift of the focus of powertrain design for heavy-duty vehicles towards the reduction of CO2 emissions. In order to combine several interesting complex solutions for CO2 reduction, such as hybridization of the powertrain, electrification of auxiliaries and the use of a waste heat recovery system, an integrated powertrain design optimization has to be performed. This requires to incorporate all components of the vehicle to be integrated in the optimization process, and thereby requires design analysis models of all vehicle components. In this work, we focus on modeling of two electrified auxiliary components; the power steering unit and the air compressor. An overview will be given of the type of models currently used in literature, which will be evaluated on whether they are suitable for an integrated design optimization process. This will be followed by an discussion of ideas for future research. The trade off between accuracy and computational efficiency of the models is one of the key parameters in this study.

Keytopics: Heavy-duty, Auxiliary units, Optimization, Compressor, Power Steering

1 Introduction

For years the design of heavy-duty powertrains has mainly focused on the emission reduction of particular matter (PM) and nitrogen oxides (NOx). However, because of this trend the fuel consumption of heavy-duty long-haul vehicles has stayed about constant over the last years [1]. Next to that, the world wide trend of CO2 reduction has already resulted in CO2 emission legislations for heavy-duty vehicles in several parts of the world such as China, Japan, Canada and the USA and will shortly be introduced in Europe [2]. Both these trends are resulting in the shift of the main focus of heavy-duty powertrain design from PM and NOx emission reduction towards the emission reduction of CO2.

1.1 Fuel reduction trends

Multiple solutions are available to reduce the emissions of CO2 of vehicles, which is directly related to the reduction of fuel consumption, without compromising the current emission standards of NOx and PM. The most well known solution is the hybridization of the powertrain, which is already extensively researched for decades.

Another interesting and more recent solution is the electrification of auxiliary components, such as the power steering system and the air compressor. Several researchers have investigated the fuel saving potential of the auxiliary components. However, the numbers differ per study, which is while the consumption of the auxiliary components strongly depends on the driving conditions. For heavy-duty trucks the portion of fuel consumed by all the engine driven auxiliaries seems to be around $4-8\%$ (in literature: $4.7-7.3\%$ [3], $3.8-5.5\%$ [4], $5-8\%$ [5]). Studies on fuel consumption reduction of auxiliaries show that the main improvement with auxiliaries is gained by off-engine operation of the auxiliaries, and the use of smarter controls. This has shown possible fuel consumption improvements of 50% of the fuel consumed by the power steering system [4] and 90% (0.1345 L/100km) of the air compressor [6], or 75% (0.5L/100km) and 85% (0.76 L/100km) according to [7].

The next step would be to optimize the sizing of the auxiliary components. There is, however, only a very small portion of research focusing on this. A study on using different topologies and sizing of the power steering system showed a reduction of 80% in the fuel consumed by the power steering system [8], compared to a 50 % reduction [4] by only using off-engine operation and control improvements. When combining the optimization of the power steering and air compressor an improvement of 84% (0.3 L/100km) was achieved in [6]. This shows the extra fuel saving potential of optimal sizing of the auxiliary components.

A third solution is the use of a waste heat recovery (WHR) system in the form of a Rankine cycle. According to some, WHR will play a key role in future efficiency improvement of heavy-duty engines [9]. The use of a waste heat recovery system on a conventional heavy-duty truck has shown a fuel consumption reduction of 3.5% [10].

All of these solutions have been investigated seperately from each other. Combining these three solutions has only be done in rare cases, where mainly electrified auxiliaries were combined with a hybrid vehicle powertrain [6, 11, 12]. To the understanding of the writer no research has focused on combining all three solutions together. Therefore, in this work, the aim is to investigate the combination of the technologies integrated in a hybrid powertrain and ultimately its effects on the design optimization of the system. This research falls within the framework of the EU project: ECOCHAMPS.

1.2 Project ECOCHAMPS

Project ECOCHAMPS is an international consortium started by multiple OEMs and Suppliers and aims at the development of modular powertrains which have a reduced powertrain efficiency of 20%, compared to state of the art vehicles [13]. Next to that, the project aims at standardization and modularization of hybrid components and electrified auxiliaries by proposing a modular pre-standard for these components. This pre-standard is called the 'Modular System and Standardization Framework' (MSF). To achieve both goals collaboration over multiples vehicle segments is used. In order to evaluate the designed standardization framework, five demonstrator vehicles are build; including two cars, a light commercial vehicle, a bus and a heavy-duty long-haul truck. The research described in this work focuses on the heavy-duty truck demonstrator.

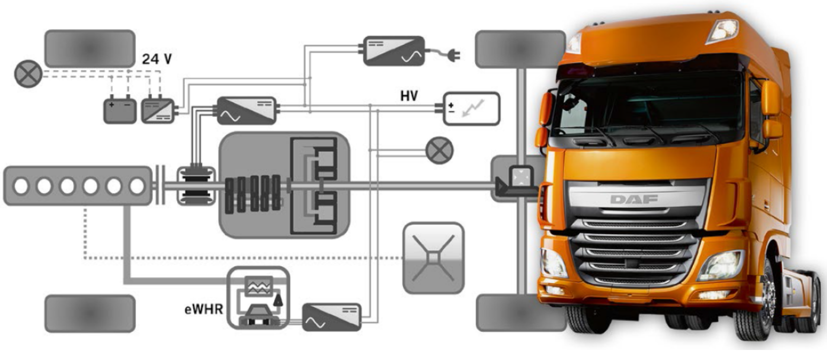

Figure 1: Powertrain topology of the parallel plug-in hybrid electric heavy-duty long-haul truck build within the ECOCHAMPS project [13]. (Source: ECOCHAMPS Consortium)

1.3 ECOCHAMPS demonstrator

The layout of the powertrain of the heavy-duty truck demonstrator vehicle is shown in Figure 1. The vehicle is a parallel plug-in hybrid electric (PHEV) heavy-duty long-haul truck. The trucks auxiliary units (e.g., the power steering and air compressor) are electrified, so the vehicle is equipped with an electro-hydraulic power steering (EHPS) system and an electric air compressor (EAC). Next to that, the vehicle is fitted with an electric waste heat recovery (eWHR) system. This eWHR system is connected to the high voltage circuit of the vehicle. This heavy-duty demonstrator vehicle makes use of all three solutions mentioned before; a hybridized powertrain, electrified auxiliaries and the use of a WHR system.

1.4 Design analysis

Next to building the actual vehicle, the design of this vehicle will be analyzed. This in order to evaluate the performance of the current designed vehicle, to quantify the remaining fuel saving potential of the vehicle, and to investigate what are interesting directions for future research. In order to evaluate the design of a vehicle, a design analysis has to be performed. In a design analysis the current design of the vehicle is compared to the optimal design of the vehicle, where the controls and sizing of the vehicle components are optimized. The process of finding the optimal design of the vehicle is often referred to as a design optimization. The complexity of the powertrain, especially for hybrid electric vehicles, requires an integrated design analysis, where all components need to be taken into account. To perform an integrated design analysis, models of all the vehicle components are required which scale the performance of the component with the size of the component. These type of models are called design analysis models. These type of models are already available for the components that are part of the main powertrain of the vehicle [14]. Examples are the the internal combustion engine, electric machine and gearbox. However, these type of models seem not be available yet for the auxiliaries and for the WHR system.

The aim is to create design analysis models with as minimal scaling variables as possible. This, in order to keep the design space, which is evaluated with a design analysis, as small as possible. The reason for keeping the design space as small as possible is the computational effort of the design analysis. At the same time the goal is to compromise the accuracy of the models as little as possible. So there is a clear trade-off between the accuracy and the computational efficiency of the model.

1.5 Paper outline

In this paper, a review is done in literature on models of two heavy-duty auxiliary components: the power steering and air compressor. These two auxiliaries are chosen, while these belong to the group of auxiliaries that consume the most fuel [4, 15]. The main goal is to evaluate whether already design analysis models are available for these components. Here the most important characteristic to look at is the trade-off between model accuracy and computational efficiency of the model. In the next sections of this paper, first the literature focusing on modeling of electro-hydraulic power steering systems and electric air compressors for heavy-duty applications will be discussed. The models available will be discussed on their applicability for a design analysis of the powertrain of the ECOCHAMPS demonstrator. This will be followed by a discussion of interesting topics for future research.

2 Electrified auxiliary modeling

In the model review of the power steering and air compressor we will focus on the type of systems build on the ECOCHAMPS demonstrator, hence, on modeling of an electro-hydraulic power steering system and an electric air compressor. Several papers have discussed the modeling of EHPS and EAC systems for heavy-duty applications. In order to evaluate the models already present, they are put together in one table for each system. In both tables the papers are grouped in the same way, based on two criteria; on one hand on the type of model used and on the other hand the main purpose of the research paper. The type of models are divided into three main types:

1. *Empirical:* Empirical models are completely based on measurement data and do not use physical relation based equations. Examples of empirical models are lookup-maps, duty cycles or quadratic fits of experimental data. Empirical models are good for a specific type and size of system, however do not scale with the size of the component.

2. *Semi-empirical:* These type of models are a combination of empirical and physical models. The equations of this type of model are based on physical relations, like the physical models. However, the parameters of these models are obtained from experimental data or are tuned in order to fit the model output to experimental data.

3. *Physical:* Physical models are constructed based on physical relations. The parameters of these type of models are obtained from data sheets and are parameters like geometrical measurements of components. While physical models are based on physical relationships, the scale the model more accurately with the size of the component.

The division in vertical direction of the table is based on the main goal of the paper. The papers discussing the modeling of EHPS and EAC systems for heavy-duty applications can be divided into four groups:

1. *Performance modeling:* The main goal of these papers is the performance modeling of the system, like modeling the power consumption of the system. The model created in the paper might be used for several purposes, but the main focus of the paper itself is creating the model.
2. *Energy consumption evaluation:* These papers focus on the evaluation of the energy or fuel consumed by the system. Most of these paper investigate the portion of fuel consumed by the vehicle that is caused by the EHPS and/or EAC system.
3. *Design optimization:* The main goal of these papers is a design optimization of the system. This could either be the sizing or hardware design of the system, or the control optimization of the system.
4. *Dynamic performance modeling:* These papers focus on the modeling of the dynamic performance of either the system itself or the complete vehicle, such as handling, steering feel or brake performance. These models do not model the energy or power consumption of the system.

2.1 Power steering

The electro-hydraulic power steering of the ECOCHAMPS demonstrator vehicle functions in the same way as a conventional hydraulic power steering system, where with hydraulic power the steering effort of the driver is assisted. However, in the case of an EHPS system the hydraulic pump of the system is not driven by the drive belt of the engine of the vehicle, but rather by an electric machine connected to the electric circuit of the vehicle. This enables 'on-demand' operation of the power steering in stead of being constantly driven by the engine, which causes high parasitic losses. There still has to be a minimal stand-by flow, however, this is lower as in the case of a belt driven power steering system [6]. A graphical representation of the layout of components of the EHPS system as connected blocks is shown in Figure 2.

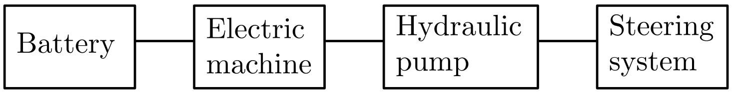

Figure 2: Block diagram representation of the electro-hydraulic power steering (EHPS) system.

Several papers have discussed the modeling of an EHPS system. In Table 1, an overview is given of the modeling methods, classified in the previous section, used for modeling of EHPS systems for heavy-duty applications. In this table a distinction is made whether the vehicle was a truck (T) or a bus (B).

Table 1: Overview of papers that discuss modeling of an electro-hydraulic power steering (EHPS) system for heavy-duty vehicles. The specific application is mentioned with the abbreviations: (T) for a heavy-duty truck and (B) for a bus. The papers are divided by the type of model used and the main objective of the paper.

Electro-Hydraulic Power Steering Literature

	Model type					
Paper Objective	Empirical		Semi-empirical		Physical	
Performance modeling	Kshirsagar2015[16]	T			Yu2015[17], Zhuan2015[18]	T B
Energy consumption evaluation	Pettersson2004[15], Andersson2004[11], Kluger2007[19], Silvas2013 [4]	T B T T	Pretsch2012 [7]	T	Morton2014[20], Zhuan2016[21]	T B
Design optimization	Nguyen2014 [22]	T	Silvas2014[8]	T		
Dynamic performance modeling					Nimbarte2013[23]	T

From Table 1 can be observed that most models used are empirical or physical type of models. Empirical models are computational efficient and are a realistic representation of the performance of the power steering. However, they are only suitable for the current sizes of components, not for a scaled version of the EHPS system. The problem with the physical type of models is the large number of parameters, which if being used in a design analysis results in a very large design space. Therefore, models to be used in a design analysis should be somewhere in the middle of these two types of models. The only paper found that clearly seem to have a model with minimal model parameters to scale the performance of the EHPS system is the model presented in [24]. In this paper an optimization is performed where all components of the EHPS were made scalable with size, except for the hydraulic pump. This would be a point of improvement for the model. Also in [7] a model usable for design analysis purposes is made for the hydraulic pump. This model could be an addition to the model in [24]. It is however unclear how the models of the other parts of the EHPS look like in this study. Whether they scale with only a minimal amount of parameters.

What is also visible in the table, is that the main focus of research is on energy or fuel consumed by the EHPS system. Which points in the direction that mainly feasibility studies are performed. Only two papers found actually optimize the system and go beyond a simple feasibility study. As the trend of auxiliary component electrification for heavy-duty vehicles is coming to the stage of being applied on a larger scale on vehicles, more thorough studies will need to be performed. Hence, in the near future more design analysis types of studies will be required. As there are only a rather limited amount of power steering models available that are suitable for design analysis studies, modeling of the power steering system in the near future should focus more on design analysis type of models. An additional benefit of these type of models is that creating a model of a different size of component will be faster.

2.2 Air compressor

The air compressor on the vehicle delivers compressed air, which is stored in vessels that are used as a buffer. The compressed air is used by several air consumers. The main air consumers are the brakes, the clutch, and the gearbox [6]. However, there are more systems that may consume air, such as the engine after-treatment system (EAS) for Adblue injection, the turbo waste gate or the suspension. In the conventional case the air compressor is driven by the drive belt of the engine. However, in the case of an electric air compressor system, the compressor is driven by an electric machine, as can be seen in Figure 3. This decoupling from the engine drive belt eliminates the drag losses that are present in the conventional system when no pressurized air is needed.

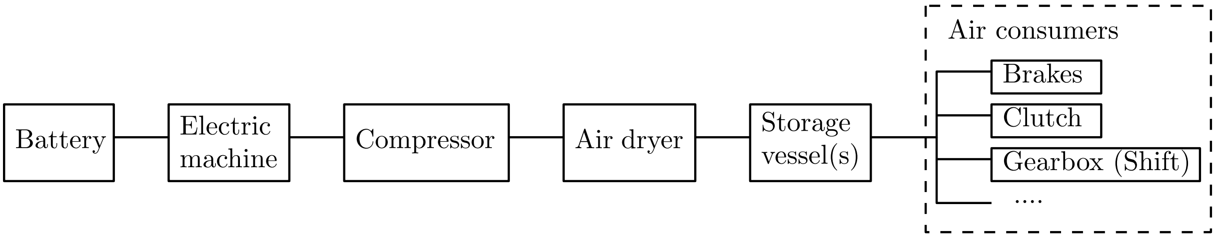

Figure 3: Block diagram representation of the electric air compressor (EAC) system including the consumers of compressed air.

In Table 2 an overview can be found on modeling of the electric air compressor and/or the consumers of the pressurized air system of heavy-duty vehicles. In this table the distinction is made between modeling for a truck (T) or bus (B). However, also whether an electric air compressor is modeled or a conventional belt driven (BD) air compressor. Part of the papers do not focus on modeling the air compressor, but rather on the air consumers, such as the brakes (Br), the suspension (S) or pneumatic shifting (Sh). Papers that do not contain a compressor model are indicated with a line under the name.

A few interesting things are visible in Table 2. First of all, only empirical and semi-empirical models are used for modeling the air compressor, no physical models. There are no models available that scale with the size of the compressor. The main reason for this is most likely that in most studies the focus of modeling of the air compressor is on energy consumption evaluation of a specific air compressor system, which does not require scalable models of the air compressor. The papers that do focus on design optimization, where [6] goes the most into detail regarding scaling of components, do not consider scaling of the air compressor. Therefore, in order to do a full design analysis of the air compressor system, scalable design analysis models of air compressor will need to be developed.

The physical type of models that are mentioned in Table 2 are only used for modeling of the air consumers of the system, which is mainly focused on the brakes, and not on the pneumatic shifting and clutching. A possible reason might be related to the fact that the modeling of the air consumers is predominantly focused on the modeling or optimization of the dynamic performance of the air supply system and/or

Table 2: Overview of research papers on an electric air compressor for heavy-duty vehicles. The specific application is mentioned with the abbreviation (T) for a truck and (B) for a Bus. Abbreviations after the comma refer to: (BD), when not an electric but a (conventional) belt driven air compressor is used. When not the compressor is modeled but the air consumers of the system, a line under the name of the author is used together with the abbreviation: (Br) for brake system modeling, (S), for suspension modeling, and (Sh), for pneumatic shifting mechanism modeling. The papers are divided by the type of model used and the main objective of the paper.

Electric Air Compressor Literature

Paper Objective	**Model type**					
	Empirical		Semi-empirical		Physical	
Performance modeling	Hendricks2002[5], Emirler2015[25]	T,BD T,BD	Moshchuk2011[26]	T,BD,S		
Energy consumption evaluation	Conklin1999[27], Andersson2004[11], Petterson2004[15], Kluger2007[19], Lycke2013[28], Kshirsagar2015[16]	T B T,BD T T,BD T	Pretsch2012[7], Nguyen2014[29]	T T	Atanasov2016[30]	T,S
Design optimization	Tretsiak2016[12], Silvas2015[6]	B T,BD	Nguyen2014[22]	T	Schonning2007[31], Wu2009[32], Patil2015[33]	T,Sh T,Br T/B,Br
Dynamic performance modeling			Subramanian2004[34], Karthikeyan2010[35], He2011[36],	T,Br T,Br T/B,Br	Suh2000[37], Wang2004[38], Chen2015[39], Yi2015[40]	T,Br T,Br T,S B,Br

vehicle. Measuring the dynamic performance or behavior, especially in multiple points in the system of air consumers is way more difficult, and therefore most likely the choice is made for the physical type of models in this case.

Next to that, modeling of the air consumed by the air consumers is only mentioned in one paper for the brakes [7], and for all air consumers in [11]. However, this last one discusses modeling for a bus and not a truck. So there seems to be minimal interest in modeling the air supply system performance based on the air consumption of the air consumer in a heavy-duty vehicle. This is however an important part, as the air consumed by the brakes, clutching and shifting depends on the gear choice, shifting moments and use of the electric machine of the main powertrain. These are the main control variables that are optimized during a design optimization. They will influence the performance of the air supply system, and thereby the electric energy consumed by the auxiliaries, which again influences the optimal solution of the control variables. Therefore, in future research design analysis models of the air consumers should be developed, in order to properly integrate the air supply system in the design optimization of the complete vehicle. The only work that is closest to a model usable for a design optimization can be found in [6]. However, improvements should be made on a scalable compressor model and modeling of the air consumed by the air consumer based on the control variables of the main powertrain.

3 Future research

The goal of future research should to integrate all components into the design optimization of the vehicle. In this way all interactions between components should be taken into account, resulting in more realistic optimal design results. For some components the possible improvement in energy consumed will be small. However, it should be taken into account that most components are interconnected with each other, and thereby can influence the optimization of other components. For example an air conditioning unit in hot conditions in stop and go traffic can draw a significant amount of power from the electric circuit or engine, which will have an influence on the optimal control trajectory of the auxiliary components and/or the main powertrain. Therefore, it is important to create design analysis models of all vehicle components and to integrate them in the design optimization of vehicles.

3.1 Integration of other auxiliaries

The first next step would be to create design analysis models of the other auxiliaries and to integrate them in the design optimization of the vehicle as well. Starting with the air conditioning system, which also belongs to the group of main consumers of the auxiliary units. Multiple research has already focused on modeling of the air conditioning system [11, 6, 41]. However, the main components of these models cannot easily scale the performance of the air conditioning with the size of the components. Ideally for the design analysis of the auxiliary system a simplified, but still sufficient accurate, model of the air conditioning that scales with only one sizing parameter is wanted. To investigate whether this is possible and whether this has already been done, research effort should be put into this.

Sizing of the alternator could also be an interesting topic. This is easily done, as it is an electric machine that can be modeled in exactly the same way as the electric machine which is part of the main powertrain. Though, this is only relevant in the case of conventional vehicles, as an HEV can use the electric machine of the main powertrain to generate electricity for the auxiliary circuit or use the battery. The ultimate goal with auxiliary system optimization is to do similar work as in [6], a combined optimization of the power steering and air compressor, to expand this with other auxiliaries and to combine it with the optimization of the components of the main powertrain of the vehicle.

3.2 Waste heat recovery system modeling

Next to integrating all auxiliary components into the design optimization, also integrating the waste heat recovery system in the design optimization is a very interesting topic. WHR is interesting to look into as the energy produced by this system can be used for multiple purposes; to power the auxiliaries, drive the electric machine or charge the battery. This creates more flexibility in the energy flows in the vehicle. The WHR system is highly integrated with the internal combustion engine and therefore needs to be integrated in the optimization process together with the engine. The most interesting part to research with the WHR system is to investigate what the influence of this system is on the design optimization of the vehicle. Whether the optimal design is drastically different when a WHR system is used. Especially what the interaction is between a WHR system and engine. Whether maybe a slightly less efficient engine work point combined with a WHR system will results in higher combined efficiency of the WHR system and the engine.

3.3 Thermal system modeling

Another interesting topic for research would be to integrate the thermal system of the vehicle in the optimization process, in a similar way as the main powertrain and the auxiliary network. A result of this could be that in the future also the design of the cooling system of the vehicle could be optimized together with both the main powertrain and the electric network of the vehicle.

4 Conclusion

In this paper, the modeling of two electrified auxiliary components was discussed; the power steering system and the air compressor. The goal was to give an overview of models currently used in literature, and to evaluate whether they are suitable to be used in an integrated design optimization of heavy-duty vehicles. The review of literature of both systems showed the rather minimal availability of design analysis models of auxiliary components, which can scale the performance of the auxiliary component with the size of the auxiliary components. Most of the papers focus on the evaluation of the energy consumed by both systems, which only requires empirical type of models. For the electro-hydraulic power steering system there were only two papers that described models, which combined together, are suitable to be used as design analysis model. The review of models for air compressors showed the lack of scalable compressor models and models for the air consumers of the air supply system. This should be a topic for future research.

Other future research should be focusing on integrating all vehicle components in the design optimization of the vehicle, by creating design analysis models of all the components of the vehicle. First starting with integrating all the auxiliary components, such as the air conditioning. The most interesting component to integrate in the optimization process is the waste heat recovery system. In the further future it would be interesting to extend the domains of the components modeled from the mechanical and electrical domain to the thermal domain, and towards integrating components such as the cooling system of the vehicle as well.

Acknowledgments

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References

[1] E. Feru, *Auto-calibration for Efficient Diesel Engines with a Waste Heat Recovery System.* Ph.d. dissertation, Eindhoven University of Technology, Eindhoven, The Netherlands.

[2] R. Smokers, "CO2 legislation and real-time emission monitoring for future HD powertrains," in *Mini-symposium: An Industrial View on Future Heavy-duty Powertrain Control*, 2017.

[3] N. Pettersson and K. Johansson, "Modelling and control of auxiliary loads in heavy vehicles," *International Journal of Control*, vol. 79, no. 5, pp. 479–495, 2006.

[4] E. Silvas, O. Turan, T. Hofman, and M. Steinbuch, "Modeling for control and optimal design of a power steering pump and an air conditioning compressor used in heavy duty trucks," in *Proceedings of the IEEE Vehicle Power Propulsion Conference*, pp. 218–223, 2013.

[5] T. Hendricks and M. O'Keefe, "Heavy vehicle auxiliary load electrification for the essential power system program: Benefits, tradeoffs, and remaining challenges," *SAE technical Paper*, no. 2002-01-3135, 2002.

[6] E. Silvas, *Integrated Optimal Design for Hybrid Electric Vehicles.* Ph.d. dissertation, University of Technology Eindhoven, Eindhoven, The Netherlands, 2015.

[7] S. Pretsch and M. Winter, "Electrification of a commercial vehicle's auxiliaries: A chance of reducing fuel consumption and CO2 emissions.," in *12th International Symposium on Heavy Vehicle Transport Techonology*, 2012.

[8] E. Silvas, E. Backx, T. Hofman, H. Voets, and M. Steinbuch, "Design of power steering systems for heavy-duty long-haul vehicles," in *IFAC Proceedings Volumes*, vol. 47, pp. 3930–3935, 2014.

[9] M. Allain, D. Atherton, I. Gruden, S. Singh, and K. Sisken, "Daimler's Super Truck Program ; 50 % Brake Thermal Efficiency 2012 Directions in Engine-Efficiency and Emissions," in *2012 Directions in Engine-Efficiency and Emissions Research (DEER) Conference*, 2012.

[10] E. Feru, N. Murgovski, B. de Jager, and F. Willems, "Supervisory control of a heavy-duty diesel engine with an electrified waste heat recovery system," *Control Engineering Practice*, vol. 54, pp. 190–201, 2016.

[11] C. Andersson, *On auxiliary systems in commercial vehicles.* Ph.d. dissertation, Lund University, Lund, Sweden, 2004.

[12] D. Tretsiak, T. Haberlein, and B. Baker, "Energy Efficient Control of the Air Compressor in a Serial Hybrid Bus based on Smart Data," *IFAC-PapersOnLine*, vol. 49, no. 11, pp. 385–392, 2016.

[13] R. Hummel, L. Haussler, and L. Eckstein, "Research Project Ecochamps," *MTZ*, vol. 77, pp. 1–8, 2016.

[14] L. Guzzella and A. Sciarretta, *Vehicle Propulsion Systems: Introduction to Modeling and Optimization.* Springer-Verlag Berlin Heidelberg, 3th ed., 2013.

[15] N. Pettersson, *Modelling and Control of Auxiliary Load in Heavy Vehicles.* Ph.d. dissertation, Royal Institute of Technology, Stockholm, Sweden, 2004.

[16] C. Kshirsagar, "System Level Modeling and Optimization of Fuel Cell Powered Auxiliary Power Unit (APU) to be used in Commercial Vehicles," *SAE Technical Paper*, no. 2015-26-0116, 2015.

[17] L. Yu, W. Xuan, J. Song, X. Zhu, and S. Cheng, "A New Type of Electro-Hydraulic Power Steering System for Heavy-Duty Commercial Vehicles," *SAE Technical Paper*, no. 2015-01-1502, 2015.

[18] Y. Zhuan, L. Renhe, and L. Qiongqiong, "Motor Control Strategy of Recirculating-Ball EHPS System for Bus Under Multi Working Conditions," *International Journal of Simulation Systems, Science and Technology*, vol. 16, pp. 2–9, 2015.

[19] M. Kluger and J. Harris, "Fuel Economy Benefits of Electric and Hydraulic Off Engine Accessories," *SAE Technical Paper*, no. 2007-01-0268, 2007.

[20] C. Morton, C. M. Spargo, and V. Pickert, "Electrified hydraulic power steering system in hybrid electric heavy trucks," *IET Electrical Systems in Transportation*, vol. 4, no. 3, pp. 70–77, 2014.

[21] Y. Zhuan and H. Ren, "Energy Conservation Mechanism of the EHPS in Pure Electric Bus," *Metallurgical and Mining Industry*, no. 1, pp. 102–108.

[22] K. D. Nguyen, E. Bideaux, M. T. Pham, and P. le Brusq, "Game theoretic approach for electrified auxiliary management in high voltage network of HEV/PHEV," in *Proceedings of the IEEE International Electric Vehicle Conference*, 2014.

[23] M. R. Nimbarte and L. P. Raut, "Efficiency Analysis of Hydraulic Power Steering System," *International Journal of Engineering Research and Applications*, vol. 3, no. 3, pp. 1230–1235, 2013.

[24] E. Silvas, E. Backx, H. Voets, T. Hofman, and M. Steinbuch, "Topology Design and Size Optimization of Auxiliary Units : a Case Study for Steering Systems," in *FISITA World Automotive Congress*, pp. 1–7, 2014.

[25] M. T. Emirler, I. M. C. Uygan, K. Koprubasi, B. Unver, B. A. Gyvenc, and L. Guvenc, "Modular Heavy Duty Vehicle Modelling and User Interface Development," *IFAC-PapersOnLine*, vol. 48, no. 15, pp. 354–360, 2015.

[26] N. Moshchuk, Y. Li, and S. Opiteck, "Air Suspension System Model and Optimization," *SAE Technical Paper*, no. 2011-01-0067, 2011.

[27] R. Conklin and B. Hudgins, "Electronic Compressor and Air Dryer Control," *SAE Technical Paper*, no. 1999-01-3771, 1999.

[28] J. Lycke, *Simulation and Control of Auxiliary Devices in Heavy-Duty Vehicles*. M.s. thesis, Royal Institute of Technology, Stockholm, Sweden, 2013.

[29] K. D. Nguyen, E. Bideaux, M. T. Pham, and P. le Brusq, "Model Predictive Control Dedicated to an Electrified Auxiliary in HEV/PHEV," *Applied Mechanics and Materials*, vol. 532, pp. 50–57, feb 2014.

[30] N. Atanasov and E. Chenoweth, "Pneumatically Shifted Air Suspension Loading for Improved Fuel Economy Benefits," *SAE Technical Paper*, no. 2016-01-8031, 2016.

[31] J. Schonning and S. Zamani, *Modeling and Control of Opticruise -a Pneumatic Force Actuator*. M.s. thesis, Royal Institute of Technology, Stockholm, Sweden, 2007.

[32] J. Wu, H. Zhang, Y. Zhang, and L. Chen, "Robust design of a pneumatic brake system in commercial vehicles," *SAE International Journal of Commercial Vehicles*, vol. 2, no. 1, pp. 17–28, 2009.

[33] J. N. Patil and S. Palanivelu, "Mathematical Model to Evaluate and Optimize the Dynamic Performance of Pneumatic Brake System," *SAE Technical Paper*, no. 2015-26-0082, 2015.

[34] S. C. Subramanian, S. Darbha, and K. R. Rajagopal, "Modeling the Pneumatic Subsystem of an S-cam Air Brake System," *Journal of Dynamic Systems, Measurement, and Control*, vol. 126, no. 1, p. 36, 2004.

[35] P. Karthikeyan, C. Siva Chaitanya, S. Subramanian, and N. Jagga Raju, "Modelling an electropneumatic brake system for commercial vehicles," *IET Electrical Systems in Transportation*, vol. 1, no. 1, pp. 41–48, 2011.

[36] L. He, X. Wang, Y. Zhang, J. Wu, and L. Chen, "Modeling and Simulation Vehicle Air Brake System," in *8th Modelia Conference*, pp. 430–435, 2011.

[37] M. W. Suh, Y. K. Park, and S. J. Kwon, "A Simulation Program for the Braking Characteristics of Tractor-Semitrailer Vehicle," *SAE Technical Paper*, no. 2000-01-3415, 2000.

[38] X. Wang, Y. Hu, C. Li, and X. Wang, "Dynamic Characteristics Analysis of Brake System for Heavy-Duty Off-Highway Vehicle," *SAE Technical Paper*, no. 2004-01-2638, 2004.

[39] Y. Chen, M. Ahmadian, and A. Peterson, "Pneumatically Balanced Heavy Truck Air Suspensions for Improved Roll Stability," *SAE Technical Paper*, no. 2015-01-2749, 2015.

[40] L. Yi, X. Bowen, and G. Bin, "Dynamic Modeling and Experimental Verification of Bus Pneumatic Brake System," *The Open Mechanical Engineering Journal*, vol. 9, pp. 52–57, 2015.

[41] J. T. B. A. Kessels and P. P. J. van den Bosch, "Automotive air conditioning: Optimization, control and diagnosis," in *Q.Zhang, S.E. Li, & K. Deng (Eds.), Automotive Air Conditioning: Optimization, Control and Diagnosis*, pp. 13–28, 2016.

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