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A combination of electric supercharger and Miller Cycle in a gasoline engine to improve thermal efficiency without performance degradation

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ABSTRACT

Miller cycle makes the expansion ratio larger than effective compression ratio by early or late closing intake valves thereby improving the thermal efficiency of gasoline engines at the risk of power degradation. Electric supercharging efficiently improves transient response and output of engines. This paper proposes an electrically supercharged non-backflow Miller cycle by combining electric supercharging and Miller cycle to improve thermal efficiency of gasoline engines without power output reduction. The results indicate that electrically supercharged non-backflow Miller cycle can effectively improve the thermal efficiency of gasoline engines. Compared to the original Otto-cycle gasoline engine, the electrically supercharged Miller-cycle engine has the highest thermal efficiency of 35.54% which is an improvement of 4.32% at 3500 rpm full load operation. The electric supercharger ensures that the power output is not reduced. Therefore, electrically supercharged non-backflow Miller cycle is an effective method to improve thermal efficiency of gasoline engines without performance degradation.

1. Introduction

Improving thermal efficiency has always been an important goal in the development of gasoline engines. Miller cycle proposed by Miller [1] in 1947 is an efficient method to improve thermal efficiency of gasoline engines. In the traditional Otto cycle, the intake valves close at the bottom dead center (BDC), while in the Miller cycle, the intake valves closing (IVC) is advanced to ahead of the BDC making the expansion ratio larger than the compression ratio (CR) which reduces the compression work due to the advancement of intake valve closing, thereby improving the thermal efficiency [2–9]. Endo [10] described the design of a commercially available large scale (280–1100 kW) gas engine working on the Miller cycle and claiming an advantage of more than 5% over conventional technologies in terms of fuel efficiency. A Miller engine with variable compression ratio proved to be much more efficient than the Otto engine for most of the working range, and compared with the Diesel engine, improvements in specific fuel consumption could be noted for most of the operations [11]. Li [12] experimentally compared the effects of early intake valve closing (EIVC) and late intake valve closing (LIVC) on the fuel economy of a boosted direct injection gasoline production engine reformed with a geometric compression ratio of 12.0 at low and high loads and discussed the mechanism behind the effects of LIVC and EIVC on improving the fuel economy. The results showed that the EIVC strategy results in the smallest absolute pumping mean effective pressure and the

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lowest rate of heat release while LIVC leads to a higher pressure during the compression stroke. An investigation on the practical range of the EIVC variable valve actuation strategy showed a 7% improvement in fuel for un-throttled engine operation [13]. A detailed assessment of the main losses carried out by Martins indicated that Diesel-like engine brake efficiency of more than 40% could be achieved when applying the Miller cycle concept [14].

When the intake valve closes before BDC, the mass in the cylinder expands with the descent of piston and the in-cylinder temperature decreases. It can be seen from the knock model proposed by Douaund & Eyzat [15] that temperature plays a significant role in the occurrence of knock and hence, Miller cycle has better anti-knock properties than Otto cycle [16,17]. A study conducted by Wan [18] showed that combining over-expanded cycle with high geometry CR, LIVC can optimize combustion phasing and reduce knock tendency of gasoline engines. The decrease of in-cylinder temperature can restrain the formation of NOx. Wang [19] carried out a study on the application of the Miller cycle to reduce NOx emissions from a petrol engine. The results showed that the lowest reduction rate of NOx emission is 46% with an engine power loss of 13% at full load compared with that of standard Otto cycle.

Miller cycle can improve thermal efficiency while insufficient availability of air that results from the intake valve control strategy results in power loss [9]. Hence, numerous studies have been conducted on the output degradation of Miller-cycle engines with boosting and have generated many interesting results [20,21]. The first mass-produced Miller-cycle engine with delayed closing timing of intake valve and an attached Lysholm Compressor which provided higher boost pressure was put on sale by Mazda [22], it was capable of avoiding engine knocking while high CR was maintained and had approximately 1.5 times larger torque than that generated by a naturally-aspirated engine of the same displacement.

Electric supercharging is a new boosting method that has attracted much attention. Imperial College, London developed an electrically assisted turbocharger consisting of a standard turbocharger modified to accommodate an electric motor/generator within the bearing housing to improve engine transient response and low-end torque by increasing the power delivered to the compressor [23]. The electrically assisted turbocharging system can make a tradeoff between power output and energy efficiency of an engine and also promote fuel economy by recycling exhaust energy [24,25]. Honeywell, Caterpillar and Mitsubishi Heavy Industries have conducted many studies on electric turbocharging and the results showed that an electric turbocharger can significantly improve the peak torque when compared with traditional turbocharged gasoline engines [26–29].

Given the potential of Miller cycle in improving the thermal efficiency of gasoline engines as well as the flexibility and ease of control of electric supercharger, this paper studies the feasibility of improving thermal efficiency while maintaining adequate power output in a 2.0 L gasoline engine by combining electric supercharging and Miller cycle. In this study, Miller cycle with EIVC which can avoid pumping loss resulted from backflow is applied. Electric supercharger does not work at low loads while the gasoline engine works in the naturally aspirated mode; at medium and high loads, the electric supercharger starts and compensates for insufficient air input to maintain adequate power output of the gasoline engine.

2. Methods and engine modeling

The basic engine is a 2.0 L Otto cycle gasoline engine and the experiment was carried out on an engine test bench. The main features of the engine are listed in Table 1. In the experiment, three PT100 sensors and three pressure sensors were mounted on the intake pipe to obtain the air temperature and pressure. A Type-K thermocouple and a pressure sensor were mounted on the exhaust pipe to get the temperature and pressure of exhaust gas. A KISTLER 4958748 contactless torque sensor was mounted on the transmission shaft to precisely measure the power output of the engine. A spark plug type pressure sensor was used to measure in-cylinder pressure. To ensure the accuracy of the measurement results, all values were measured in 200 cycles and averaged.

This paper studies the potential of electrically supercharged non-backflow Miller cycle to improve thermal efficiency of a gasoline engine based on GT-Power code, concurrent testing and simulation [30]. The actual engine was considered as an assembly of several subsystems, such as intake system, engine body, exhaust system, and so on. The physical models of the subsystems were established with corresponding modes provided by GT-power, and the computing models and the parameters were installed, Table 2 shows the main input parameters of the model. The E-charger is described by a standard map-based approach, while the flow behavior within the cylinder head and the intake and exhaust pipes is modelled by the flow coefficients experimentally measured by the engine manufacturer. The two zone Weibe model is adopted to calculate in-cylinder combustion and Douaud-Eyzat model is embedded to the combustion model to assess knock. For the computation of heat transfer, the most widely applied Woschni model is employed. And a specially developed friction model is employed to calculate friction loss. A prototype of the gasoline engine was built and the computational results were compared with test data for validation of the main parameters such as air intake per cycle, brake power, brake torque, and Brake Specific Fuel Consumption. A satisfactory agreement between the computed and measured values can be observed and the maximum deviation is under 3%.

Table 1
Main parameters of the original engine.

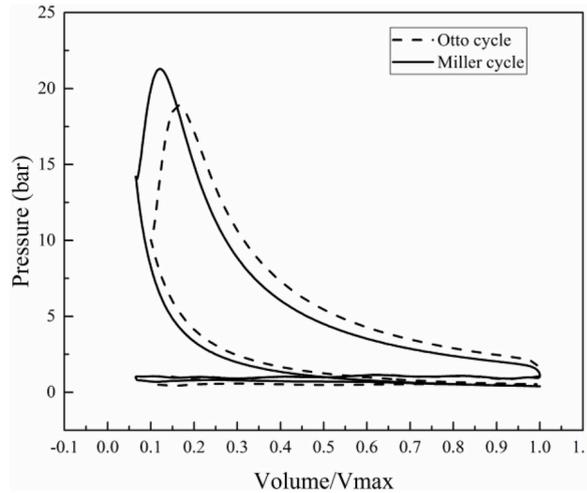| Type	Gasoline, 4 stroke, 4 cylinders in line
Bore/Stroke	86/86 mm
Displacement	2.0 L
Connecting rod length	142.8 mm
Compression ratio	10

Fig. 2. Pressure-volume diagram for original engine a Miller-cycle engine (n = 1500 rpm, BMEP = 3 bar).

3. Results and discussion

A decrease in the mass flow rate of intake air can be observed with the advancement of IVCs. There is a backflow in the original Otto cycle when IVC is 576 °CA and advancing the IVC could realize a non-backflow Miller cycle. The brake thermal efficiency of the gasoline engine increases remarkably with the advancement of IVC and this is a benefit of the application of non-backflow Miller cycle. It is clear that the maximum brake mean effective pressure (BMEP) decreases with the increasing engine speeds, the maximum BMEP is around 0.82 bar at the operation of IVC 450 at 5500 rpm as full load. The brake efficiency increases with the advance of IVC which mainly benefits from the application of larger geometric CR and Miller Cycle. The expansion stroke is larger than the compression stroke in Miller Cycle engines making burned gas to be adequately expanded in order to take full advantages of the released fuel energy, and then the brake efficiency is improved. Therefore, the improvement of thermal efficiency of the Miller-cycle gasoline engine is accompanied by power loss and hence, the application of Miller cycle is mainly limited to hybrid vehicles. Taking the brake efficiency, the maximum BMEP, and air flow into consideration, IVC 450 is determined as the research intake valve plan.

Fig. 2 presents the p-V diagrams of the original Otto-cycle engine and the non-back flow Miller-cycle engine at 1500 rpm 3 bar BMEP when the IVC of the Miller-cycle engine is 450 °CA. Compared to Otto cycle, the intake pressure of the Miller-cycle engine increases by 0.21 bar and the peak cylinder pressure increases from 18.89 bar to 21.29 bar. That is because the geometric CR is increased to 15.42 for keeping the effective CR constant in Miller cycle. The mass of intake air decreases from 16.17 mg/cycle to 14.60 mg/cycle with the advancement of IVC but this is not a significant decrease. Fig. 3 indicates that the peak cylinder pressure rises from 31.38 bar to 33.04 bar and the mean intake pressure rises by 0.58 bar when electrically supercharged Miller cycle is applied. The throttle percentage also reaches maximum at lower loads when compared with Otto cycle and this promotes the reduction of throttling loss. The pumping loss in Otto cycle is larger since the electrically supercharged Miller cycle improves the
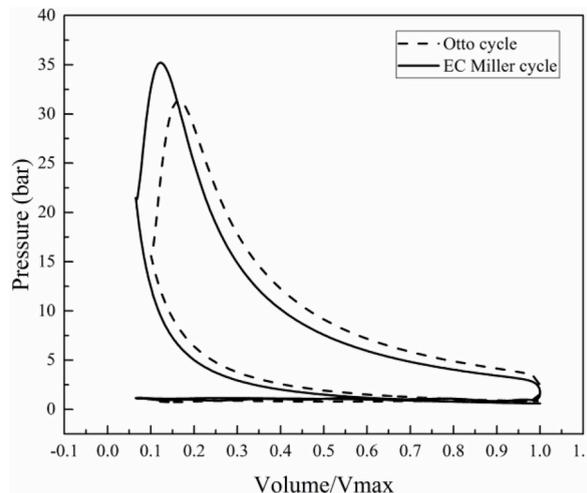

Fig. 3. Pressure-volume diagram for original engine and electrically supercharged engine (n = 1500 rpm, BMEP = 7 bar).
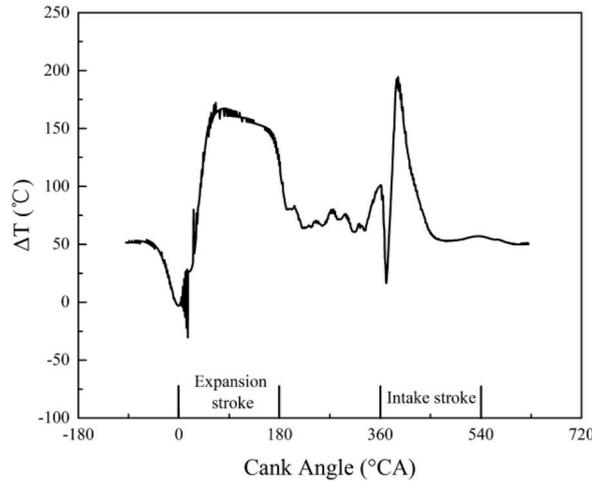
Fig. 4. Reduction of in-cylinder temperature (n = 1500 rpm, BMEP = 3 bar).

intake pressure. Although the pumping loss is still negative at low loads, the values are still more desirable than those for Otto-cycle engines.

Fig. 4 shows the reduction of in-cylinder temperature. ΔT is defined as $\Delta T = T_O - T_M$, where T_O and T_M are the cylinder temperatures of the Otto-cycle engine and the Miller-cycle engine, respectively. It is evident that the effect of Miller cycle on cylinder temperature is mainly observed during the expansion stroke and intake stroke. Here, less energy is released because of the decrease of the mass of injected fuel reducing the cylinder temperature and the temperature rise of the intake air also becomes lower. The decrement of the peak temperature is 60.79 °C in the Miller-cycle engine. The decrease in cylinder temperature is helpful for the suppression of knock as well as for the reduction of heat transfer loss, thereby increasing the thermal efficiency.

Fig. 5 and Fig. 6 show the thermal efficiencies of the original Otto-cycle engine and the electrically supercharged Miller-cycle engine, respectively, at all working conditions. Different levels of improvement in the thermal efficiency can be observed in the electrically supercharged Miller-cycle engine by comparing Figs. 5 and 6. The thermal efficiency of the electrically supercharged Miller-cycle engine achieves its peak of 35.54% at 3500 rpm full load operation, which is 4.32% more than the thermal efficiency of the Otto-cycle engine under the same conditions. The maximum increment in the thermal efficiency of the electrically supercharged Miller-cycle engine is 5.44% which is improved from 20.20% to 25.64% at 3500 rpm 2 bar BMEP. The working range of the electric supercharger expands with increasing engine speed. The speed of the electric supercharger ranges from 45000 rpm to 145000 rpm. BMEP values ranging from 0 to 7 bar give high thermal efficiencies the efficiency decreases with increasing engine speed since the electric supercharger compensates for the intake air loss due to EIVC, an electrically supercharged Miller cycle can ensure adequate power output while improving the thermal efficiency of the gasoline engine.

4. Conclusions

The objective of this paper is to study the potential of electrically supercharged Miller cycle to improve thermal efficiency of gasoline engines without power loss. Miller cycle was achieved by advancing intake valve closing, and an electric supercharger was
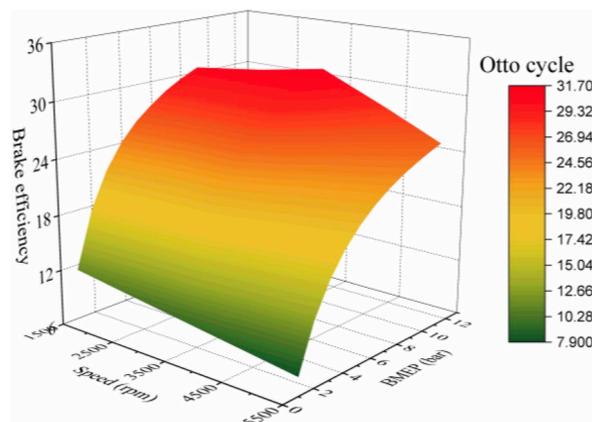

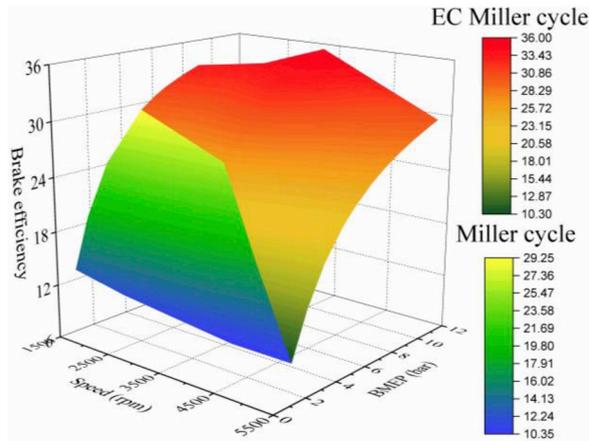**Fig. 5.** Brake efficiency of the original engine at all operations.

Fig. 6. Brake efficiency of E-charged Miller-cycle engine at all operations.

applied to compensate for the intake air loss. Electric supercharger was not activated at low loads when gasoline engine works in naturally aspirated mode; at high loads, the electric supercharger starts and compensates for the intake air loss that results from EIVC.

The study is based on a 2.0 L gasoline engine in which the IVC was advanced to 450°CA and geometric CR was increased to 15.42 to keep effective CR at 9.38. Compared to the original Otto-cycle engine, the compression work and pumping loss decreased because of the application of electrically supercharged non-backflow Miller cycle and the throttle percentage achieved maximum at lower loads reducing the throttling loss. The thermal efficiency of the gasoline engine was improved a peak value of 35.54% is obtained, which is an improvement of 4.32% at 3500 rpm full load compared with Otto cycle and the largest improvement is 5.44% improved from 20.20% to 25.64% at 3500 rpm 2 bar BMEP. Owing to the electric supercharger, the power output of the gasoline engine did not deteriorate with the advancement of IVC. The cylinder temperature decreased with the application of non-backflow Miller cycle and this helped to suppress knock and reduce heat transfer loss.

As mentioned above, an electrically supercharged Miller cycle can ensure adequate power output while improving the thermal efficiency of the gasoline engines. Therefore, the combination of electric supercharger and non-backflow Miller cycle is an effective path to improve the thermal efficiency of gasoline engines without power loss.

Author contributions

Bin Chen, Li Zhang and Jinlin Han conceived, designed and performed the experiment and the simulations; and Qing Zhang helped to execute some experiments.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

References

[1] R.H. Miller, Supercharging and internal cooling cycle for high output, Trans ASME 69 (1947) 453–457.
[2] K. Okamoto, F.R. Zhang, S. Shimogata, F. Shoji, H. Kanesaka, H. Sakai, Study of a Miller cycle gasoline engine for Cogeneration systems effect of a Miller cycle on the performance of a gas engine, SAE Spec. Publ. (1996), https://doi.org/10.4271/960949.
[3] D. Clarke, W.J. Smith, Implementation and analysis of the miller cycle using an inlet control rotary valve, variable valve actuation and power boost, SAE Spec. Publ. (1997), https://doi.org/10.4271/970336.
[4] S. Shimogata, R. Homma, F.R. Zhang, K. Okamoto, F. Shoji, Study on Miller cycle gas engine for cogeneration systems numerical analysis for improvement of efficiency and power, SAE Spec. Publ. (1997), https://doi.org/10.4271/971709.
[5] H. Stebler, G. Weisser, H. U Horler, K. Boulouchos, Reduction of NOx emissions of D.I. diesel engines by application of the Miller system: an experimental and numerical investigation, SAE Spec. Publ. (1996), https://doi.org/10.4271/960844.
[6] S.S. Hou, Comparison of performances of air standard Atkinson and Otto cycles with heat transfer considerations, Energy Convers. Manag. 48 (2007) 1683–1690 https://doi.org/10.1016/j.enconman.2006.11.001.
[7] J.C. Lin, S.S. Hou, Performance analysis of an air-standard Miller cycle with considerations of heat loss as a percentage of fuel's energy, friction and variable specific heats of working fluid, Int. J. Therm. Sci. 47 (2008) 182–191 https://doi.org/10.1016/j.ijthermalsci.2007.02.002.
[8] J.A. Caton, The thermodynamic characteristics of high efficiency, internal-combustion engines, Energy Convers. Manag. 58 (2012) 84–93 https://doi.org/10.1016/j.enconman.2012.01.005.
[9] R. Mikalsen, Y.D. Wang, A.P. Roskilly, A comparison of Miller and Otto cycle natural gas engines for small scale CHP applications, Appl. Energy 86 (2009) 922–927 https://doi.org/10.1016/j.apenergy.2008.09.021.

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[10] H. Endo, K. Tanaka, Y. Kakuhama, Y. Goda, T. Fujiwaka, Development of the lean burn Miller cycle gas engine, 5th International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines, Nagoya, 2001.

[11] B. Ribeiro, J. Martins, Direct comparison of an engine working under Otto, miller and diesel cycles: thermodynamic analysis and real engine performance, Fr. Hist. 23 (2007) 360–382 https://doi.org/10.4271/2007-01-0261.

[12] T. Li, Y. Gao, J. Wang, Z. Chen, The Miller cycle effects on improvement of fuel economy in a highly boosted, high compression ratio, direct-injection gasoline engine: EIVC vs. LIVC, Energy Convers. Manag. 79 (2014) 59–65 https://doi.org/10.1016/j.enconman.2013.12.022.

[13] D. Cleary, G. Silvas, Unthrottled Engine Operation with Variable Intake Valve Lift, Duration, and Timing, SAE World Congress & Exhibition, 2007, https://doi.org/10.4271/2007-01-1282.

[14] M.E.S. Martins, T.D.M. Lanzanova, Full-load Miller cycle with ethanol and EGR: potential benefits and challenges, Appl. Therm. Eng. 90 (2015) 274–285 https://doi.org/10.1016/j.applthermaleng.2015.06.086.

[15] A.M. Douaud, P. Eyzat, Four-octane-number method for predicting the anti-knock behavior of fuels and engines, SAE Spec. Publ. (1978), https://doi.org/10.4271/780080.

[16] C. Wu, P.V. Puzinauskas, J.S. Tsai, Performance analysis and optimization of a supercharged Miller cycle Otto engine, Appl. Therm. Eng. 23 (2003) 511–521 https://doi.org/10.1016/s1359-4311(02)00239-9.

[17] W. Gottschalk, U. Lezius, L. Mathusall, Investigations on the potential of a variable miller cycle for SI knock control, Clin. Chem. 2 (2013) 1535–1539 https://doi.org/10.4271/2013-01-1122.

[18] Y. Wan, A. Du, Reducing Part Load pumping loss and improving thermal efficiency through high compression ratio over-expanded cycle, SAE Technical Papers (2013), https://doi.org/10.4271/2013-01-1744.

[19] Y. Wang, L. Lin, S. Zeng, J. Huang, A.P. Roskilly, Y. He, X. Huang, S. Li, Application of the Miller cycle to reduce NOx emissions from petrol engines, Appl. Energy 85 (2008) 463–474 https://doi.org/10.1016/j.apenergy.2007.10.009.

[20] S. Zhu, K. Deng, S. Liu, S. Qu, Comparative analysis and evaluation of turbocharged Dual and Miller cycles under different operating conditions, Energy 93 (2015) 75–87 https://doi.org/10.1016/j.energy.2015.09.028.

[21] K. Hatamura, M. Hayakawa, T. Goto, M. Hitomi, A study of the improvement effect of Miller cycle on mean effective pressure limit for high-pressure super-charged gasoline engines, JSAE Rev. 18 (1997) 101–106 https://doi.org/10.1016/s0389-4304(96)00069-0.

[22] M. Choshi, K. Asanomi, H. Abe, S. Okamoto, M. Shoji, Development of V6 Miller cycle engine, JSAE Rev. 15 (1994) 195–200 https://doi.org/10.1016/0389-4304(94)90034-5.

[23] N. Terdich, R. Martinez-Botas, Experimental efficiency characterization of an electrically assisted turbocharger, SAE Technical Papers (2013), https://doi.org/10.4271/2013-24-0122.

[24] I. Arsie, A. Cricchio, C. Pianese, M.D. Cesare, W. Nesci, A comprehensive powertrain model to evaluate the benefits of electric turbo compound in reducing CO2 emissions from small diesel passenger cars, SAE Technical Paper (2014), https://doi.org/10.4271/2014-01-1650.

[25] F. Millo, F. Mallamo, E. Pautasso, G. Ganio Mego, The potential of electric exhaust gas turbo-charging for HD diesel engines, SAE Technical Paper (2006), https://doi.org/10.4271/2006-01-0437.

[26] K.R. Pullen, S. Etemad, W. Thornton, J. Villegas, Electrically driven supercharger using the TurboClaw®compressor for engine downsizing, 10th International Conference on Turbochargers and Turbocharging (2012) 357–363.

[27] T. Noguchi, T. Wada, 1.5-kW, 150,000 r/min ultrahigh-speed PM motor fed by 12-V power supply for automotive supercharger, Power Electronics and Applications 2009 (2009) 1–10 https://doi.org/10.1109/peds.2007.4487698.

[28] S. Tavernier, S. Equoy, Design and characterization of an E-booster driven by a high speed brushless DC motor, SAE Technical Paper (2013), https://doi.org/10.4271/2013-01-1762.

[29] K. Nishiwaki, M. Iezawa, H. Tanaka, T. Goto, B. An, Development of high speed motor and inverter for electric supercharger, SAE Technical Paper (2013), https://doi.org/10.4271/2013-01-0931.

[30] T. Morel, L.A. Lapointe, Concurrent simulation and testing concept in engine development, SAE Spec. Publ. (1994), https://doi.org/10.4271/940207.