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Systems Engineering Framework and Key Technologies for Electric Commercial Vehicles

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Abstract: The development of vehicles powered by novel energy sources has reached a worldwide consensus. In particular, purely electric vehicles have been identified as a national strategic emerging industry in China and a key field of the "China Manufacture 2025" program. This study reviews the history, technical roadmaps, and characteristics of the development of electric commercial vehicles in China. Based on the requirements of "zero-emission" and "24-hour uninterrupted and safe operation" borne from the Beijing Olympics, this paper proposes the concept of a systems engineering framework for electric commercial vehicles with three core components—the vehicular platform, battery charging/swapping stations, and operations monitoring. This study also introduces and investigates key technologies for these three components. Finally, this study discusses the main technical measures for improving the systems engineering of electric commercial vehicles to achieve a target of 5 million new energy vehicles by 2020 and operate at –25 °C during the Beijing Winter Olympics in 2022. The study aims to realize an electric commercial vehicle with superior performance and no technical defects that can be used without environmental restrictions.
Keywords: electric commercial vehicle; battery charging/swapping station; operations monitoring; systems engineering; Winter Olympics

1 Introduction

The world has reached a consensus on the necessity of developing new energy vehicles (NEVs). Since the 15th Five-Year Plan of China, steady progress has been made in key technologies related to NEVs and their parts. China has attained an advanced level of technology in electric buses and currently leads the world in terms of energy consumption indicators [1]. During the 2008 Beijing Olympic Games (henceforth referred to as the Beijing Olympics), 50 electric buses were operated continuously, day and night, in the zero-emissions zone of the Olympic Park. "Zero breakdown operation," which was a national target for this operation, was duly achieved; this contributed to the realization of the "truly exceptional" Beijing Olympics. During the 2010 Shanghai World Expo, the 120 electric buses that operated within the World Expo Park withstood high temperatures and humidity levels for half a year, making 90.18 million trips with a vehicle availability of 99.8%. As a follow up of the "ten cities, thousand vehicles" model city program, 39 800 new energy buses, cars, and urban commercial vehicles were successfully deployed in 25 model cities. The scale of NEV usage in China expanded rapidly in 2014, as the first year of China's grand NEV push. In 2014, 74 763 NEVs were sold, with electric cars accounting for 60.3% of this number. By the end of 2016, NEV ownership in China reached 1.09 million cars, with electric cars accounting for 67.98% of the total (741 000 cars). As of October 2017, 288 000 electric commercial vehicles have been cumulatively sold in China, including 194 000 large, medium, and light electric buses. China therefore has the greatest number of electric buses in the world. China's electric bus manufacturers (represented by BYD Auto Co., Ltd. and Yutong Bus Co., Ltd) have already begun sales or exhibitions in 50 countries and 200 cities, including high-end markets in advanced

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countries such as the U.K., France, the U.S., Japan, and Australia [1]. Owing to the implementation of the electric powertrain strategy, the scale of NEV and electric car usage in China has grown substantially. The development of NEVs has already quickened in China, which already has the largest number of NEV ownerships in the world. China has therefore achieved world-class standards in NEV technology, and its electric commercial vehicle platforms and technologies are now being exported to countries and regions such as the European Union. The electric commercial vehicle industry of China is now walking a path paved by technological advances.

2 Systems engineering framework for electric commercial vehicles

2.1 Contents

As the development of the electric commercial vehicle industry is dependent on various aspects, including power batteries, cost controls, charging, and mode of operation, it is necessary to plan, develop, and promote the usage of electric commercial vehicles from a systems engineering perspective. As illustrated in Fig. 1, the systems engineering framework for electric commercial vehicles includes three major subsystems: the electric commercial vehicle platform, battery charging/exchange infrastructure, and a real-time operations monitoring and management system. The establishment of mutual support between these subsystems will be crucial for the formulation of a comprehensive solution to the technical requirements of electric commercial vehicles, which include maximizing driving range, minimizing charging time, and supporting safe and efficient operation.

The underlying concept of this systems engineering framework is based on the zero-emissions electric bus project used during the 2008 Beijing Olympics. In the Olympic Park (which includes competition venues such as the Beijing National Stadium and Beijing National Aquatics Center, and core areas such as the Olympic Village and Media Village), the use of zero-emissions electric buses was a promise made by China to the International Olympic Committee (IOC). The use of electric buses independently developed by China during the project was also a manifestation of the "Green Olympics, High-Tech Olympics, and People's Olympics" concept. The National Engineering Laboratory for Electric Vehicles (NELEV) in the Beijing Institute of Technology has led a collaborative effort to develop the electric buses used at the Beijing Olympics, construct high-speed intelligent battery charging/swapping stations, and develop technologies for vehicle operations monitoring and management. This team has already succeeded in introducing systematic innovations in vehicle design, system integration, core and manufacturing technologies, and engineering applications related to electric vehicles. Furthermore, the refinement and application of the systems engineering framework developed by NELEV for the electric commercial vehicles of China has been realized via the implementation of the Beijing Olympics electric bus project and the subsequent adoption of electric public transportation systems by the sanitation, logistics, and taxi industries of Beijing.

Nearly 10 years have passed since the Beijing Olympics. During this period, the electric commercial vehicle industry of China has developed at a breakneck pace while achieving various technological breakthroughs driven by systems engineering. For example, significant advances have been made in self-driving,

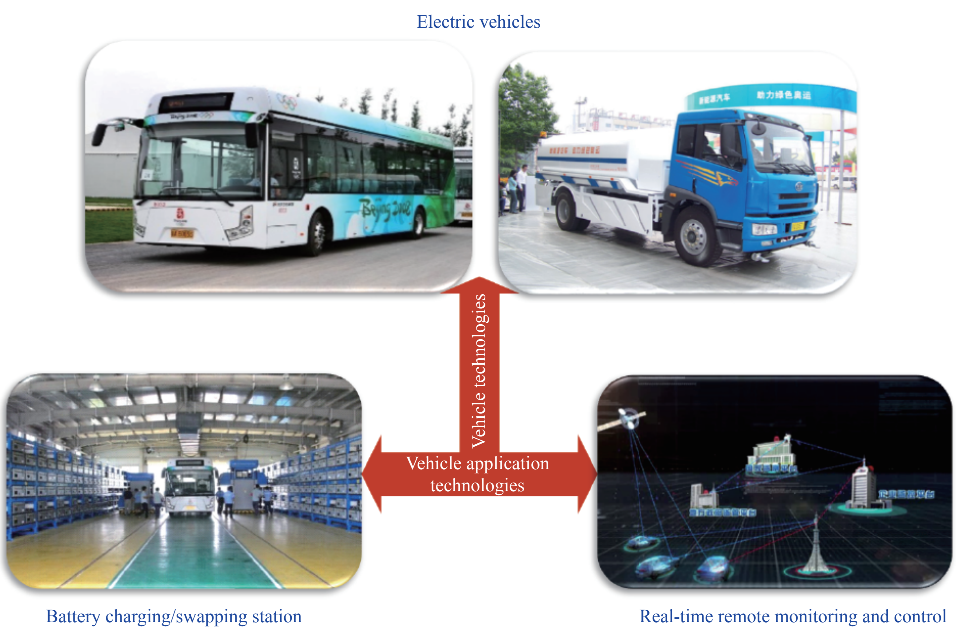


Fig. 1. Major technological subsystems of the systems engineering framework for electric commercial vehicles.

reducing weight, and safety for electric commercial vehicle platforms, and China continues to lead the world in the development and usage of electric commercial vehicle technologies. Extensive progress has also been made in the construction of battery charging/swapping infrastructure. Many commercial operators in China have begun to install public charging facilities around the country, while they have been paying attention to the importance of industrial coordination and platform integration. With the continuous improvement of vehicle operations monitoring and management technologies, operational safety monitoring systems for NEVs are gradually being formed at the national, local government, and enterprise levels.

2.2 Electric commercial vehicle platform technologies

In China, highly comprehensive technological and industrial chains have been formed in the past few years, owing to the continued dominance of Chinese electric commercial vehicles on the international stage. This has also led to the manufacturing of electric buses, logistics vehicles, sanitation vehicles, taxis, rental cars, and trucks on industrial scales.

With electric buses as an example, the current state of research in China on the key technologies of electric commercial vehicle platforms can be illustrated in the five areas described below.

2.2.1 Vehicle design and system integration technologies

The plan developed by the Beijing Olympics electric bus project team for a highly-efficient electric bus is shown in Fig. 2. This research team overcame the limitations of conventional modification-based approaches, established and refined design theories and systems integration frameworks for electric buses, and defined a standardized technical platform for systematic vehicle/parts development and power system matching. Furthermore, the team developed a compartmentalized and electric low-floor chassis with an exchangeable battery box, integrated powertrain, and integrated air conditioning system. This provided an elegant solution to important technical problems such as reducing

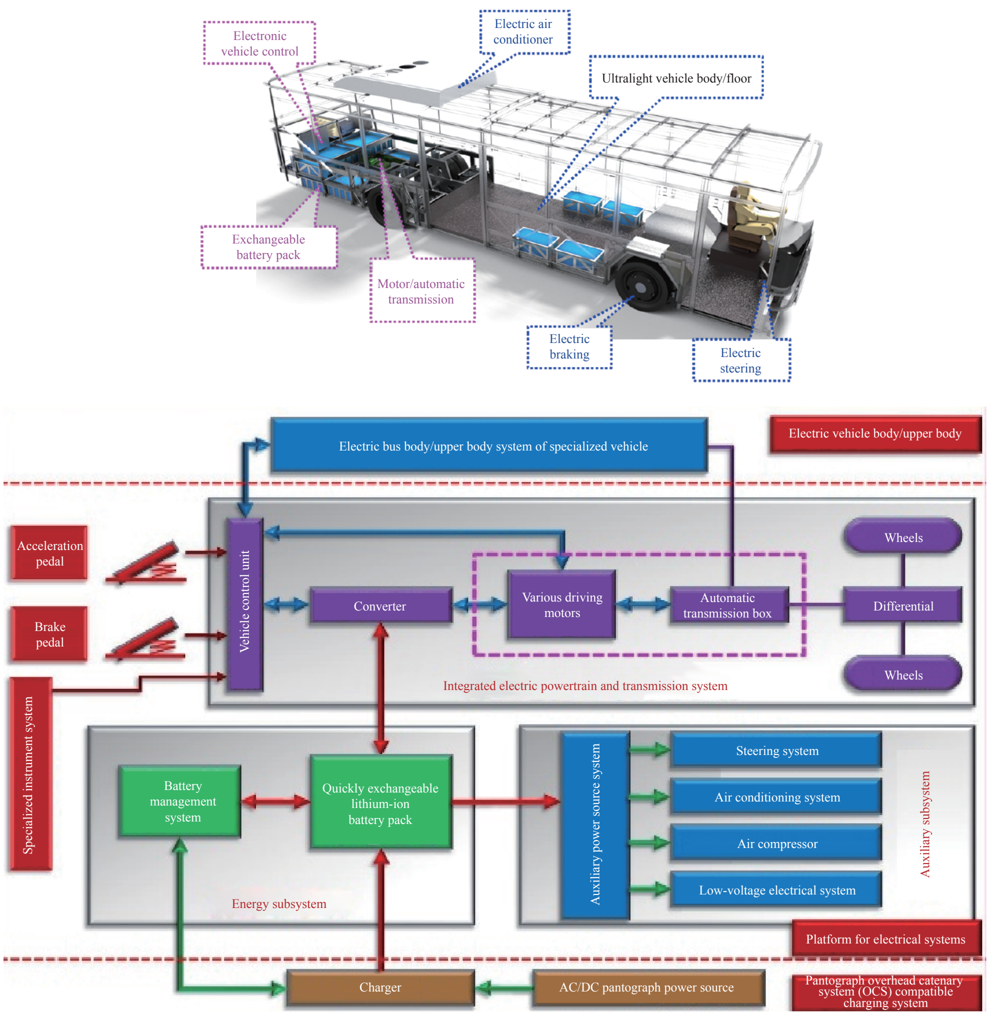


Fig. 2. Configuration of a highly efficient electric bus powertrain system.

vehicle weight, structural and high-voltage safety, double insulation, system reliability, and electromagnetic compatibility. In summary, the research team established a technical pathway for independent innovations and net-positive design and development in the electric car industry of China.

To supplement the aforementioned electric bus powertrain system, a transmission-less single-motor direct-drive system for urban buses and a distributed driving motor system for ultralow-floor buses were developed recently [2,3], and have been adopted by the electric bus industry for certain use cases.

2.2.2 Digital information control technologies for vehicles

A digital information control system specifically designed for electric buses has been developed for electric commercial vehicle platforms in China, based on the controller area network (CAN) bus protocol (Fig. 3). This system includes core components such as the vehicle controller, vehicle body controller, and smart instruments. This system allows for fieldbus-based information sharing and intersystem coordination and control, and offers functions such as vehicle fault diagnostics, fault alarms, and hierarchical protection.

2.2.3. Technologies for powertrain battery pack usage and safety

The Beijing Olympics electric bus project team proposed a theory that quantifies how inconsistencies in the time characteristics of each battery cell in a powertrain battery pack affect battery life, and provided a method to analyze such differences [4]. They also developed a modularized packaging system for lithium-ion batteries, which allows for the connection of power and communication lines in a synchronous and automated manner during rapid battery swapping processes. This alleviates the constraints imposed by powertrain batteries in the usage of electric buses, effectively extending the service lifetime of battery packs and increasing driving range [5,6]. The contact resistance of the power line after being attached to the bus is less than 0.1 mΩ, and the contact has a rated current of 100 A. To ensure battery pack consistency, the battery cells used for each battery pack were selected based on comparisons between the capacities and power and voltage curves of each cell. The long-term consistency of each battery pack was maintained within 0.03 V, as illustrated in Fig. 4.

2.2.4 Integrated powertrain-transmission system

The Beijing Olympics electric bus project team developed a clutch-free, multi-speed, electronically-controlled automated manual transmission (AMT) powertrain-transmission system, as shown in Fig. 5. This system effectively increases the cost efficiency and dynamic performance of electric buses as it optimizes the efficiency of the integrated powertrain-transmission system via CAN bus-based control [7–10]. The team also developed a dead-time compensation method based on space-vector-based pulse-width modulation (SVPWM) and a highly efficient, fully digital vector control AC motor drive system, which improve the efficiency of the power transmission system. The team also tackled technical problems such as the double insulation of the system in the floating ground state, electromagnetic compatibility, and static electricity discharge. Redundant control and fault diagnostic systems were also used to improve system reliability.

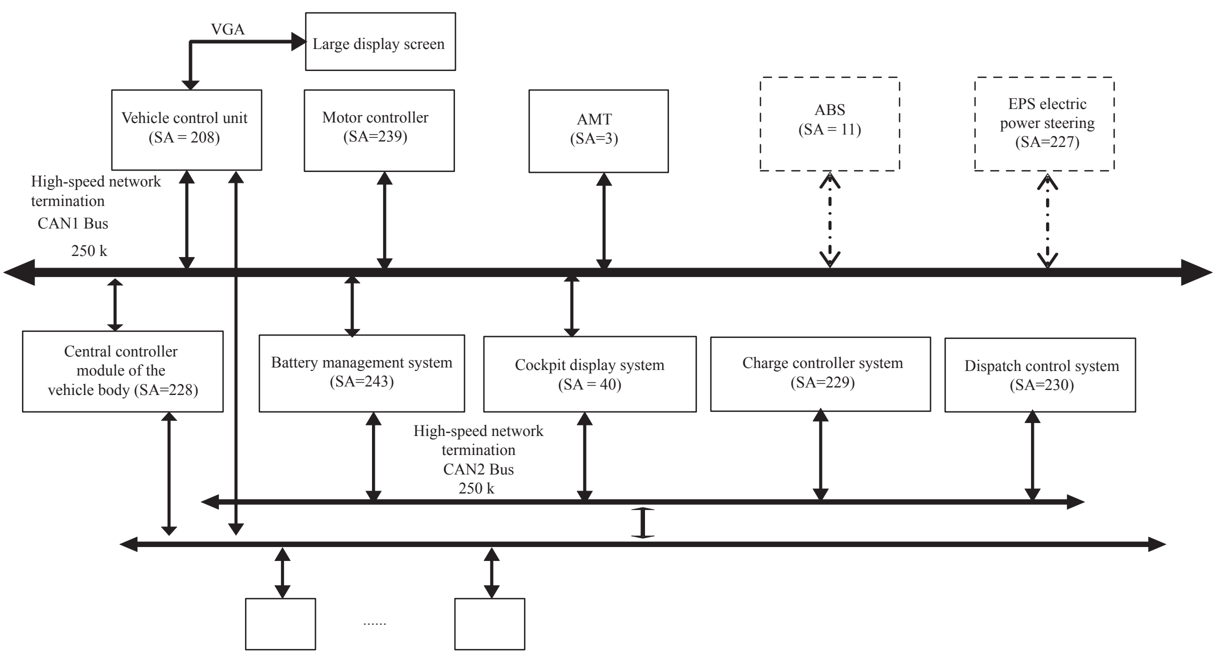


Fig. 3. Topology of the CAN network for electric buses.
Note: VGA—video graphics array; AMT—automated manual transmission; ABS—anti-lock braking system; EPS—electric power steering; SA—source address.

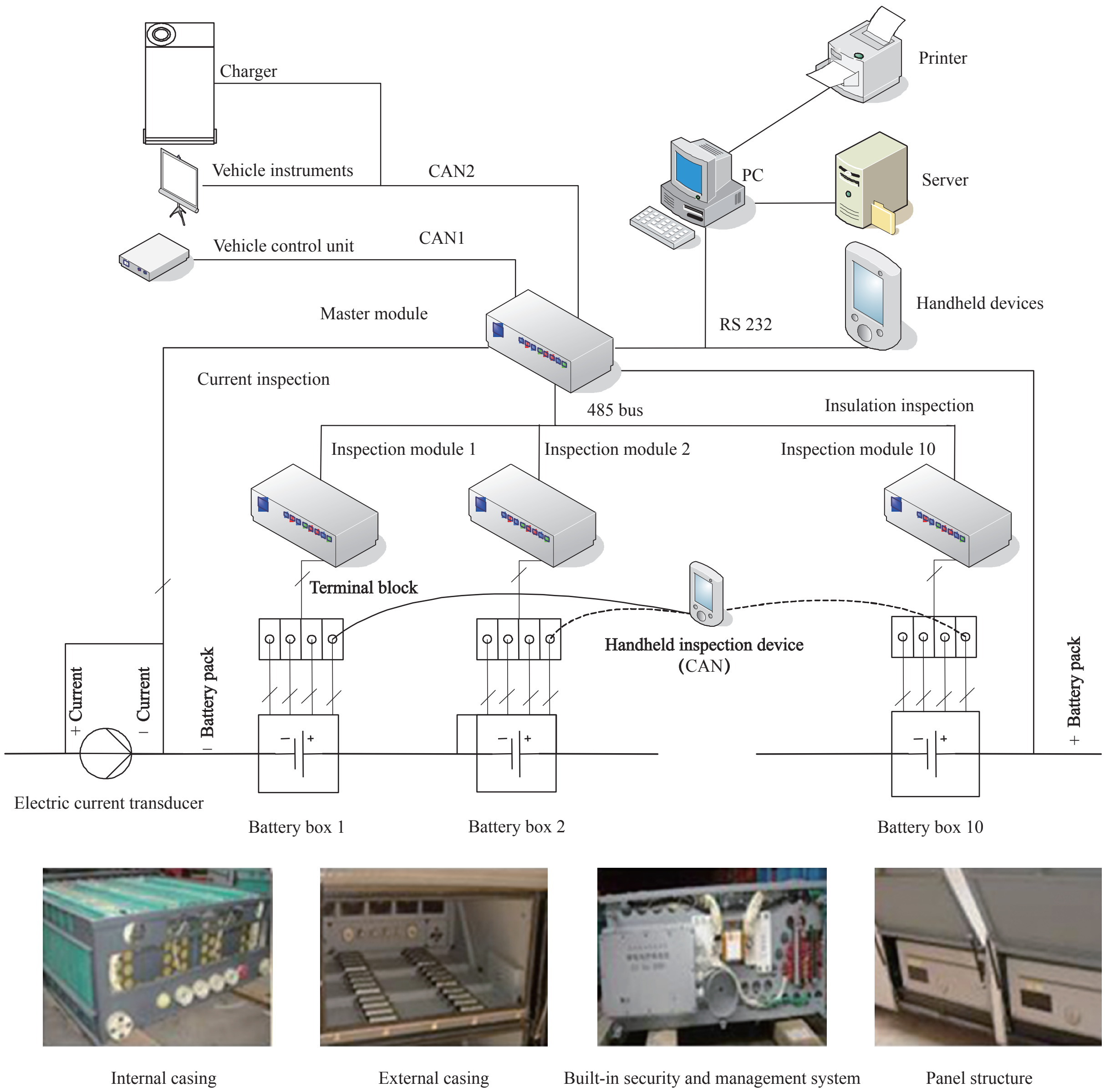


Fig. 4. Technologies and systems for powertrain battery pack usage.

2.2.5 Integrated electric air conditioning technology

For the first time, scroll-compressor-based electrically driven air conditioning was successfully developed for electric buses (Fig. 6), controlled using a DC-to-AC power inverter module. Stepless variable frequency drive, base frequency refrigeration, and temperature maintenance via frequency reduction were thus realized via an electrically-driven scroll compressor. This new system is a radical departure from the conventional air conditioning systems used in large buses, and saves a significant amount of energy by comparison. Common problems in vehicle air conditioning systems such as refrigerant leakage and shaft seal issues were resolved using a fully-sealed scroll compressor with fully-welded connections to ensure that the system was fully sealed without leakage. This also simplifies the installation of the air conditioning system. The integration of air conditioning systems in large buses has therefore been achieved through this system. The air conditioning system was made to be reversible using a heat pump cycle and a four-way reversing valve, so that heating and cooling could be toggled simply by applying the appropriate controls. The integration of cooling and heating operations was thus achieved in a vehicle air conditioning system. Two independent air conditioning systems were constructed using two scroll compressors and two condenser-evaporator systems, and may be utilized either independently or simultaneously, allowing for a natural combination of air conditioning effectiveness and energy efficiency.

2.3 Battery charging/swapping infrastructure

Challenges such as long charging times, low vehicle utiliza-

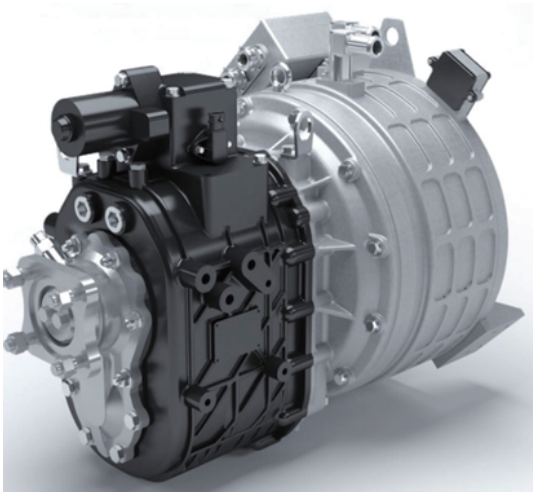


Fig. 5. Integrated automated manual transmission electric drive system.

tion rates, and charging safety have long hindered the development of the electric vehicle industry. High-speed charging and fast battery pack swapping are the solutions currently available for these problems.

2.3.1 Battery charging/swapping stations

In 2008, the world's largest electric bus battery charging/swapping station was used for the Beijing Olympics, as illustrated in Fig. 7. During the Olympic Games, this station provided battery charging/swapping services on a 24-hour basis for 50 electric buses as well as vehicle and battery maintenance services [11], and proved to be a tremendous success. Automated battery swapping machines were equipped in the quick battery swapping zone to facilitate rapid modular battery swaps, and it only took 5 min to swap the batteries of each vehicle. Based on the characteristics of electric buses and the needs of the Olympic Games, theoretical vehicle dispatch models and schemes were designed according to the driving and charging times of the vehicles. A dispatch monitoring center was also set up at the charging station.

Vehicle technology indicators have been defined in the NEV program of the 13th Five-Year Plan of China, which include specific energy consumption and driving range indicators for all NEVs. A reasonable battery/car mass ratio would be 15%–20%. In fact, Tesla have been fined in Singapore owing to the low energy efficiency ratios of their electric cars' battery systems. The driving range and charging times of an NEV are correlated with the specific energy or loading of its batteries. Furthermore, more than 70% of the NEV owners in major cities such as Beijing do not have a fixed parking space for installation of charging piles. These problems have made battery swapping an important technological pathway for the propagation of NEV usage.

Around 2010, the State Grid Corporation of China proposed a technological pathway where the NEV charging infrastructure would be dominated by battery swapping facilities and supple-

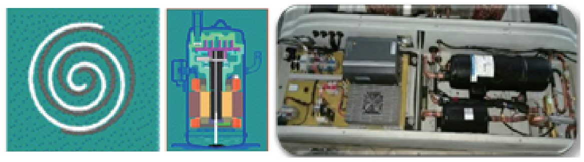


Fig. 6. Integrated cooling-heating electric air conditioning system.

mented by battery charging stations. To solve land-use problems, charging stations were miniaturized and containerized battery swapping stations were developed. As a result, the charging station areas used for the Beijing Olympics were reduced from 5000 m^2 to approximately 300 m^2. In addition, the charging stations exported from China to Poland are containerized (Fig. 8). Owing to the miniaturization technologies developed, each charging station requires only 120 m^2 to serve 120 electric taxis or 1000 private passenger cars. The key technological steps toward the establishment of a battery swapping-based charging infrastructure are: ① planning and construction, ② interconnection and sharing, ③ automatic positioning and the bridging of public transport interchanges, and ④ interlocking technologies.

2.3.2 High-power charging

Many multinational car makers have proposed 350 kW-1000 V high-power charging systems to significantly reduce the charging times of powertrain batteries. The users of electric commercial vehicles require high-power charging, since it offers significant advantages in terms of its adaptability for vehicle usage patterns, and its potential for improving charging efficiency while decreasing the vehicle-to-charging pile ratio. However, high-power charging is still being discussed and studied in China, as it is extremely important to select a charging power that suits the unique conditions of China. High-power charging will have an impact on the safety of electric vehicles and the efficiency and stability of power grid operations, and balancing charging power and safety is therefore a difficult problem that must be tackled carefully. Furthermore, high-voltage, high-power charging also places higher demands on the voltage- and current-handling capacities of battery systems, high-voltage protection systems, high-voltage interfaces, electronic controllers, and high-voltage transmission circuits, which all affect costs. For example, high-power charging is expected to increase current costs threefold, and technological advances will gradually drive further improvements in charging rate, the capacity of powertrain batteries, and driving range. Therefore, high-power charging requires careful investigation, and a detailed analysis should be conducted on the strengths, weaknesses, and complementarity of high-speed charging and rapid battery swapping for electric commercial vehicles.

2.4 Operations monitoring and management technologies

As the scale of NEV operations continues to expand, the

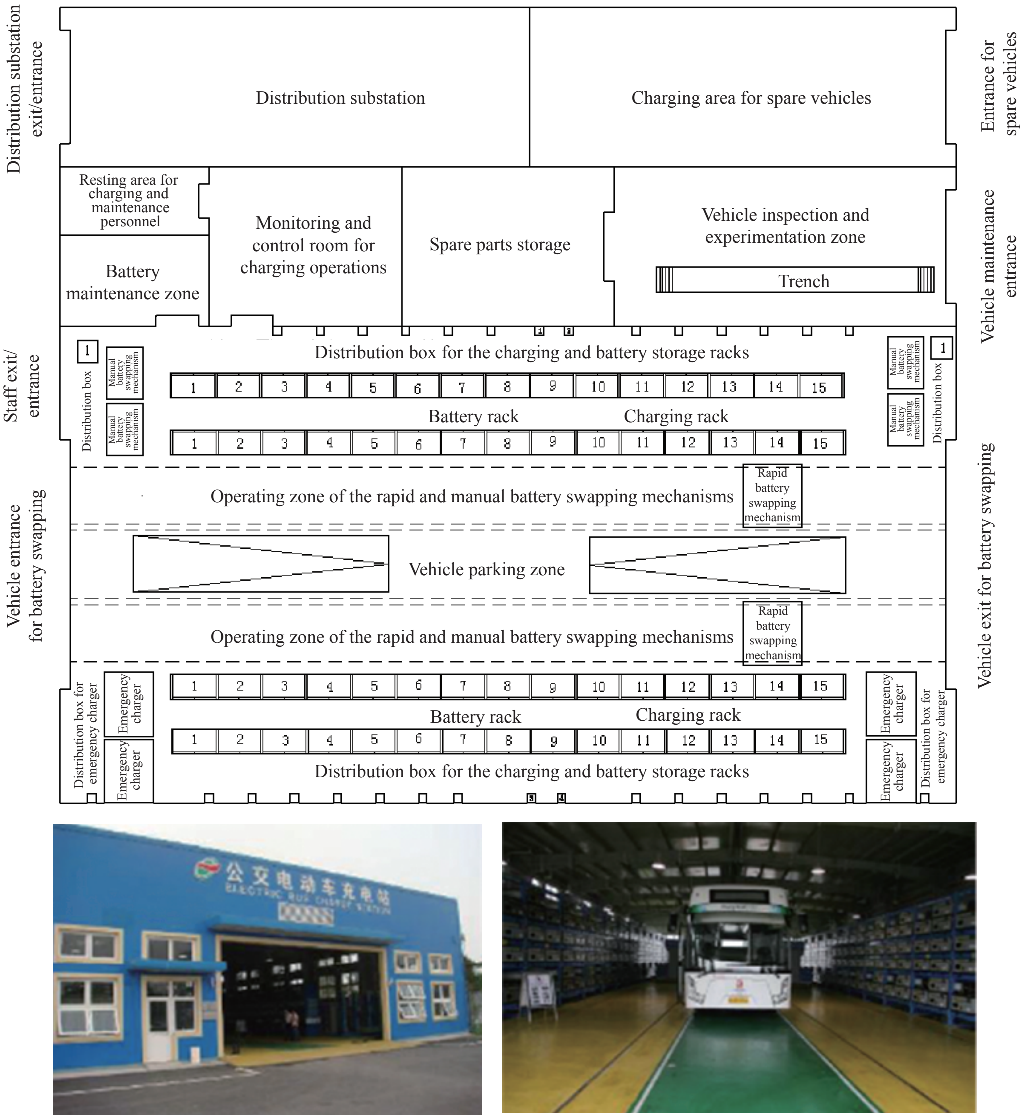


Fig. 7. Automated high-speed battery charging/swapping station for the Beijing Olympics.

Fig. 8. Containerized battery charging/swapping station.

Ministry of Industry and Information Technology (MIIT) of China is now leading efforts to establish national and local government and enterprise-level monitoring and management systems for NEV operations. The objectives of these systems are to monitor vehicle safety, enforce corporate responsibility, trace vehicular travel, assess the effectiveness of financial subsidies, and track product quality and energy consumption, according to the goals of the national monitoring system.

Given the experience gained from the real-time monitoring and management of electric bus operations in Beijing since the Beijing Olympics, the Beijing Institute of Technology has led efforts to establish the "Beijing City Electric Vehicle Monitoring and Servicing Center" and the "National New Energy Vehicles Monitoring and Management Center," with the support of the MIIT, the Ministry of Finance, and the Beijing Municipal Government. In addition, the Beijing Institute of Technology has provided technical support for the development and construction of monitoring platforms for local governments and the NEV industry. This has resulted in steady progress in the formation of an NEV safety monitoring framework comprising national and local government and enterprise-level platforms. As of today, 400 NEV manufacturers have applied for entry into the national monitoring platform, and 4000 types of NEV vehicles have passed the compliance tests of the standards system, thus allowing the addition of these vehicles to the national monitoring platform at any time according to national needs.

3 Expectations for electric commercial vehicle technologies

At present, next-generation communication technologies, new energy sources, and new materials are rapidly being adopted by the automobile industry. As the 2022 Beijing Winter Olympic Games approaches, electric commercial vehicles will play an important role in safeguarding its transportation services. Systematic technological upgrades of electric commercial vehicle platforms will also be of utmost importance, owing to the demands imposed by operations at temperatures as low as −25 °C during the Winter Olympics.

3.1 Overcoming low-temperature restrictions: research on all-climate powertrain batteries and electric vehicle system technologies

Improvements to the energy density, cycle lifetime, safety, and cost of powertrain batteries are of critical importance. The energy density and power performance of lithium-ion powertrain batteries drop significantly at low temperatures, which severely restricts their use in low-temperature environments. One of the venues for the 2022 Beijing Winter Olympics is the Zhangjiakou region in Hebei, which has average winter temperatures around −10 °C. Likewise, the Chongli District outdoor venue can be as cold as −23 °C. To satisfy the demands of such harsh environmental conditions, a new battery technology called all-climate battery cells has been developed (Fig. 9), which represents a revolution in low-temperature battery performance. By inserting a nickel sheet inside the battery, the battery cell can "self-heat" using a minimal amount of battery energy at temperatures below 0 °C. The battery automatically halts this self-heating process once its temperature has reached a range where the battery can operate normally, thus preventing further energy loss [12]. This technology improves the power of lithium-ion powertrain batteries at −30 °C by more than 10 times, without reducing the performance and service lifetime of battery cells at normal temperatures. The Beijing Institute of Technology, CITIC Guoan MGL Power Source Tech Co., Ltd., and EC Power (U.S.) have collaborated for developing and industrially producing these self-heating lithium-ion powertrain battery systems for extreme cold regions. This powertrain battery system can increase its temperature at a rate of > 10 °C/min, and the self-heating process consumes less than 5% of the battery capacity. "All-climate battery cells" will therefore allow promotion and usage of NEV vehicles without environmental restrictions.

3.2 Overcoming low-temperature restrictions: research on highly efficient heat pump air conditioning technologies

During winter and summer, vehicular air conditioning consumes a large portion of the energy of an electric commercial vehicle. Therefore, increasing the cooling/heating efficiency of air conditioning systems is important for reducing vehicular energy consumption and increasing driving range. Low-temperature enthalpy-increasing technologies are important for upgrading next-generation electric commercial vehicles, as they are highly efficient and exhibit improved performance under extremely cold conditions. A low-temperature enthalpy-increasing air conditioning system utilizes technological breakthroughs such as wide-temperature-range, variable-capacity air-source heat pump (ASHP) cooling/heating cycles and low-ambient-temperature, high-efficiency heat pump air conditioning systems, in combination with low-temperature, enthalpy-increasing technologies, high-efficiency heat exchangers, high-efficiency fan motors, and optimal windshield design. The heating efficiency of such systems is expected to have an energy efficiency ratio of 1.6, and improves the heating capacity of conventional air conditioning systems at −15 °C by 20%–50%. This system can also operate

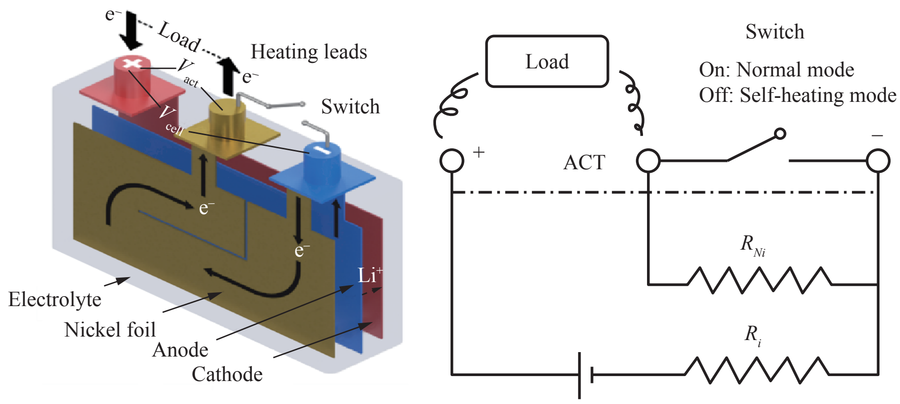
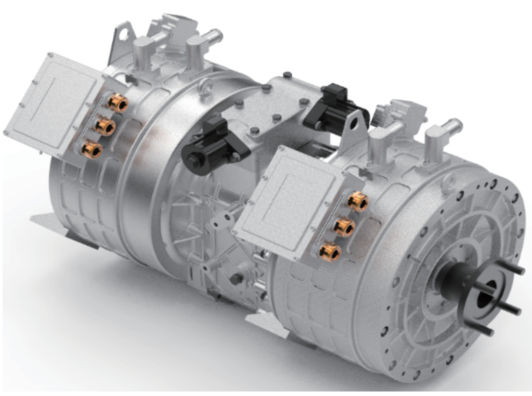


Fig. 9. All-climate powertrain battery cell.

normally at −25 °C. Hence, this system is capable of satisfying the demands of high-efficiency heating even in extremely cold regions.

3.3 Improvements to vehicle dynamics: the development of highly efficient electric drive systems

Further improvements of vehicle dynamic performance and the reduction of energy consumption will place even greater demands on the integration of electric motors, motor controllers, and electric drive assemblies. The key technologies required for the realization of these improvements include highly-efficient, high-power-density motors and controllers, high-density motor-transmission integration, and high-voltage integrated controllers. Possible solutions for these requirements include dual-motor seamless-shift AMT electric drive systems and highly-efficient, highly integrated distributed electric drive systems, as shown in Fig. 10. In addition, the development of "double 90% efficiency" electric drive systems (that is, more than 90% of the entire operation range has an efficiency ≥ 90%) is also an important focus for this area of research.



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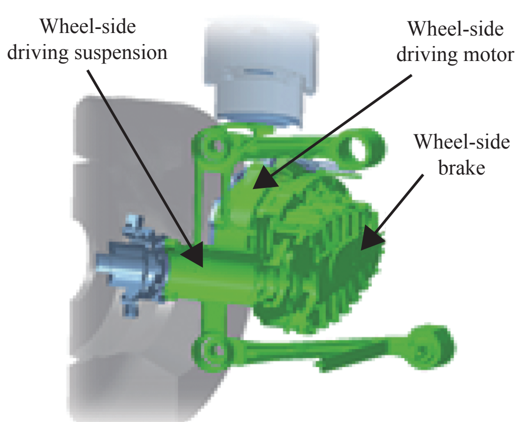

(b)

Fig. 10. Components of high-efficiency electric driving systems.

3.4 Increasing vehicle smartization: research on network vehicle controllers and intelligent driving technologies

Smartization is one of the primary technological features of next-generation electric cars, and is an important technological tool for improving overall vehicle performance. The key technologies for vehicle smartization include drive-by-wire chassis systems [13], vehicle network-controlled electrical-electronic architectures, network vehicle controllers and their associated information security systems, cloud-based multi-source information fusion, decision-making, and control calibration, and intelligent driving assistance. The Hebei venue of the Beijing Winter Olympics is a mountainous area, complicating winter driving conditions due to steep gradients and ice- and snow-covered surfaces of the roads, and thus placing stringent demands on intelligent driving assistance. It is therefore very important to redesign and develop intelligent network control technologies, driving motors, and AMT controls, and intelligent system controllers to improve vehicle reliability and safety.

4 Conclusions

This paper proposes and defines a systems engineering framework for electric commercial vehicles by analyzing and discussing its three major components: electric commercial vehicle platforms, battery charging/swapping stations, and real-time operations monitoring. To satisfy the requirements of the Beijing Winter Olympics in 2022, which necessitates operation at temperatures as low as −25 °C, it is of utmost importance to overcome the current low-temperature restrictions of electric commercial cars and improve overall vehicle performance such as dynamics and safety. The technological pathways and key technologies for improving electric commercial vehicle platforms were discussed from the perspectives of four technologies: self-heating lithium-ion powertrain batteries, low-temperature enthalpy-increasing air conditioning, highly-efficient electric drive systems, and intelligent vehicle control.

References

[1] Ouyang M G. New energy vehicle research and development in China [J]. Science and Technology Review, 2016, 34(6): 13–20. Chinese.

[2] Liu W, Khajepour A, He H W, et al. Integrated torque vectoring control for a three-axle electric bus based on holistic cornering control method [J]. IEEE Transactions on Vehicular Technology, 2017 (99): 1.

[3] Liu W, He H W, Sun F C, et al. Integrated chassis control for a three-axle electric bus with distributed driving motors and active rear steering system [J]. Vehicle System Dynamics, 2017, 55(5): 601–625.

[4] Sun F C, Xiong R, He H W. Estimation of state-of-charge and

state-of-power capacity of lithium-ion battery considering varying health conditions [J]. Journal of Power Sources, 2014 (259): 166–176.

[5] Sun F C, Chen K, Lin C, et al. Experimental study on heat generation and dissipation performance of PEV Lithium-ion battery [J]. High Technology Letters, 2010, 16(1): 1–5.

[6] He H W, Xiong R, Zhang X W, et al. State-of-charge estimation of lithium-ion battery using an adaptive extended Kalman filter based on an improved Thevenin model [J]. IEEE Transactions on Vehicular Technology, 2011, 60(4): 1461–1469.

[7] Lin C, Chen G Q, Meng X, et al. Strategies of control for electric bus transmission [J].Transaction of Beijing Institute of Technology, 2007, 27(1): 25–28. Chinese.

[8] Zhang S, Xiong R, Zhang C N, et al. An optimal structure selection and parameter design approach for a dual-motor-driven system used in an electric bus [J]. Energy, 2016 (96): 437–448.

[9] Lin C. Wang W W, Sun F C. Pure electric city bus structure and design [J]. Chinese Journal of Mechanical Engineering, 2005, 41(12): 25–29. Chinese.

[10] Gao W, Zou Y, Sun F C. Two-parameter optimal shifting control for the AMT of a battery electric bus [J]. Automotive Engineering, 2016, 38(3): 344–349. Chinese.

[11] Sun F C, He H W. Industrialization of electric vehicles and key technologies [C]. International Conference on Power Electronics Systems and Applications. Hong Kong, IEEE, 2011.

[12] Wang C Y, Zhang G S, Ge S H, et al. Lithium-ion battery structure that self-heats at low temperatures [J]. Nature, January 20, 2016. dx.doi.org/10.1038/nature16502.

[13] Sun F C, Liu W, He H W, et al. An integrated control strategy for the composite braking system of an electric vehicle with independently driven axles [J]. Vehicle System Dynamics, 2016, 54(8): 1031–1052.