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Review Paper

An Overview of and Prospects for Research on Energy Savings in Wheel Loaders

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Abstract

Wheel loaders consume a large amount of energy, and research on energy savings in wheel loaders has been carried out for decades. This paper introduces several types of wheel loaders and compares their structures. The research progress of the energy savings of three different forms of wheel loaders is reviewed, including a diesel engine wheel loader, a hybrid wheel loader, and an electric wheel loader. In particular, the energy-saving control methods of an electric wheel loader in the working cycle are analyzed, as construction machinery electrification is an emerging trend. Based on the analysis of the driving features and the working process of a wheel loader, energy-saving control methods are introduced including the resistance reduction method, optimized control strategies, intelligent control, and unmanned WL research. Comparing various energy-saving research methods and the advantages of electric wheel loaders, the pure electric wheel loaders are advised to be researched at present and in the future. Controlling the torque distribution of the front and rear motors of electric wheel loaders and assistant drive control are proposed to be significant research prospects for energy savings in wheel loaders usage.

Keywords: Wheel loader; Electric wheel loader; Energy savings; Control strategy

1. Introduction

A wheel loader (WL) is a kind of earth-moving construction machinery, which is widely used in highway, railway, construction sites, ports, mines, and other construction projects [1]. To promote social and economic development, most countries in the world have vigorously increased infrastructure construction, which has led to a continuous rise in the demand for WLs. According to the research report by Facts & Factors [2], the size & share of the global WLs market is predicted to grow to around US$ 19,568.7 million by 2028 with a compound annual growth rate of roughly 3.1% between 2022 and 2028. WLs can be classified into several categories, as illustrated in **Figure 1**. Based on loading weight, they can be divided into mini loaders, medium loaders, and heavy loaders. With regards to the working type, they can be classified as front unloading, skid-steer unloading, and backhoe unloading. If classified by transmission, they can include hydraulic-mechanical transmission, mechanical transmission, and electric drive transmission. Traditional WLs are driven by diesel engines, which have a large displacement and relatively lower operating efficiency, leading a large amount of energy consumption and can cause air pollution [3] of NOX, CO, HC and PM which are harmful to human health [4]. Increasing fuel efficiency and using cleaner energy have become the most important way for achieving energy savings and emissions reduction in the past two decades [5]. Energy saving and environmental protection is a development direction of construction machinery. Applying new energy types, improving the structure of loa-

Nomenclature

AC	Alternating Current
AT	Automatic Transmission
AMT	Automatic Manual Transmission
DC	Direct Current
DCT	Dual Clutch Transmission
DEWL	Distributed Electric Wheel Loader
DEM	Discrete Element Method
EWL	Electric Wheel Loader
PMSM	Permanent Magnet Synchronous Motor
T/C	Torque Convertor
WL	Wheel Loader

ders, and developing high efficiency control programs are all included in the research into energy savings on WLs [6]–[8]. Electric loaders can achieve more flexible drive arrangements, better energy-saving control, a higher work productivity, and lower work noise [9].

The paper summaries the common three structure of wheel loaders, and compares the energy-saving research stress on each. Through the comparative study of the previous part on WLs, the paper aims to lead to the discussion of electric wheel loader (EWL). Several features of the EWL are summarized and introduced for the first time. The contribution of this paper is to conclude that EWL is an inevitable research trend, and proposes two feasible research priorities on EWL.

The paper consists of four parts. Section 2 provides a comparison between three different types of wheel loaders in terms of their structure and the related research on each. Section 3 presents the characteristics of EWLs in electric driving process, the typical working cycle of four stages and forces on the EWL when working. Section 4 introduces and compares the research methods and energy-saving research on EWLs. Section 5 discuss the feasibility of future research on EWLs and the technical issues that need to be studied. Section 6 provides a summary of the study and proposes prospects for research on energy savings in EWLs.

2. Driving types of WL

At present, there are three driving modes of WLs either on the market or being researched: a diesel engine, an electric motor, and a hybrid with both a diesel engine and an electric motor. As off-road vehicles, WLs have similar kinematic characteristics to road vehicles, but they also have their own characteristics [10]. The first one is, a WL usually has an articulated chassis for its steering system. The second, besides driving system, a WL must work with the hydraulic system to support the arm, boom, bucket and steering system. What's more, WLs work with frequent load changes compared with ordinary vehicles.

Figure 1. Classification for wheel loaders

2.1. Diesel Engine WLs

The typical structure of a diesel engine WL is shown in **Figure 2** a diesel engine powers the front and rear final gears via a transfer case, with an oil pump for shoveling and excavating, which is also driven by the diesel engine.

In terms of the diesel engine WL, the larger resistance related to the unreasonable design shape of the bucket, the smaller driving force, due to the low power of the engine, the poor torque converter (T/C) performance, and the loss of hydraulic power are the main reasons for its inefficiency.

2.1.1. Resistance of a Diesel Engine WL

Takahashi et al [11] analyzed the forces acting on the bucket. According to the change in force in different shoveling processes, the Coulomb earth pressure theory was applied to analyze the movement and force of the bucket at different stages, which provided a theoretical basis for the excavation operation of the loader [12]. Ning et al [13] modelled the resistance of a WL bucket by applying the earth pressure theory. Coetzee et al [14] established a DEM model to predict the shovel loading resistance by simulating the shovel loading process of the loader. Segla [15] analyzed the force of a WL bucket based on the kinematic constraints of all the joints in the mechanism. Through the analysis and study of the forces acting on the bucket, the shoveling resistance can be reduced by improving the shape of the bucket, destroying the compactness of the material, optimizing the digging process, etc. The optimization of shoveling process should be a more effective way to minus the resistance for its lower cost in design and manufacture.

2.1.2. Transmission Efficiency

The transmission system with T/C transmits torque from the engine to the wheels, but mechanical losses are inevitable due to the friction of the gears and hydraulic loss. Huang et al [16] proposed a method to indirectly measure the WLs' transmission efficiency of the T/C through its speed ratio. Li et al [17] studied the design and optimization of the T/C. Qin [18] analyzed the working condition of a WL and found that by improving the performance of the T/C, the drive force increased by 10%. Aside from optimizing the performance of the torque converter, which is similar to an AT of an automobile, another effective change is to replace the transmission system with a clutch and gearbox. Oh et al [19] presented gear ratio and shift schedule optimization strategies to improve the energy efficiency in a dynamic simulation of a WL equipped with a DCT and an AMT. They showed through a simulation that the AMT based WL was more energy efficient than a T/C based WL, with an 11.9% energy consumption savings. However, the use of an AMT can lead to a delay in the response of the control mechanism if the shifting is not well controlled, which is a disadvantage. As a more efficient research method, You et al [20] proposed a parameter matching design method for a hydraulic mechanical power reflux transmission (HMPRT), and the transmission efficiency improved by 2.06% with optimized parameters.

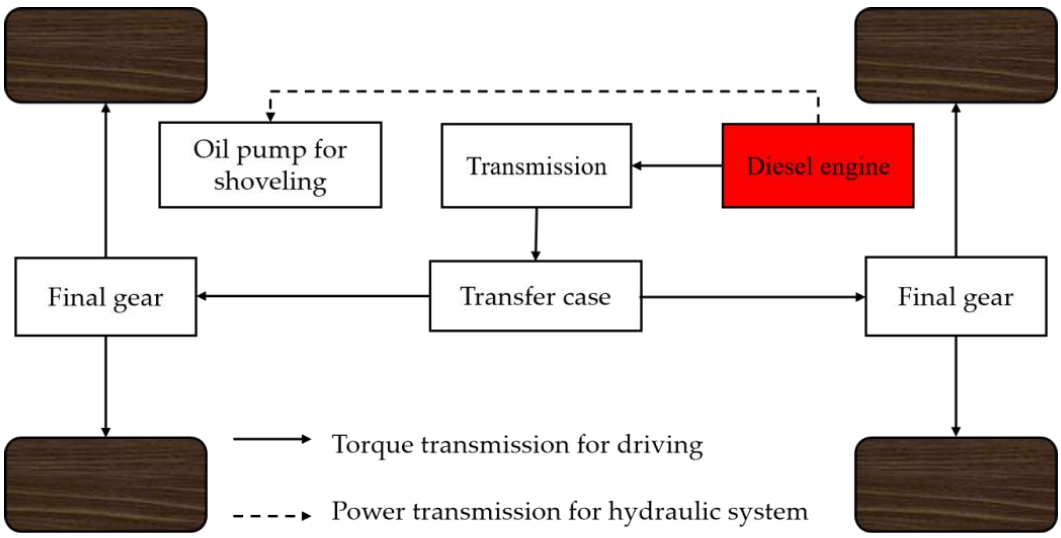

Figure 2. Structure of a diesel engine WL

For transmission types of road vehicle, it is well known that MT saves more energy than automatic transmission. The research on WLs or other heavy trucks [21], [22] has much in common with that of road vehicles. Therefore, the hybrid WL [23]–[25] and pure electric drive WL [26]–[29] have become research hotpots. Due to improving the driver's maneuverability, MT are gradually replaced by AT and hybrid drive systems or electric drive system in modern WLs.

2.2. *Hybrid WL*

WLs usually work in difficult conditions, resulting in energy wastage during the frequent braking and starting. Therefore, it is effective to use a hybrid electric structure to recycle the wasted braking kinetic energy and power off the engine when the resistance is not high, in order to save energy in a WL [30]. The hybrid structure of construction machinery was compared and discussed [10] in detail, which also mentioned hybrid WL.

A hybrid structure usually has three forms of drive: series, parallel, and series–parallel, the structures of each form are shown in **Figure 3**-**Figure 5** respectively. In the series drive, an engine drives a generator to generate electricity that can be stored in the battery pack, and the DC power in the battery is converted into AC power for the motor to generate torque to drive the transmission system. In the parallel drive, the transmission system can be driven by both the engine and the motor or individually driven by one of them. In the form of series–parallel drive, an engine drives the transmission system and drive generator, providing electricity to the motor to drive the transmission system. In general, hybrid WLs consume less fuel to maintain the engine at a high-efficiency working condition and keep longer working range compared that of pure electric WLs.

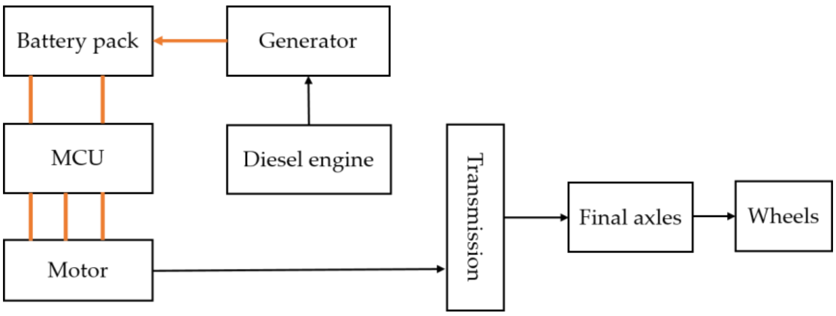

Figure 3. Hybrid series drive structure of WL

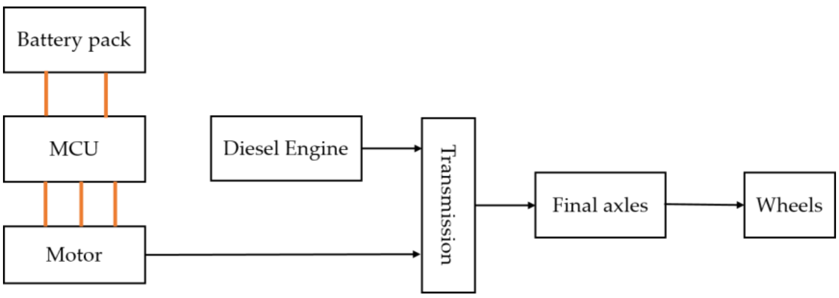

Figure 4. Hybrid parallel drive structure of WL

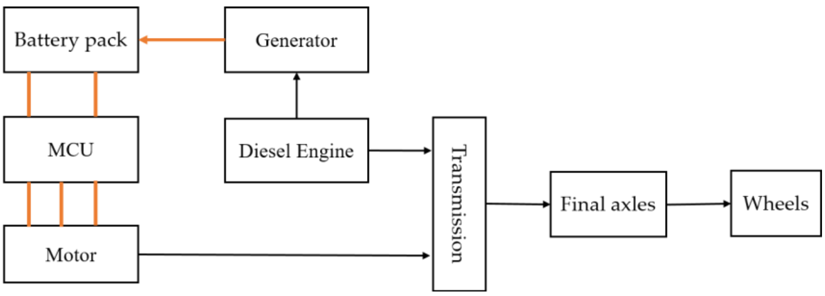

Figure 5. Hybrid series–parallel drive structure of WL

In 2008, Volvo [30] developed a prototype of a hybrid WL. In 2011, Kawasaki realised a type of hybrid WL, which integrated electric motors, planetary gears, generators, ultra-capacitors, and other components [31].

For the hybrid transmission, one main difference from other types is the energy management. A decade ago, the main research direction of the energy management strategies for a hybrid WL was the optimization-based control strategy. The optimization-based control strategies are divided into two types: global optimization and real-time optimization [32]. A global optimization algorithm generally applies to a fixed driving cycle [33], [34], whereas real-time optimization applies to the definition of an instantaneous cost function [31], [35]. A tunable energy management strategy was proposed and studied [24] by changing the hybrid weight factor; the powertrain hybridization degree was adjusted without any additional hardware. This study showed that the higher use of the hydraulic accumulator power indicated a higher degree of hydraulic hybridization. Other control strategies such as a genetic algorithm [36] and Fuzzy algorithm [37] are also applied in the current research on hybrid WLs. The above control algorithms are also widely used in the field of hybrid engineering machinery.

2.3. *Pure Electric Wheel Loader*

The EWL is becoming a research focus due to the increasingly stringent emission requirements. The application of electrification to the WLs [38], [39] is also an effective way to save energy. Jin et al [26] applied the PMSM to a conventional WL, showing that the efficiency of the PMSM reached 95% at the vehicle velocity of 5 km/h, by testing the running, dragging, and steering conditions. The common structure of an EWL is shown in **Figure 6**. Two motors connected by a coupling are assembled on the loader's suspension to drive the front and rear wheels, and the oil pump for the hydraulic system supporting the steering, loading and unloading process is also driven by an electric motor instead of an engine. **Figure 7** shows a prototype of EWL driven by two motors without a coupling, which is convenient to test single drive or full drive. In some EWLs, only one motor is assembled as the drive device to propel the drive axle, aiming at reducing cost. Compared with engine drive structure and hybrid structure, pure electric drive structure has much simple components in transmission, contributing to the reduction of 20–30% maintenance costs [40].

3. Characteristics of EWLs

As an electric drive construction machinery, the EWLs incorporate many of the features of an electric on-road vehicle and engine-drive WLs. The electric driving process, the typical working cycle and forces on the EWL in working condition are included.

3.1. *Electric Driving Process*

The typical structure of the motor-driven running system is mentioned in section 2.3, which is necessary for the EWL to drive forward and backward. The general operation flow of the drive is shown in **Figure 8**. After the driver depresses the brake pedal, the shift lever is operated, and the resulting electrical signal is sent by the VCU to the MCU, which determines the direction of rotation of the motor; when the driver releases the brake pedal and slowly depresses the accelerator pedal,

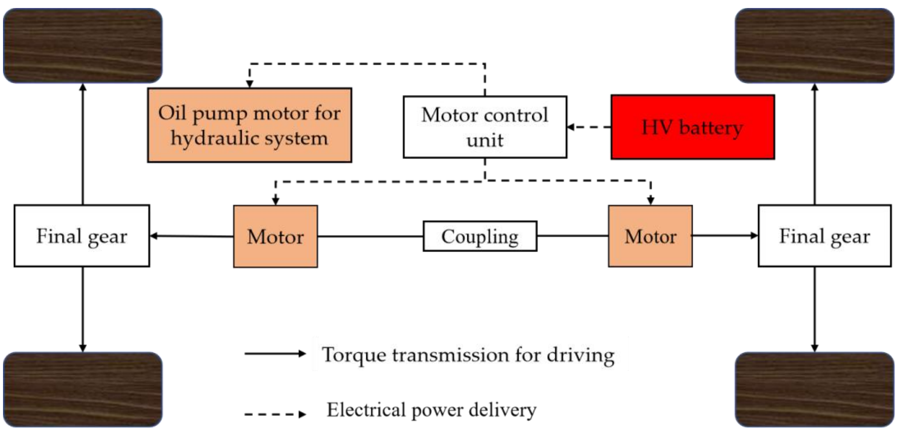

Figure 6. Typical structure of an electric WL

Figure 7. An electric wheel loader with two motors

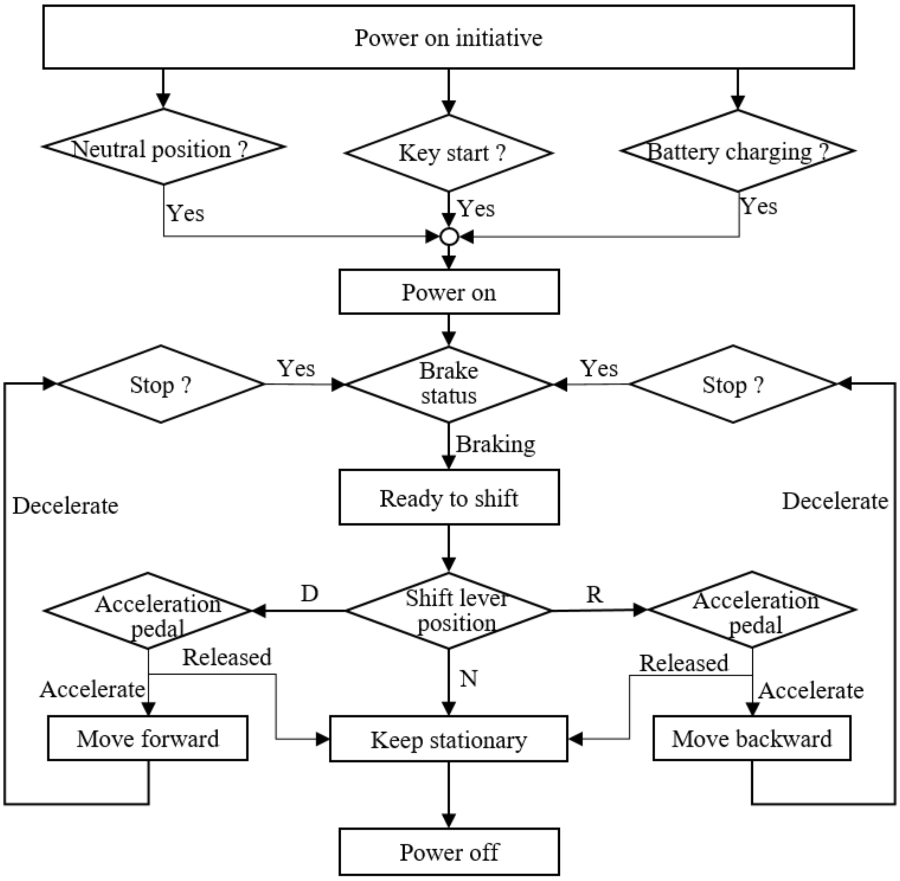

Figure 8. Electric drive process of EWL

the current in the motor increases and generates torque to drive the vehicle. The EWL must stop before putting on R gear if the driver wants to reverse; otherwise, it will produce shock to the motor and waste energy. As a reference, the existing energy-saving research on electric vehicle driving system mainly by improving the efficiency of the transmission system in structure and control methods [41]–[44].

3.2. *Working Cycle*

According to the division of the target, the main tasks of a WL can be divided into loading material and carrying material, which are included in the typical V-pattern work [45], shown in Figure 9. The V-pattern work can be divided into four stages. The WL fills up the bucket with materials at the first stage and returns to the proper point to unload at the second stage. At the third stage, the WL unloads the material and returns to the initial point at the fourth stage.

The start (end) times of each working stage of the loader are listed in Table 1. During the loading process, the bucket will be lifted and lowered, and the angle of the bucket can be controlled through the transmission of the boom and the hydraulic

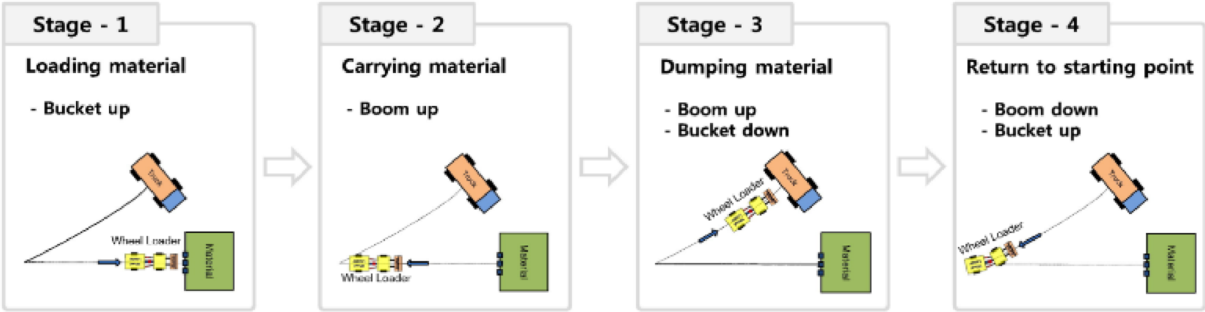

Figure 9. The stages of a WL's V-pattern work cycle [45]

Table 1. Start and end points of each operation stage [46]

Working stage	Timing	Relationship between loader and material
Loading material	Start	
	End	Bucket is filled with material and leaves the working face
Carrying material	Start	
	End	Bucket is lifted for discharge
Dumping material	Start	
	End	Bucket discharges all materials
Return to starting point	Start	Bucket discharges all materials
	End	Bucket begins to contact with material

mechanism. If the bucket descends to the ground, it will be affected by the supporting force of the ground, which will cause the change of gravity center of the WL.

3.3. Force Features

The driving characteristics of a WL are that it is driven by the rear/front wheels or by four wheels, and its walking speed is relatively low (usually under 10km/h) during the working stages [47]. Like regular vehicles, the WL is subject to driving resistance while moving, but the difference is that the forces on the bucket cause a great change in the forces on the wheels when shoveling materials. The resistance of the WL under the shoveling condition is shown in Figure 10. The force on the bucket from the material can be equivalent to a horizontal force marked with F_{Rl} and a vertical force marked with F_{v_down}. Moreover, the direction of the vertical force may change up and down according to the motion of the bucket. The other main forces are rolling resistance on front and rear wheels.

This force acts on the loader, reducing the pressure of the front wheel of the WL to the ground. If the bucket is supported by the ground facing upwards, the excessive force may even cause the front wheel to be lifted completely. In

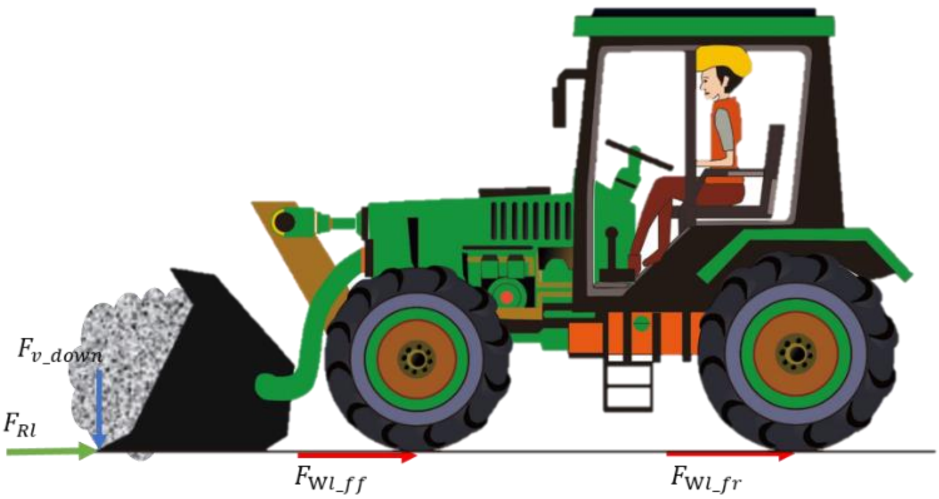

Figure 10. Resistance of WL in a straight-line working condition

the actual operation process, the driver generally cannot accurately judge whether the bucket is in the "leveling shovel" state, which makes it easy to cause the front wheel to slip and generate parasitic power. Parasitic power consumes energy and increase the wear of the tires [48]. On the other hand, if the angle of the bucket is not properly controlled, it will also cause the WL to receive too much horizontal and longitudinal force during the shovel movement, and the motor cannot drive the wheel forward in an efficient working area, even causing overload.

4. Energy-saving research on EWLs

4.1. *Research Methods*

For the pure electric mode of WLs, ways to improve the efficiency consist of energy recovery management, controlling the drive motors' work at a high efficiency range during shoveling and running process, independently or collaborative controlling the working and running motors, autonomous driving, etc. As for the research methodology, the approach can be classified into experimental and simulation approaches.

4.1.1. *Experimental Research*

The experimental approach is characterized by much greater control over the research environment; in this case, some variables are manipulated to observe their effect on other variables. Jin et al [26] applied the PMSM to a conventional WL, showing that the efficiency of the PMSM reached 95% at the vehicle velocity of 5 km/h, by testing the running, dragging, and steering conditions. However, they did not test the shoveling condition, which has the highest energy consumption condition. Yang [9] mainly conducted performance comparison tests for electric loaders and traditional loaders, including operational performance and noise performance tests. The test results indicated that the operational performance and noise performance were both better than that of conventional ones. However, the disadvantage of the experimental method is that the research cost is high and the repeatability is poor.

4.1.2. *Simulation Research*

Due to the high cost and poor repeatability of the experimental approach, the simulation method can be used. The simulation approach involves the construction of an artificial environment within which the relevant information and data can be generated.

Oh et al [45] developed a driver model for a WL's V-cycle working pattern and a 3D dynamic simulation model to analyze the working performance and energy flow in each component of the WL. In addition, a driver-model-in-the-loop simulation was conducted using the developed driver model. In the case study [7], short-term and long-term simulations were implemented on four WL cycles to test the energy management strategy of EWL. Li et al [49] applied three types of motors to drive the same EWL by joint simulation; the material insertion characteristics, acceleration, and hill-climbing characteristics of the walking system with three motors, including the shoveling and unloading performance of the hydraulic system with three motors, were analyzed. To overcome the disadvantage of model simulations that ignore too many practical factors, combining simulation with experimental verification is an effective method.

4.2. *Energy-Saving Control Methods*

4.2.1. *Reduce Resistance*

Based on the introductions and discussions above, a representative way is to decrease the force acting on the bucket, as the wheels will likely slide if the resistance generated by the force on the bucket is too large and the ground cannot offer enough adhesion force. Creative power is generated if this occurs [50], and the mechanical energy offered by the engine or electric motor is wasted in both the wear of the tires and the loss of hydraulic energy.

Yao et al [51] conducted in-depth research on the calculation method of the bucket insertion resistance based on the multi-coefficient method and proposed a calculation method of insertion resistance suitable for small particle diameters. As an improvement, Zeng et al [12] conducted a force analysis on the digging process of the loader bucket. With the development of computer simulation software, Coetzee et al [14] established a DEM model to predict the shovel loading resistance by simulating the shovel loading process of the loader. Based on EDEM software, Helgesson [52] analyzed the influence of the bucket's structural parameters on the working resistance. However, the above literature only gave the force analysis and suggestions for the structural improvement of the loader bucket, while few content were discussed about the improvement of driving mode or control strategy.

4.2.2. *Optimized Control Strategies*

As an electro–mechanical–hydraulic composite product, it is not enough to analyze the force of the WL's excavation or shoveling conditions in order to save energy. Zhang [53] proposed a control strategy to reduce the insertion resistance by changing the motion posture of the boom when the traction force could not overcome the ground resistance. Lu et al [54] took advantage of an intelligent control method to reduce the transient shoveling resistance by modifying the hydraulic system of the working device of the existing loader, containing the control handle module, control module, multi-way valve (hydraulic control reversing valve, pressure reducing valve, and check valve), relief valve, hydraulic cylinder module, power source, etc. The control handle is supplied with oil by the pilot pump, and the main valve adopts the dosing pump oil supply. The intelligent drag reduction shovel loading function is turned on when slipping occurs on the wheels, and the controller will input a control signal to the hydraulic system when the loader slippage is detected on the tire. Reforming the hydraulic system and adding control strategies on WLs is more the state of art in the research of energy-saving control. Lin et al. [55] applied a pin axis sensor, boom cylinder displacement sensor, rotary cylinder displacement sensor, etc., to measure the required data on a WL, after digitizing the shovel loading resistance; this can provide important evaluation indicators for the bucket design and important data support for the energy consumption and efficiency of the whole machine.

4.2.3. *Intelligent Control Algorithms*

Owing to the development of intelligent control and mechanical learning in computer science, researchers are paying more attention on the modification of control algorithms and image identification. Oh et al [45] subdivided the V-type operation of a WL into multiple events, which were defined by parameters such as vehicle speed, cylinder displacement, starting point, and distance to the vehicle. In this study, a drive model system was constructed, and the Model Predictive Control algorithm was utilized, which found that energy consumption of the V-pattern work depended on the expected path.

On the control of electric WL, Jinli University has done a number of studies in recent years. Yang et al [56] carried out optimal control research on the torque distribution of an EWL. A dynamic model of a front/rear-wheel-drive WL was built, and equations for the vertical tire load, tire driving torque, wheel longitudinal force, and motor driving torque were listed. On the optimal torque distribution control method, the objective function, constraint conditions, and optimization algorithm of the control object were analyzed. In this study, the weighted minimum value of the tire load variance and average value was used to maximize the overall efficiency of the motor; the longitudinal driving torque and rotational speed of the motor were used as constraints; four algorithms were used to estimate the torque distribution of the EWL nonlinearly. The simulation results shows that the motor efficiency has increased by up to 14.86% in straight line operation, and the slippage of tires has significantly reduced. This study was an indirect approach for improving the energy efficiency on the shoveling of WLs. However, there was no experiment to verify the correctness and repeatability of the simulation results. Gao et al [57] built longitudinal dynamic models and working device models for a DEWL, when the shoveling force was concentrated at the top of the bucket. Through an experiment, the longitudinal shoveling load force increased by approximately 25%–40% and the efficiency was improved by roughly 40%.

The inferential approaches are commonly applied in electric vehicles [58]–[60] and will probably be an effective way in the research of EWLs. For WLs, the resistance force on the wheels, the road adhesion coefficient, the shoveling resistance, and many other factors are nonlinear; hence, it is important to assume the next state to be calculated for the control system, which were applied in [56], [57].

4.2.4. *Unmanned WL*

McKinnon et al [61] proposed a method based on the distance and intensity data from time-of-flight cameras for the identification of specific sized rocks to be processed. They partially addressed the dependence of autonomous or semiautonomous excavation equipment on manual monitoring. Koyachi et al [62] developed an automatic WL that enabled a short work cycle of the shovel excavation, handling, and unloading process. They pointed out that the shoveling position was determined in terms of the relationship between the material and the loader; they used stereo vision to measure the shape and position of the material and calculate its center to create guidelines for the shoveling position. Li et al [63] adopted a YOLOv4 object detection network for material detection during the shoveling process of an autonomous WL, and the average detection accuracy was 93.03%.

The researches mainly focused on autonomous driving and shoveling in WLs, aiming at more safe, intelligent and energy saving for WLs. In contrast, research on assistant driving of EWLs needs to be on the agenda.

5. Discussion and Conclusions

5.1. *The Research Viability of EWL*

As compared in section 2, due to the air pollution caused by engine emission, clean energy is expected to utilize in WLs. As a multi-sensor parameter device, even if the diesel engine is equipped with electronic control technology, it still needs complex control to make the performance superior and less energy consuming. In addition, the loader's V-type operating conditions also make it necessary to shift frequently, resulting in frequent wear of shift mechanisms and transmission gears. At finally yet importantly, the characteristic curve of diesel engine shows that it cannot work at medium and low speeds to obtain good fuel economy and high torque.

In contrast, EWLs have several distinct advantages. The first one is that the motor obtains high torque when it works at low speed, which is adequate for the working condition of a WL. The second, WLs are usually applied in fixed scenery, which is convenient to charge the batteries of an EWL, reducing idle consumption compared with that of a diesel engine. Third, the motor has the merits of high control accuracy and good response characteristics, which is conducive to the application of coordinated control and inferential approach. Finally, for areas with high emission standards and specific workplaces, EWLs can also achieve the requirement of zero emissions and low noise.

The research and application on pure EWLs might be more popular for the hybrid one has complex structure and high maintenance cost.

5.2. *The Characteristics of WL*

From the existing research, the WLs were studied almost as if they were on-road vehicles in terms of the longitudinal dynamics. However, the working procedure of WLs is quite different from that of on-road vehicles. The driving characteristics should be carefully observed and studied to research the energy savings of a WL. Most researchers overlooked the fact that before the bucket is inserted into the main body of the stockpile in the process of shoveling, the driver sets the bucket on the ground, in preparation for shoveling as much material as possible. This is because the driver cannot ensure that the height of the material pile is always maintained in a sufficient state. In order to avoid the reduction in the bucket's full load rate, the driver will subconsciously manipulate the handle to lower the boom in advance by experience, so that the bucket contacts the ground in a timely manner. The action happens in working site is shown in **Figure 11**.

This is likely to cause another influence in that since the driver cannot sense the height of the bucket being lowered, a vertical upward supporting force F_{v_up} and a horizontal shoveling resistance F_{Rl} to the bucket will be produced when the loader is going to shovel, shown in **Figure 12**. These will lead to a rise in energy consumption; in addition, the force F_{v_up} will probably decrease the force F_{pf} from the front wheels on the ground, which will reduce the maximum adhesion of the ground to the front wheels. The front wheels will slip if the torque generated by the front motor remains constant, which is greater than the maximum adhesion. This consideration is important to study in the control strategy of shoveling from the perspective of the overall energy saving of the loader. New scientific discoveries and technical inventions can be conducted using the above methodology.

Figure 11. The bucket of a WL creating positive pressure to the ground

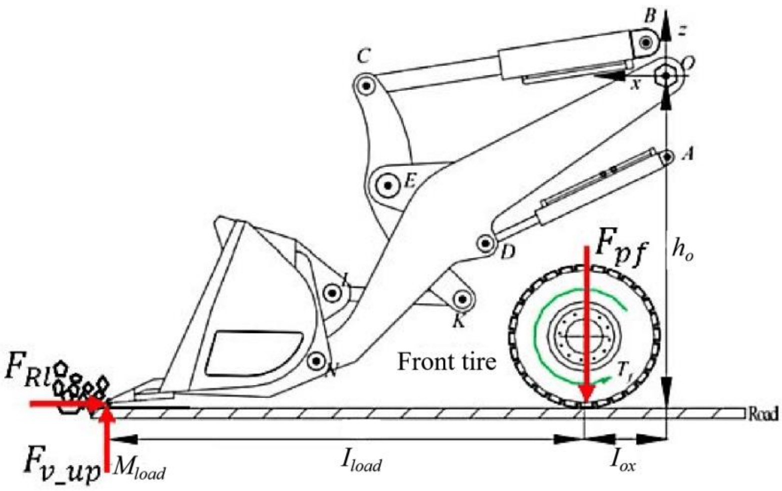

Figure 12. The change in the forces on the bucket and front wheel of a loader.

5.3. *The Overall Control of Whole System*

To reduce the resistance on the bucket, to decrease the rolling resistance, to improve the transmission efficiency, are effective ways to lower the energy consumption of WLs, according to the vehicle theory. The research could combine the mechanic features of EWL with vehicle dynamics and mechanics of motors, which has not been deeply studied in the existing literature.

In addition, as the working pump of the hydraulic system is driven by the engine power in diesel engine loaders, researchers [64], [65] have studied the design or control of the hydraulic system. Yet, we found that the new type of electric WL decouples the hydraulic working system from what was previously driven by the engine. An electric working motor is applied to drive the hydraulic pump independently, which will provide better control for the velocity and power in the loading material and dumping material stages, thereby decreasing the electricity consumption. As the running system and the hydraulic system are both driven by electric motors, the cooperative control of motors can be developed and integrated with vehicle control system in EWLs.

In terms of intelligent control of WLs, the electric type is easier to realize than the engine-drive type. Electric drive structure has less sensors and simpler composition, which will contribute to the developing of information-aware connected and unmanned WLs. The assistant drive control of EWL can be a research branch, for unskilled drivers consume more energy and obtain less productivities.

In general, the current research on pure electric loaders is relatively rare and concentrated in a few countries such as China, South Korea, and Sweden. In the process of the electrification of construction machinery, due to the structural changes and the wide application of control algorithms, the research on EWLs should be comprehensively promoted and evaluated from the aspects of structural modelling, semisimulation, and experimental verification. Some mature research methods on road electric vehicles can be used for reference too.

6. Summary

WLs are very important earthmoving machinery in construction and infrastructure industries. The diesel engines are most commonly powertrain of WLs at present. However, the severe emission pollutant, the heavy noise and the high fuel consumption are environmentally unfriendly factors. Especially for the manufactures and employers, the energy consumption of WL are vital for their business. The energy crisis is also a constant worldwide topic. Therefore, for a better energy-saving effect and high performance, the EWL can be taken as the research object in the present and the future, and systematic research can be conducted on the energy-saving control. In addition to the electric drive system, which needs to be studied like on-road vehicles, EWLs can be implemented for specific work on the following two aspects.

6.1. The Control of the Torque Distribution of Drive Motors in the Shoveling Process of WLs.

The nonlinear control algorithms can be used as the method to predict the driving resistance torque and wheel pressure to the ground during the shoveling process. Set the front and rear motor driving torque to be sufficient but lower than the adhesion force of the respective wheels as the boundary condition, build drive system models can explore whether the control effect can effectively reduce the probability of the front wheel slipping.

6.2. Assistant Drive Control Research of EWL

Assistant drive is an effective way to help unskilled drivers handle the EWLs at high performance, while autonomous EWLs are not easy to develop and promote on the market. The difficulty of the loader assisted driving research is the synergistic control of the motor control system, the electro-hydraulic system and the driving operating system.

Considering the mechanical characteristics of EWLs, the hydraulic system can be viewed as an important part of assistant driving research. If the pressure of the boom and bucket cylinders, the displacement or angle of the vital components, the speed of working motor, etc., are taken as the parameters to control and the lifting height of the boom, then, based on the parameters both in the working mechanism and the running mechanism, the state of the bucket can be determined by cooperative perception, to explore whether the front wheel can be prevented from slipping, caused by the bucket being supported by the ground during the shoveling process.

Author's Declaration

Authors' contributions and responsibilities

Conceptualization, F.X. and H.Y.; methodology, F.X. and SV.W.; investigation, F.X.; resources, H.Y.; writing—original draft preparation, F.X. and H.Y.; writing—review and editing, F.X. and SV.W.; visualization, H.Y.; supervision, SV.W.; funding acquisition, F.X. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

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Additional information

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