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Electrification of Heavy-Duty Construction Vehicles

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ABSTRACT

The number of heavy-duty construction vehicles is increasing significantly with growing urban development causing poor air quality and higher emissions. The electrification of construction vehicles is a way to mitigate the resulting air pollution and emissions. In this book, we consider tracked bulldozers, as an example, to demonstrate the approach and evaluate the benefits of the electrification of construction vehicles. The book is intended for senior undergraduate students, graduate students, and anyone with an interest in the electrification of heavy vehicles.

The book begins with an introduction to electrification of heavy-duty construction vehicles. The second chapter is focused on the terramechanics and interactions between track and blades with soil. The third chapter presents the architecture and modeling of a series hybrid bulldozer. Finally, the fourth chapter discusses energy management systems for electrified heavy construction vehicles.

KEYWORDS

hybrid electric tracked bulldozer, terramechanics, system modeling, energy management, dynamic programming, model predictive control, hybrid energy storage system

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Preface

This book introduces the electrification of heavy duty construction vehicles. It provides working characteristics and electrified configuration of heavy-duty construction vehicles and also their energy management systems. The book is intended for engineers in construction vehicle companies striving to develop an electrified vehicle and graduate and senior undergraduate students in mechanical and automotive engineering. This book is also accessible to anyone interested in learning about the electrification of heavy-duty construction vehicles. It uses a step-by-step approach using pictures, graphs, tables, and examples so that the reader can easily grasp difficult concepts.

After a short introduction, the terramechanics of a heavy-duty construction vehicles is presented. The architecture of the electrified heavy-duty construction vehicle and modeling of a series hybrid vehicle are introduced. Energy management systems for electrified heavy-duty construction vehicles are discussed and developed. The book ends with conclusions and references.

Hong Wang, Yanjun Huang, Amir Khajepour, and Chuan Hu
November 2017

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CHAPTER 1

Introduction

Off-road applications include equipment used for construction, earthmoving, agriculture, forestry, material handling, recreation, marine purposes, etc. The use of diesel engines in off-road applications is a significant source of nitrogen oxides (NOx) and particulate matter (PM10). In order to prevent global warming, conserve natural resources, and adjust to even more stringent emission regulations, manufacturers of earthmoving equipment are more than ever aware of the importance of producing environmentally friendly machines with significantly improved fuel economy. Although traditional methods have played an important role in reducing energy usage in hydraulic construction machinery, they still result in low fuel efficiency and harmful exhaust gases. New technologies are needed to further reduce fuel consumption and pollutant emissions. With their successful applications in road vehicles, electrified systems are being introduced to traditional construction machineries. Over the past decade, major manufacturers and research institutions worldwide have undertaken several projects to develop hybrid construction vehicles—including the hybrid electric bulldozer, hybrid excavator, and hybrid wheel loader. In this book, a hybrid electric tracked bulldozer (HETB) composed of an engine-generator, ultracapacitor energy storage system, and two driving motors is presented to study electrification of heavy construction vehicles and its impact in improving fuel economy.

Hybrid electric construction machineries are different from road hybrid electric vehicles (HEVs), mainly in three aspects: operation, key components, and reliability (as its components need to be more reliable and robust than road vehicles). As there are differences between hybrid electric construction vehicles and HEVs, their control strategy is also different. In this book, rule-based, dynamic programming and a model predictive controller (MPC) are developed to reduce the fuel consumption of HETBs. The results of three different strategies are compared to show the improvement in fuel efficiency.

In the following, terramechanics analysis of heavy-duty construction vehicles and interactions between track and blades with soil are studied. Using this study, and an architecture for an electrified tracked bulldozer, the modeling of the vehicle is presented. This is followed by a detailed analysis of the energy management of this electrified heavy-duty construction vehicle (including rule-based, dynamic programming and MPC-based energy management), concluding with the hybrid energy source application on this electrified heavy-duty construction vehicle.

CHAPTER 2

Terramechanics of Heavy-duty Construction Vehicle and Interactions Between Track and Blades with Soil

The external loads on bulldozers are the results of interactions between the track and blades with soil. This chapter discusses the mechanics regarding the interaction between the moving device/working part of the bulldozer, and the ground to improve the traction performance and operating efficiency of the bulldozer; and also provides the theoretical foundation for the subsequent driving dynamics analysis of the tracked bulldozer. The interaction forces are also needed in the dynamics and energy management of the electrified vehicle.

During the operation of a tracked bulldozer, the cutting edge of the working part (bulldozing plate) cuts the soil. The energy consumed by the machine, in order to overcome the cutting resistance of the soil, is exerted by the reacting force of the surface soil on the machine [1]. Therefore, during the operation of the machine the cutting resistance of the soil, the support capacity, and horizontal reacting force of the surface soil on the machine, are important factors affecting its performance and efficiency. For many years, the machine's running resistance, work resistance, traction performance, trafficability, etc., were designed and evaluated only using calculation parameters with very large safety factors [2]. For example, in order to simplify the design, the rolling resistance of the bulldozer is often denoted by the product of the rolling resistance coefficient and the weight of the whole machine under certain road conditions [3]. In fact, there are numerous complex factors that can affect the rolling resistance of the moving device for the tracked bulldozer. With the rapid development of science and technology, performance expectations of machines are getting higher, and the effect of many unknown factors (previously covered up by safety coefficients) have gradually become more prominent. The research significance of this chapter is the in-depth study of the interaction between the machine and the ground, and further revealing the interaction forces between the bulldozer and the ground.

2.1 GROUNDING PRESSURE OF TRACK AND ITS EVALUATION INDEX

A tracked bulldozer is driven by the tracks, which plays an important role in the functional application of tracked vehicles, since it bears the weight of the vehicle body and generates traction forces. A tracked vehicle has a ground area dozens or even hundreds of times larger than a wheeled vehicle. Furthermore, the quality of the whole tracked vehicle is fairly evenly distributed on each track shoe through the road wheel. This feature both reduces the pressure of the track on the ground (which can improve the trafficability of the tracked vehicle) and enlarges the contact area between the track vehicle and the ground which can enhance the drivability of tracked vehicles [4].

The ground pressure of the track is the pressure exerted by the track against the ground, which is an important factor of the tracked bulldozer, and has a great impact on the vehicle's driving resistance, traction performance, and trafficability. The ability of the tracked bulldozer to pass the soft ground is usually measured by the Nominal Ground Pressure (NGP), whose value equals to the weight of the bulldozer divided by the ground contact area of the track. NGP is based on the assumption that the track-ground pressure is evenly distributed.

$$NGP = \frac{G}{2bL} \tag{2.1}$$

where,

- G the use weight of the bulldozer (N);
- b the track width (m);
- L the ground contact length of track (m).

In fact, the experimental study of B.G. Schreiner [5] proved that tracked vehicles with the same NGP can have different maneuvering characteristics on the soft ground, i.e., the indicator NGP cannot be used to correctly evaluate maneuverability characteristics of high-speed tracked vehicles on the soft ground. In addition, D. Rowland had studied the pressure changes of 21 kinds of tracked vehicles using sensitive pressure sensors buried in 23 cm of soil, indicating that the ground pressure of tracked machines is not evenly distributed, but related to the quantity and rigidity of the thrust wheels, and the flexibleness of the track, etc. The quantity of the thrust wheels is measured by the ratio of the space between the adjacent thrust wheels S to the track pitch t. The space between the adjacent thrust wheels is called small separation distance when $S/t \leq 2$, and is called large separation distance when $S/t > 2$. The ground pressure will be relatively evenly distributed when there are many thrust wheels, the spacing ratio $S/t \leq 2$, and the track rigidity is large; on the contrary, the ground pressure will be unevenly distributed. The driving speed of the tracked bulldozer is relatively slow, and $S/t \leq 2$, thus NGP under the thrust wheels can be represented by (2.1).

2.2 TRACKED BULLDOZER EXTERNAL DRIVING RESISTANCE

The driving resistance of a tracked bulldozer usually refers to the resistance generated in the traveling of the entire moving device, beginning with the drive wheel. It includes two parts: one is generated by the frictional resistance in the friction pairs of the moving devices, including the friction loss, etc., in the drive bearing, called internal driving resistance; another is generated by the vertical deformation of the soil under the front track when the vehicle is running, called external driving resistance.

2.2.1 COMPACTION RESISTANCE

When a tracked bulldozer travels on soft soil, if the sinking depth is shallow, then the sinking is mainly caused by the vertical plastic deformation of the soil, which includes soil compaction, and the movement of a part of the soil relative to the other part of the soil. The calculation of soil vertical plastic deformation resistance is generally by aid of the principle of energy conservation, which argues that the compaction resistance of the tracked bulldozer is generated by the energy consumption of the vehicle sinking caused by the compaction of the soil body. Therefore, the compaction resistance can be calculated through the energy consumed by the soil compaction, that is, making the work done by the compaction resistance on a certain distance equal to the work done through compacting soil by the bulldozer on the same distance.

As shown in Fig. 2.1, when the tracked bulldozer moves a distance of L, the work P consumed by the vehicle for compacting the soil is:

$$P = \int_0^z 2bLp\,dz \tag{2.2}$$

where,

p the load acting on the unit supporting surface of the soil (N/m^2);

z sinking depth (m).

When the tracked bulldozer moves a distance of L, the work to overcome the driving resistance F_c should be equal to the work done by compacting the soil for the vehicle. That is,

$$F_c \bullet L = P = 2bL \int_0^z p\,dz$$

$$F_c = 2b \int_0^z p\,dz \tag{2.3}$$

Applying the Biluliya's pressure subsidence formula [165]:

$$p = kz^n \tag{2.4}$$

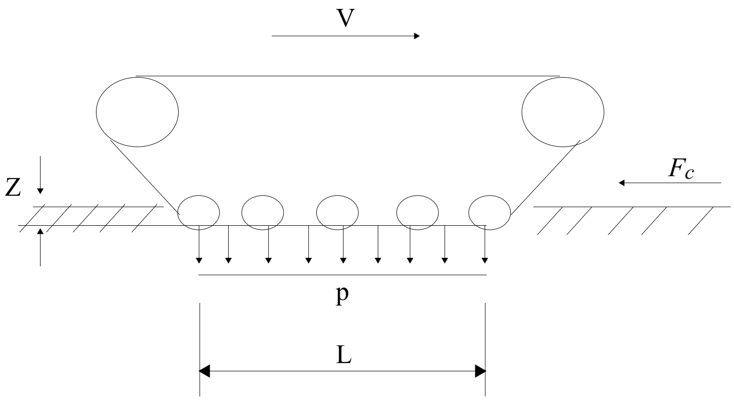

Figure 2.1: Schematic diagram for the calculation of the compaction resistance.

where,

k	deformation modulus of the soil (KN/m^{n+2}), $k = \frac{k_c}{b} + k_\varphi$;
k_c	coefficient of cohesion of the soil (KN/m^{n+1});
k_φ	internal friction coefficient of the soil (KN/m^{n+2}); and
n	deformation index of the soil, zero dimension.

Then,

$$F_c = 2b \int_0^z k z^n dz = 2bk \frac{z^{n+1}}{n+1} \tag{2.5}$$

According to (2.1), we have

$$p = \frac{G}{2bL} \tag{2.6}$$

Thus,

$$z = \left(\frac{p}{k}\right)^{\frac{1}{n}}$$

$$F_c = \frac{2b}{(n+1)k^{\frac{1}{n}}} \left(\frac{G}{2bL}\right)^{\frac{n+1}{n}} \tag{2.7}$$

Equation (2.6) clearly shows that the external driving resistance of the tracked vehicle depends on the vehicle parameters and the physical and mechanical properties of the soil. From the above equation we can make the following three conclusions:

1. Reducing the ground pressure can reduce the vehicle's driving resistance, that is, increasing the ground contact area or reducing the vehicle weight will reduce the driving resistance.

2. When the ground contact area is constant, the long and narrow track has smaller driving resistance than the short and wide track.

3. The external driving resistance of the vehicle is highly related to the physical and mechanical properties of the soil. In the dry and dense soil, the vehicle driving resistance is small, however when the vehicle works in soil with less carrying capacity (such as marshes), once the ground pressure is greater than the ultimate load capacity of the soil, the soil body will be destroyed, and the vehicle cannot move.

2.2.2 BULLDOZING RESISTANCE

When the bulldozer is running on soft ground, the bulldozer's subsidence is considerable. In addition to the compaction resistance, due to the formation of the wheel cutting of the compacted soil, the moving device of the track is also subjected to the effect of bulldozing resistance. When the tracked bulldozer is running, there is a soil uplift at the front of the track. The resistance of the soil uplift at the front of the moving device is commonly called the bulldozing resistance. The principle of formation of the bulging resistance is similar to that of the retaining wall, and can be calculated using the passive earth pressure theory on the retaining wall.

The force situation of the bulldozer track shoe is shown in Fig. 2.2, where the track shoe is subject to a passive earth pressure F_b.

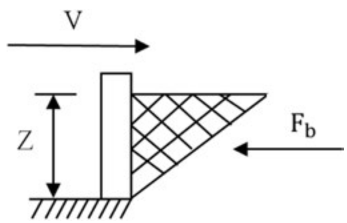

Figure 2.2: The schematic diagram of the bulldozing resistance.

According to the Langkin earth pressure formula [165], the following equation can be used to approximately express the passive earth pressure of the tracked bulldozer:

$$F_b = \gamma Z^2 b K_\gamma + 2bZcK_{pc} \tag{2.8}$$

$$K_\gamma = \left(\frac{2N_\gamma}{\tan\varphi} + 1\right)\cos^2\varphi$$
$$K_{pc} = (N_c - \tan\varphi)\cos^2\varphi$$

where

N_γ, N_c	bearing capacity factor in the whole shear failure;
γ	weight of the soil (N/m^3).

In summary, the bulldozing resistance of the bulldozer moving device is related to the soil parameters, and is also in direct proportion to the track width. Reducing the track width can reduce the bulldozing resistance.

2.2.3 OPERATING RESISTANCE

The operating resistance of the bulldozer F_T mainly includes [5]: tangential cutting resistance F_1, advancing resistance of the soil before the blade F_2, friction resistance between the cutting edge and soil F_3, horizontal component force of the friction resistance when the soil crumb is rising along the blade F_4.

$$F_T = F_1 + F_2 + F_3 + F_4 \tag{2.9}$$

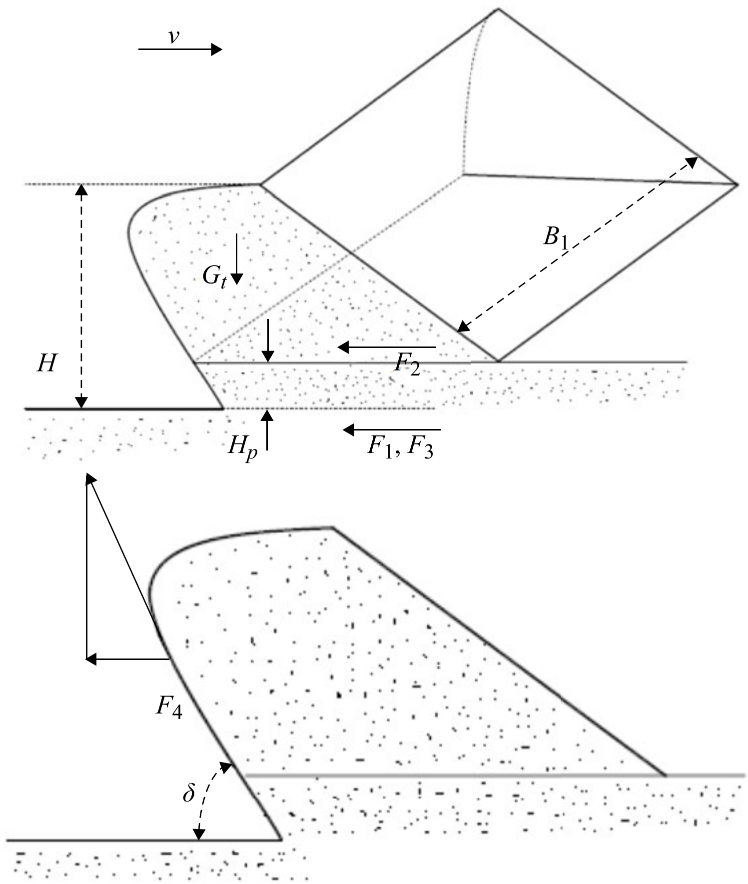

Figure 2.3: Schematic diagram of the operating resistance of the bulldozer.

(1) Tangential cutting resistance F_1

$$F_1 = 10^6 B_1 h_p k_b \tag{2.10}$$

where,

- B_1 width of the bulldozer shovel (m);
- h_p cutting depth of the bulldozer shovel (m);
- k_b cutting ratio resistance (MPa).

(2) Advancing resistance of the soil before the blade F_2

$$F_2 = G_t \mu_1 \cos\alpha = \frac{V \gamma \mu_1 \cos\alpha}{k_s} \tag{2.11}$$

$$V = \frac{B_1 \left(H - h_p\right)^2 k_m}{2 \tan\alpha_0} \tag{2.12}$$

where,

- G_t the gravity of the mound before the bulldozing plate (N);
- V the volume of the mound before the bulldozing plate (m^3);
- k_s loose coefficient of the soil;
- k_m filling coefficient of the soil;
- H height of the shovel blade (m);
- μ_1 friction coefficient of between soil and soil;
- γ weight of the soil (N/m^3);
- α gradient (°);
- α_0 repose angle of the soil (°).

(3) Friction resistance between cutting edge and soil F_3

$$F_3 = 10^6 B_1 X \mu_2 k_y \tag{2.13}$$

where

- k_y ratio resistance of the cutting edge compacting the soil after the cutting edge is worn (MPa);
- X ground contact length of the cutting edge after abrasion (m);
- μ_2 friction coefficient between the soil and steel.

(4) Horizontal component force of the friction resistance when the soil crumb is rising along the blade F_4

$$F_4 = G_t \mu_2 (\cos\delta)^2 \cos\alpha \tag{2.14}$$

where,

δ cutting angle of the bulldozer shovel (°).

2.2.4 OTHER RESISTANCES

(1) Grade resistance F_i

$$F_i = G \sin\alpha \tag{2.15}$$

where,

G working weight of bulldozer (N);

α gradient (°).

(2) Air resistance F_w

$$F_w = \frac{C_D A}{21.15} v^2 \tag{2.16}$$

where

C_D air resistance coefficient;

A windward area (m^2);

v vehicle relative driving speed (km/h).

(3) Acceleration resistance F_j

$$F_j = \delta m \frac{du}{dt} \tag{2.17}$$

where,

δ conversion factor of the vehicle rotation mass;

m mass of the whole vehicle (kg);

$\frac{du}{dt}$ driving acceleration (m/s^2).

Since the velocity and acceleration of the bulldozer are very low during operation, the air resistance and acceleration resistance can be neglected.

2.3 TRACKED BULLDOZER TANGENT TRACTION FORCE

Under the action of the vehicle, the horizontal thrust generated by the deformation of the ground is called tangential traction or soil thrust. When the vehicle is running, the drive wheel will rotate or drive the track to rotate under the action of the driving torque, and this motion will be