Hybrid Genetic Algorithm and Linear Programming for Bulldozer Emissions and Fuel-Consumption Management Using Continuously Variable Transmission

Masoud Masih-Tehrani[1] and Salman Ebrahimi-Nejad[2]

Abstract: This paper develops a hybrid optimization approach combining genetic algorithm (GA) and integer linear programming (ILP) to solve the nonlinear optimization problem of managing the fuel consumption and emissions of a tracked bulldozer. Furthermore, the authors propose that a continuously variable transmission (CVT) can better exploit the efficient zones of the engine maps. The original transmission system of the Caterpillar D6T bulldozer consists of a five-gear transmission, whereas the gear ratios of the proposed CVT are continuous and can be assigned according to transmission design. The fuel consumption and three emission items of the engine, unburned hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx), are studied. Vehicle–terrain interactions are formulated and the excavation program is characterized by excavation depth and speed. The target of the multiobjective optimization problem is a combination of fuel rate and three emission items. Results show that, for digging depths less than the bulldozer blade maximum digging depth, the target can be improved by more than 31% using CVT incorporated with GA compared to the conventional transmission, obtained by shifting engine operating points from low efficiency zones to optimum points. Finally, integer linear programming is used in a hybrid manner with GA to solve for the optimum combination of excavation steps in tasks of specified digging depths more than the maximum digging depth of the bulldozer blade. Results show that the proposed method can improve the target value up to 18% with the same digging time, and can improve the target value up to 32% using the hybrid optimization approach without time constraint. **DOI: 10.1061/(ASCE)CO.1943-7862.0001490.** © *2018 American Society of Civil Engineers.*

Author keywords: Bulldozer; Continuously variable transmission; Excavation management; Emissions reduction; Fuel consumption; Excavation optimization.

Introduction

In order to tackle global energy concerns regarding the depletion of fossil fuel reserves and the sharp increase in energy demands, it has become crucial for researchers to consider alternative energy sources such as solar and wind energies and biofuels, as well as making the best use out of the remaining fossil fuels. Improving fuel efficiency can reduce the detrimental environmental effects of fossil fuels and help meet strict emissions regulations, ensuring sustainable development.

However, today, diesel engines have been well established as the leading power-train solution, especially popular in heavy-duty vehicles, owing to their significant fuel economy and ability to fulfill stringent emissions regulations. Compared to gasoline engines, diesel engines have a high fuel efficiency, better torque characteristics, and higher power density. Therefore, many researchers have mainly focused their interests on the fields of engine-control techniques or developing alternative fuel blends for diesel engines.

Moreover, environmental and energy-related issues of heavy construction and mining machinery such as bulldozers, excavators, and dumper trucks have become fundamental at the global scale and there is a strong need to develop energy-saving and environmentally friendly technologies (Tsuji et al. 2012). Therefore, the environmental aspects of heavy construction vehicles and mitigation solutions have become interesting research areas in recent years. For example, Zhang et al. (2016b) conducted a simulation-based analysis on the performance of a tunnel-boring machine in tunneling excavation operations. Zhang (2015) conducted a simulation to estimate the fuel consumption and emissions (HC, CO, NOx, PM) of asphalt paving operations using a combination of construction equipment, including pavers, dump trucks, and rollers. Chong et al. (2016) performed a modeling of energy consumption in the process of asphalt mixture production using thermodynamic models in order to estimate energy use, costs, and greenhouse gas emissions and improve production efficiency. Furthermore, Praticò (2017) proposed metrics for management of hot-mix asphalt plants and a method for process selection based on economic and environmental sustainability. Zhang et al. (2017) used case-based reasoning to improve the planning of deep foundation construction technical specifications. Most recently, Park et al. (2017) presented a so-called dozer workability estimation method that links engine output losses to internal variables of a dozer machine and external environmental parameters in order to identify the optimal set of forward and reverse gears that maximizes economic performance.

A number of studies have also been conducted on the hybridization of bulldozer powertrains and modeling energy management strategy of hybrid bulldozers (Zhang et al. 2016a; Pan et al. 2015; Wang and Sun 2014) to improve the fuel consumption and

---

[1] Assistant Professor, Vehicle Dynamical Systems Research Laboratory, School of Automotive Engineering, Iran Univ. of Science and Technology, Tehran 16846-13114, Iran (corresponding author). ORCID: https://orcid.org/0000-0002-2936-7565. Email: masih@iust.ac.ir

[2] Assistant Professor, Vehicle Dynamical Systems Research Laboratory, School of Automotive Engineering, Iran Univ. of Science and Technology, Tehran 16846-13114, Iran. Email: ebrahiminejad@iust.ac.ir

Note. This manuscript was submitted on September 6, 2017; approved on November 27, 2017; published online on April 25, 2018. Discussion period open until September 25, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

J. Constr. Eng. Manage., 2018, 144(7): 04018053

emissions of bulldozers. However, based on the available literature, there still seems to be a wide gap between general investigations on the design of diesel engines and alternative fuels, and studies focusing on both engine and vehicle design effects, including the drive-train and vehicle–terrain interactions, to obtain the performance and emissions of road vehicles or specific construction operations. Mata et al. (2016) proposed a procedure for predicting NOx emissions and fuel consumption of a city bus. They proposed that online reprogramming of the electronic control unit (ECU) can help achieve optimum driving conditions by modifying gear changes, which is feasible for a city bus with automatic transmission. The work done by Giakoumis and Alysandratou (2016) compared engine and vehicle performance of a number of heavy-duty diesel trucks of different masses, wheel-bases, frontal areas, aerodynamic resistance coefficients, wheel radii, and transmission systems in an urban driving cycle. Although the study might fall short of a systematic comparison, the authors pointed out the importance of a carefully-designed drive-train configuration through the selection of an appropriate gearbox. By comparing two vehicles equipped with a 16-speed gearbox and a 6-speed gearbox, they concluded that the 16-speed gearbox decisively influenced the whole drive-train behavior and was a significant contributor to the superior vehicle performance and emissions profile. The greater number of speeds in the gearbox resulted in milder acceleration phases and hence lower amounts of emission.

In this article, the fuel consumption and emissions of bulldozer will be improved by incorporating a continuously variable transmission (CVT) instead of a manual transmission. A CVT is an automatic transmission system that has a continuous range of gear ratios. Market trends show the continuing success of CVTs in passenger cars and heavy road vehicles (Greiner et al. 2015). Therefore, a number of research works have concentrated on CVT tuning for trucks and other heavy commercial vehicles. Wang et al. (2015) tried to improve the shift performance of a tractor hydraulic power-split CVT by identifying the effective factors influencing CVT shift dynamics, such as engine speed, clutch oil flow rate, and shift timing. Howard et al. (2013) tested a John Deere 8295R tractor with a CVT comparing it with a standard geared transmission. The fuel consumption of the CVT case was studied at six different load levels, each with three travel speeds, and was shown to be much better than that of the standard gear case. Electric driven CVTs (e-CVTs) have been used in hybrid passenger cars. Rossi et al. (2014) proposed a new layout design of e-CVT based on concentric and coaxial arrangements of the electric engines for agricultural tractor applications.

Three emission items, unburned hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx), are modeled and optimized in the current work, using a cost function that reflects the trade-offs among these emission items and between fuel consumption and emission. Therefore, the optimization problem of this article has strong nonlinearity and complexity specifications, and a genetic algorithm (GA), which is a famous optimization method and has been proved as a suitable method for solving such complicated problems in many fields of engineering, is used to obtain an optimal solution. Then, a hybrid optimization approach combining GA and integer linear planning (ILP) is defined to solve the nonlinear optimization problem of managing the fuel consumption and emissions of a tracked bulldozer in excavation programs. This method is especially useful for cases when the target depths are more than the maximum digging depth of the bulldozer and the digging depth can be achieved in multiple stages. Two types of optimization problems are defined that either impose a constraint on the number of stages (the digging time) or optimize the excavation program without time constraint. The CVT is used in this research work as the transmission of the bulldozer, which can better exploit the efficient zones of the engine maps. The excavation program is characterized by excavation depth and speed, and the target of the optimization problem is a combination of fuel rate and three emission items.

A bulldozer is a heavy construction vehicle used for pushing rocks or earth, farming, and road construction. During excavation and earth removal, the bulldozer blade is kept below earth level, doing work to ground materials such as clays, soils, sands, and rocks directly (Tsuji et al. 2012), and the tracks are in constant interaction with the terrain; therefore, bulldozer performance is highly affected by soil terramechanics. So, interactions between the terrain and bulldozer blade and tracks, which determine the motion resistance and the traction force of the tracked vehicle, are also formulated into the optimization problem.

The remainder of the article is organized as follows. In the next section, a Caterpillar D6T bulldozer (US) is introduced as a case study and engine specifications such as fuel consumption and emission characteristics are modeled. The vehicle–terrain interactions are studied in the section "Vehicle–Terrain Interaction Modeling." The sandy loam terrain is selected in this article as a case study. A semiempirical method is used for modeling the traction force and motion resistance of the tracked bulldozer. The traction optimization problem is defined in the section "Traction Problem Optimization." For each problem, the digging depth and bulldozer speed are specified, and the bi-objective cost function, the targets of which are fuel consumption and a weighted combination of emissions, is optimized. The section "Excavation Program" presents a robust algorithm for specifying the optimum excavation process using linear programming. Finally, concluding remarks are presented in the section "Conclusions."

Caterpillar D6T Bulldozer

The Caterpillar D6T bulldozer (Caterpillar 2018) is studied in this article. The main specifications of the bulldozer are listed in Table 1. As seen in the table, the bulldozer gearbox has three main (1, 2, and 3) and two auxiliary (1.5 and 2.5) gears.

The engine specifications for Caterpillar 3126E engine (275 hp/205 kW) exist in ADVISOR software (Markel et al. 2002). The data include fuel economy, HC, CO, and NOx at brake torque for 13 test modes from Battelle (Columbus, Ohio) over European Stationary Cycle (ESC, also known as OICA/ACEA),

Table 1. Main specifications of the Caterpillar D6T bulldozer

Parameter	Value
Suspension type	Tracked
Track width (m)	0.610
Track length (m)	3.206
Operating mass (kg)	20,985
Blade type	6A
Blade width (m)	4.160
Blade height (m)	1.151
Digging depth (m)	0.555
Transmission efficiency (%)	85
Gear 1.0 (km/h)	3.7
Gear 1.5 (km/h)	4.7
Gear 2.0 (km/h)	6.5
Gear 2.5 (km/h)	8.2
Gear 3.0 (km/h)	11.3
Engine power (kW)	154

Source: Data from Caterpillar (2018).

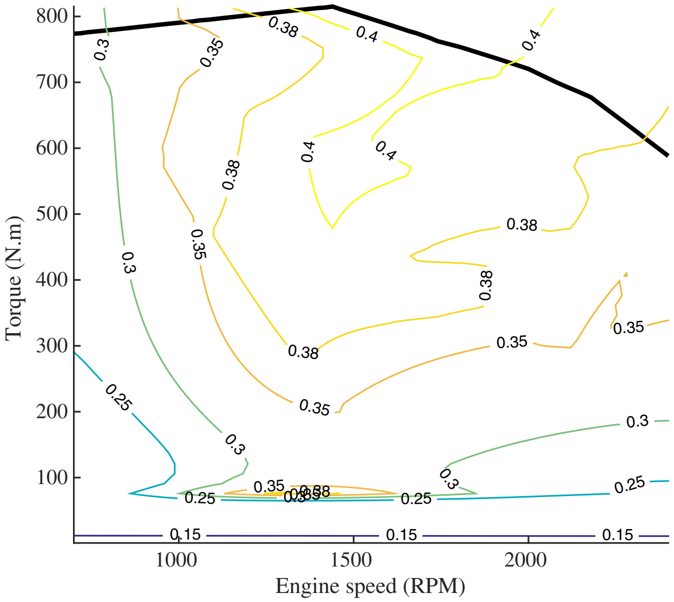

Fig. 1. Engine fuel efficiency map, showing fuel efficiency $(\mathrm{kW \cdot h/g})$ as influenced by engine speed and engine torque.

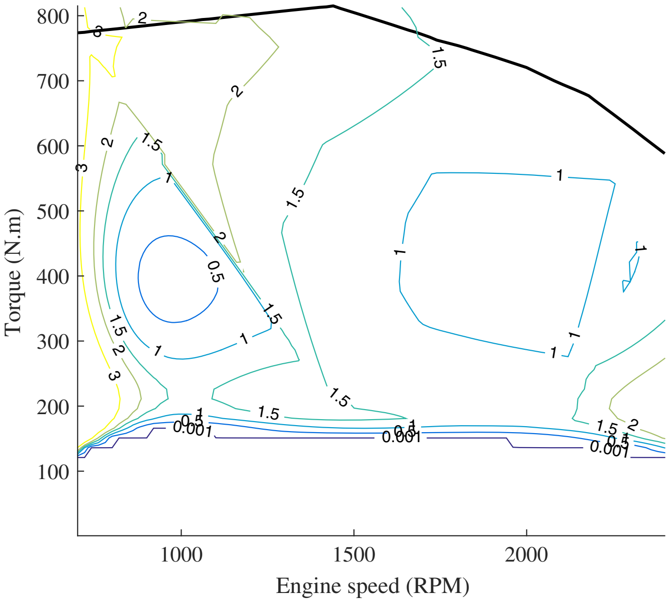

Fig. 3. Engine CO emission map $[\mathrm{g/(kW \cdot h)}]$.

National Renewable Energy Laboratory (NREL), US Department of Energy. For the Caterpillar D6T bulldozer, the maps are scaled for power satisfaction.

The engine fuel efficiency map is shown in Fig. 1. The thick solid line shows the maximum engine torque versus engine speed. As shown in Fig. 1, the high efficiency zone of this engine is in the medium engine speed range, where the engine torque is greater than 500 N · m. In order to optimize bulldozer fuel efficiency, bulldozer operation dynamics are controlled in order for the engine to operate in the optimal zone.

Engine exhaust HC, CO, and NOx emission maps are shown in Figs. 2–4, respectively. As shown in these figures, the low emission zones differ significantly for three types of emissions and fuel efficiency maps. Therefore, a trade-off exists between fuel consumption and engine emissions. A sophisticated optimization algorithm should be used for this complicated problem.

Vehicle–Terrain Interaction Modeling

In Table 2, the terrain (sandy loam) specifications are listed.

A semiempirical method is proposed by (Bekker 1960; Wong 2010) to determine the motion resistance and traction force of a track vehicle. The method proposed by Bekker assumes that the track has a rigid footing and that the vertical force applied on the track by the terrain can be equivalent to that beneath a sinkage plate at the same depth in a pressure-sinkage test. If the longitudinal position of the vehicle center of gravity is located at the track contact length center, the normal pressure distribution is supposed to be

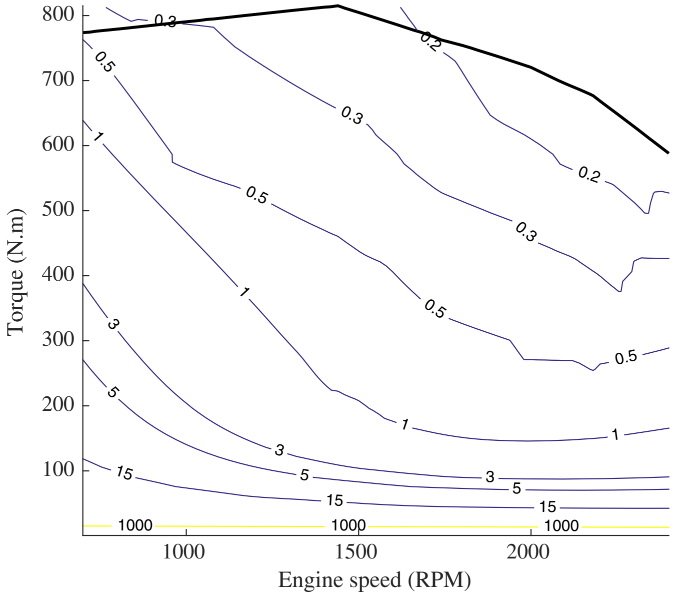

Fig. 2. Engine HC emission map $[\mathrm{g/(kW \cdot h)}]$.

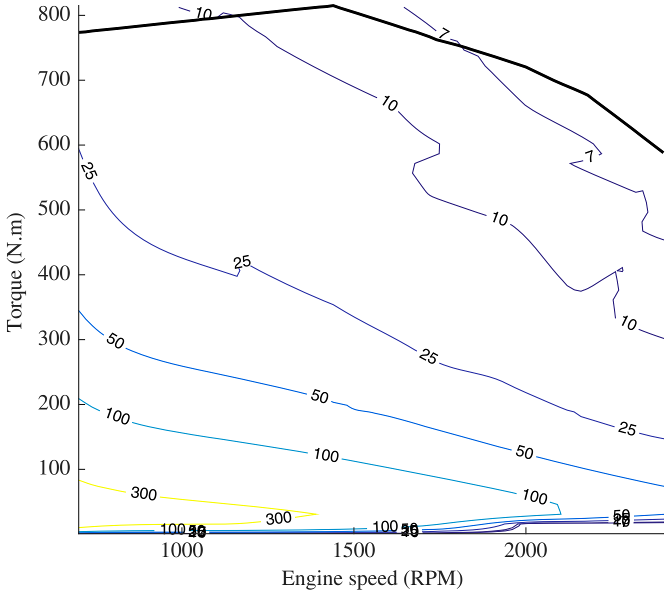

Fig. 4. Engine NOx emission map $[\mathrm{g/(kW \cdot h)}]$.

Table 2. The terrain (sandy loam) specifications

Parameter	Description	Unit	Value
n	Exponent of sinkage	—	0.7
ϕ	Angle of shearing resistance	degrees	29
c	Cohesion	kPa	1.72
k_ϕ	Frictional modulus	kN/m^{n+2}	1,515.04
k_c	Cohesive modulus	kN/m^{n+1}	5.27

Source: Data from Mastinu and Ploechl (2014).

uniform. The motion resistance (R_c) due to pressing the terrain by a track with uniform pressure based on Bekker's pressure-sinkage method is expressed by (Mastinu and Ploechl 2014)

$$R_c = \frac{1}{(n+1)b^{1/n}(k_c/b + k_\phi)^{1/n}} \left(\frac{W}{l}\right)^{(n+1)/n} \quad (1)$$

The drawbar pull (F_{DP}) (Cutini and Bisaglia 2016) is expressed by

$$F_{DP} = F - R_c \quad (2)$$

where F = wheel thrust, which is the total force in the direction of travel as determined from tangential stress measurements at the soil–wheel interface. For a regular track with constant normal pressure, the drawbar pull-slip relation is given by (Mastinu and Ploechl 2014)

$$\begin{aligned} F_{DP} &= b\int_0^l \left(c + \frac{W}{bl}\tan\phi\right)(1 - \mathrm{e}^{-ix/K})dx \\ &= (Ac + W\tan\phi)\left[1 - \frac{K}{il}(1 - \mathrm{e}^{-il/K})\right] \end{aligned} \quad (3)$$

where i = track slip (Kumar et al. 2017); x = longitudinal direction; K = shear deformation modulus; and A = track area. The drawbar pull curve in terms of slip for sandy loam terrain is shown in Fig. 5.

According to Eqs. (1)–(3), drawbar pull depends on terrain characteristics (n, c, ϕ, k_c, k_ϕ, and K) and vehicle specifications (W, b, and l). In addition, drawbar pull depends on the track slip ratio (i), which is related to engine speed. Therefore, the bulldozer traction and digging control can be performed by changing the engine operating point. The engine operating point is defined by engine speed (rpm) and torque.

The force acting on a vertical bulldozer blade (F_P) with a plane surface can be determined as follows (Wong 2008):

$$\begin{aligned} F_P &= bb\int_0^{h_b} \sigma_p dz = bb\int_0^{h_b} (\gamma_s z N_\phi + 2c\sqrt{N_\phi})dz \\ &= bb\left(\frac{1}{2}\gamma_s h_b^2 N_\phi + 2ch_b\sqrt{N_\phi}\right) \end{aligned} \quad (4)$$

where h_b = cutting depth of the blade; bb = blade width; σ_p = passive earth pressure; γ_s = weight density of the terrain; and N_ϕ = flow value that is equal to $\tan^2(45° + \phi/2)$.

The vehicle speed (V) in relation to the engine speed (n_e) can be determined using (Wong 2008)

$$V = \frac{n_e r}{\xi_0}(1 - i) \quad (5)$$

where r = radius of the drive sprocket; and ξ_0 = total transmission ratio, which is the number of revolutions of the engine crank shaft per revolution of the track drive sprocket. As seen in Eq. (5), the vehicle speed is related to the engine speed and the track slip. Track slip is dependent upon the drawbar pull, terrain type characteristics, and engine torque.

All the equations are used in this section are derived and validated by experimental tests (Bekker 1960, 1969; Wong 2008, 2010; Mastinu and Ploechl 2014; Cutini and Bisaglia 2016; Kumar et al. 2017).

Traction Problem Optimization

Excavation is the main mission of a bulldozer. For excavation optimization, the focus is on the digging depth and vehicle speed. On the other hand, fuel consumption and emissions of engine can be minimized in an optimum traction program. These targets, when gathered in an optimization problem, form a bi-objective problem, the targets of which are fuel consumption and a weighted combination of emissions. The optimization problem can be further simplified by assigning weights to fuel consumption and emissions (i.e., 0.5), and the bi-objective optimization problem is transformed into a single-objective optimization model. Therefore, the proposed model is simplified into a single-objective optimization model.

For a specific excavation program in which the digging depth and bulldozer velocity are specified, the engine operation point can be controlled to minimize the fuel consumption rate and exhaust emissions. The optimization variables are engine speed (n_e), engine throttle position (th), and transmission gear number (gn) for the case of a manual gearbox, or total transmission ratio (ξ_0) for the case of a CVT. The optimization problem can be defined as Eq. (6):

$$\begin{aligned} \text{Minimize: } & Target = Target(n_e, th, gn(\xi_0)) \\ & \qquad = W_1 \times fuelrate + W_2 \times emission \\ \text{subject to: } & h_b = h_{\text{dem}} \\ & V = V_{\text{dem}} \end{aligned} \quad (6)$$

where W_1 and W_2 are weight factors of the target function. The optimization problem [Eq. (6)] has two constraints that are specified by the excavation program. The values of h_{dem} and V_{dem} are the demanded digging depth and bulldozer velocity, respectively. The target of the optimization problem [Eq. (7)] is

$$Target = 0.5 \times \frac{fuelrate}{3} + 0.5 \times \left(\frac{\text{HC}}{0.02} + \frac{\text{CO}}{0.007} + \frac{\text{NOx}}{0.4}\right) \quad (7)$$

The coefficients of Eq. (7) are for normalization of fuel rate, emission factors, and weight factors of the optimization problem.

The calculation steps are as follows:

- The thrust force is determined from engine torque and total transmission ration (ξ_0). The engine torque (M_e) is calculated from n_e and th by Eq. (8)

  $$M_e = th \times M_{\max}(n_e) \quad (8)$$

  where th = throttle position and is a normalized number between 0 and 1. The $M_{\max}$ is engine maximum torque at a specific engine speed (n_e). The thrust force (F) is determined from

  $$F = \frac{M_e \xi_0 \eta_t}{r} \quad (9)$$

  where η_t is transmission efficiency (Table 1).
- The track slip ratio is determined by draw bar pull from Fig. 5. The draw bar pull (F_{DP}) is calculated from Eqs. (1), (2), and (9).
- The digging depth (h_b) is calculated by an iterative method from the draw bar pull [Eq. (4)].

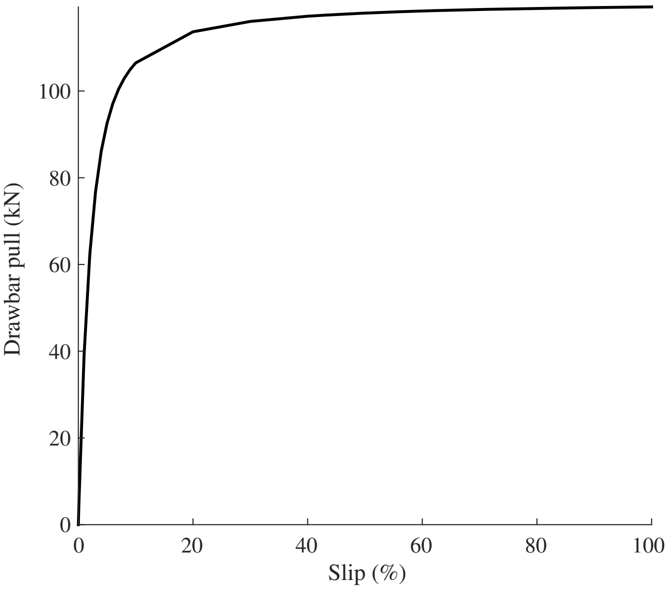

Fig. 5. Drawbar pull-slip curve for a tracked vehicle.

- The vehicle speed is determined from Eq. (5).
- For solving the optimization problems of this article, the genetic algorithm of MATLAB is used (Houck et al. 1995). The GA method is run for a reasonable time to ensure convergence. Solution of the GA method in each iteration is set as the initial population of the next GA run. Integer programming is activated for high speed and accuracy (Yokota et al. 1996).

The properties of the GA are listed in Table 3.

Here, the traction optimization problem can be summarized in a flowchart (Fig. 6). As shown in this diagram, the optimum engine working points are determined by the "engine and vehicle controller," which is worked out based on a GA. The cost function and constraints are calculated from the terramechanics equations and specified digging depth. Furthermore, the traction optimization problem is defined and solved for two cases: CVT and manual gearbox.

Five excavation programs are studied as individual cases here. The results of optimization problems [Eqs. (6) and (7)] for conventional manual transmission and CVT are shown in Table 4. As seen in this table, the targets of fuel rate and emissions [Eq. (7)] are improved between 11 to 31% when the conventional manual transmission is replaced by the CVT. These improvements in the overall

Table 3. Properties of the GA

Parameter	Description	Value
PopulationType	Data type of the population.	"Bitstring" and "Doublevector"
PopulationSize	Size of the population.	50
EliteCount	Positive integer specifying how many individuals in the current generation are guaranteed to survive to the next generation.	3
CrossoverFraction	The fraction of the population at the next generation, not including elite children, that is created by the crossover function.	0.8
MigrationFraction	Scalar between 0 and 1 specifying the fraction of individuals in each subpopulation that migrates to a different subpopulation.	0.2
MaxGenerations	Maximum number of iterations before the algorithm halts.	300
TimeLimit	The algorithm stops after running after TimeLimit seconds.	Inf
MaxStallGenerations	The algorithm stops if the average relative change in the best fitness function value overMaxStallGenerations generations is less than or equal to FunctionTolerance. If StallTest is "geometricWeighted", then the algorithm stops if the weighted average relative change is less than or equal to FunctionTolerance.	50
TolFun	The algorithm stops if the average relative change in the best fitness function value over MaxStallGenerations generations is less than or equal to TolFun.	1×10^{-6}
TolCon	Determines the feasibility with respect to nonlinear constraints.	1×10^{-3}

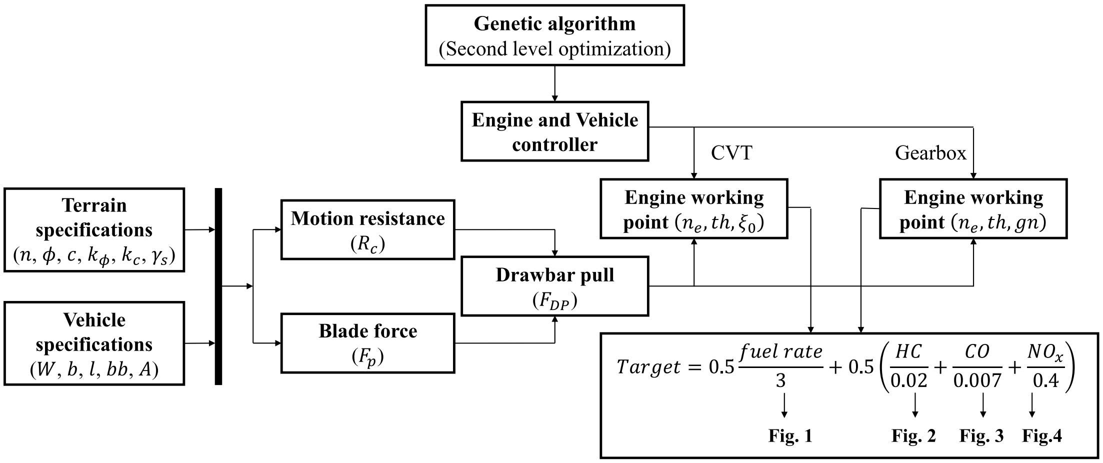

Fig. 6. Flowchart of the traction optimization problem.

Table 4. Excavation program optimization

Case number	Digging depth (m)	Bulldozer velocity (km/h)	Transmission type	Target (improvement)	Fuel rate (g/s)	HC (g/s)	CO (g/s)	NOx (g/s)
1	0.2	4	Gearbox	0.62	1.31	0.0260	0.0000	0.45
			CVT	0.54 (13.63%)	1.10	0.0205	0.0000	0.44
2	0.2	5	Gearbox	0.57	1.34	0.0183	0.0000	0.47
			CVT	0.51 (11.00%)	1.19	0.0158	0.0000	0.43
3	0.5	2	Gearbox	1.22	2.16	0.0243	0.0216	0.35
			CVT	0.84 (31.18%)	1.76	0.0137	0.0106	0.44
4	0.55	5	Gearbox	1.95	4.55	0.0084	0.0417	0.31
			CVT	1.38 (29.37%)	4.32	0.0090	0.0189	0.32
5	0.55	7	Gearbox	2.17	5.80	0.0084	0.0419	0.32
			CVT	1.75 (19.27%)	5.98	0.0080	0.0243	0.26

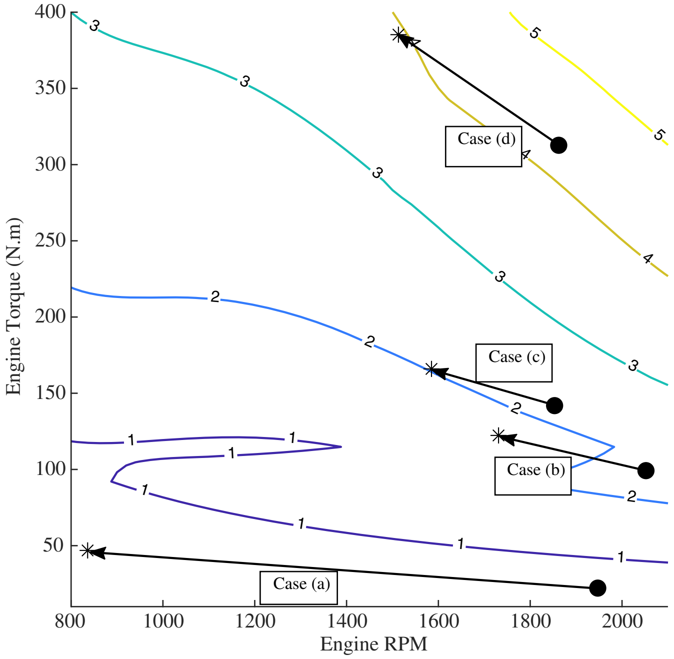

Fig. 7. Engine fuel consumption map (g/s) and comparison in three different case studies for gearbox and CVT transmissions.

target function are divided between the four components of the target (fuel rate and three emission items).

A simple illustration of the effects of replacing the manual transmission with a CVT and optimization is presented for the four cases in which the fuel consumption was minimized. Fig. 7 shows the shift in operating points on the engine fuel consumption map. The filled circular points correspond to the cases of manual transmission, and the starred points correspond to the CVT cases. As presented in this figure, in these cases, the manual transmission points are in the higher fuel consumption contours in comparison with the CVT points. Similar results can also be presented for HC, CO, and NOx. Detailed results are listed in Table 5.

Excavation Program

A bulldozer has a specific task for excavating an area, e.g. 5-m digging depth in a 100-m-long path. On the other hand, the maximum digging depth of the dozer blade is a limited value (about 0.55 m for the case of this paper). Therefore, the excavation process should be done in several steps. Here, an excavation program can be defined. The variables of the program are the number of the digging steps and the digging depth in each step.

The number of digging processes with a specific digging depth is chosen as the optimization variable. Different digging depths are assumed: 0.05 m, 0.10 m, 0.15 m, 0.20 m, 0.25 m, 0.30 m, 0.35 m, 0.40 m, 0.45 m, 0.50 m, and 0.55 m [the maximum digging depth of the blade is 0.555 m (Table 1)]. The optimum excavation problem can be defined as Eq. (10)

$$
\begin{aligned}
&F_{\text{val}} = Minimize \sum_{i=1}^{11} x_i Target_i \\
&\text{subject to:} \sum_{i=1}^{11} x_i h_i = dig_{\text{set}} \\
&\sum_{i=1}^{11} x_i = roundup(dig_{\text{set}}/0.55) \\
&i = 1, \ldots, 11{:}\ LB_i = 0 \\
&i = 1, \ldots, 11{:}\ UB_i = roundup(dig_{\text{set}}/0.55) \qquad (10)
\end{aligned}
$$

$$h = [0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55]m$$

Table 5. Fuel rate optimization results for four case studies (Fig. 7)

Case study	Digging depth (m)	Bulldozer velocity (km/h)	Transmission type	Engine rpm (n_e)	Engine throttle position (th)	Fuel rate (g/s) (improvement)
a	0.1	3	Gearbox	1,948	3	0.52
			CVT	836	6	0.48 (8.09%)
b	0.2	7	Gearbox	2,053	14	1.85
			CVT	1,731	16	1.69 (8.75%)
c	0.3	5	Gearbox	1,854	19	2.11
			CVT	1,585	21	1.92 (9.07%)
d	0.5	5	Gearbox	1,863	42	3.95
			CVT	1,513	48	3.62 (8.38%)

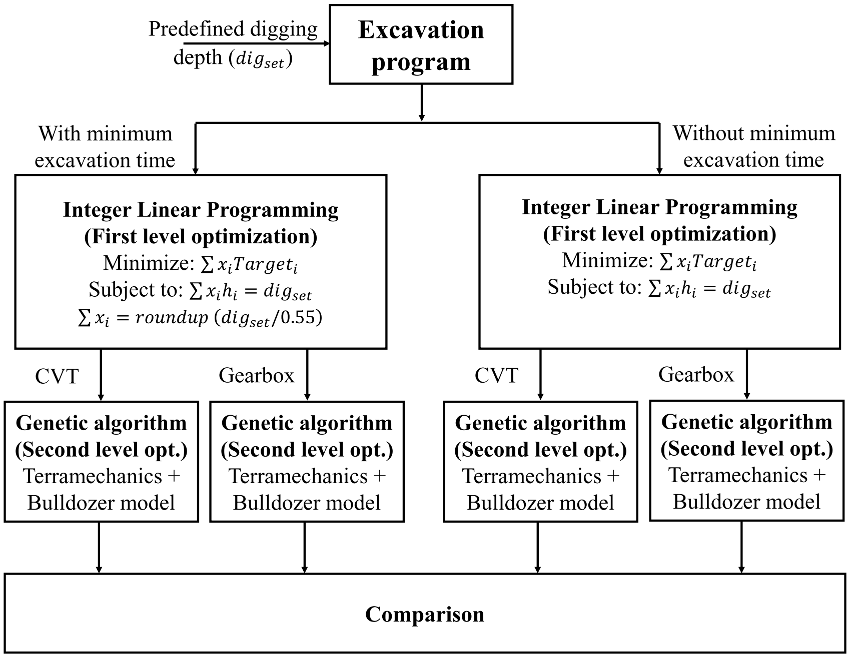

Fig. 8. Flowchart of the excavation program.

As seen in Eq. (10), the optimization cost function (F_{val}) is the summation of fuel consumption and emission targets in a high-speed excavation process [$Target_i$ in Eq. (7) for 7 km/h bulldozer velocity] with respect to the digging steps (x_i). Index i indicates each digging depth option ($h = 0.05 \times i$ m). The variable x is the optimization variable and specifies the number of active digging depth steps; for example, $x_3 = 2$ means that the bulldozer digs the path twice with 0.3-m digging depth each time. The first constraint means that the sum of the digging depths of all steps should be equal to the predefined digging depth (dig_{set}). The second constraint means that the sum of the excavation processes should be equal to $roundup(dig_{\text{set}}/0.55)$ value. This constraint guarantees the minimum possible number of excavation stages and hence minimum process time duration. The lower bound (LB) of the variables is set to zero (for any digging step that is not used in a digging program). The upper bound (UB) of the variables is set to $dig_{\text{set}}/0.55$ value. The UB is rounded up to generate an integer number.

Eq. (10) shows an optimization problem with a linear objective function and a linear constraint, and the variables are integers. Therefore, a highly efficient integer linear programming method can be devised for solving the optimal excavation program. The simplified definition of the problem is: to dig a specific path with a predefined digging depth (dig_{set}), what is the optimum number of digging steps and how deep should each step be dug? The target is maximum overall excavation speed and minimum fuel consumption and emissions.

Now, the excavation program can be summarized in a flowchart (Fig. 8). As shown in this diagram, the optimization is done at two levels: The first-level optimization is done by ILP, and the second-level optimization is performed using GA. Moreover, the first-level optimization is performed for two cases: with and without time limits. As mentioned in the previous section, the second-level optimization (GA) is performed for CVT and gearbox cases. The results for all four cases can be compared by the excavation manager.

To find the excavation program with the optimum speed, the number of digging steps are minimized. For each digging step, the maximum vehicle speed (7 km/h in this case study) is assumed. The fuel and emissions targets comparisons for gearbox and CVT transmissions in different digging depths for 7 km/h bulldozer velocity are listed in Table 6.

Another optimum excavation problem can be defined as Eq. (11). In this problem, the second constraint of Eq. (11) is eliminated. Therefore, the number of digging processes can be greater than the $roundup(dig_{\text{set}}/0.55)$ value

$$F_{\text{val}} = Minimize \sum_{i=1}^{11} x_i Target_i$$

$$\text{subject to}: \sum_{i=1}^{11} x_i h_i = dig_{\text{set}}$$

$$i = 1, \ldots, 11: LB_i = 0$$

$$i = 1, \ldots, 11: UB_i = roundup(dig_{\text{set}}/0.55) \qquad (11)$$

The fuel and emissions target function values for conventional and CVT transmissions, with and without time optimization, are

Table 6. Fuel and emissions targets comparisons for gearbox and CVT transmissions in different digging depths for 7 km/h bulldozer velocity

Digging depth (m)	Fuel and emissions target (gearbox)	Fuel and emissions target (CVT)	Improvement (%)
0.05	0.72	0.66	8.53
0.1	0.57	0.57	0
0.15	0.55	0.50	9.26
0.2	0.54	0.54	0
0.25	0.61	0.60	1.86
0.3	1.00	1.00	0
0.35	1.14	1.12	1.66
0.4	1.25	1.25	0
0.45	1.48	1.37	7.48
0.5	1.53	1.53	0
0.55	2.17	1.75	19.27

Table 7. Fuel and emissions targets for gearbox and CVT transmissions in different digging sets, with and without time optimization, for a field with 700 m length

Overall digging depth	Fuel and emission target (gearbox) [Eq. (10)]	Fuel and emissions target (CVT) [Eq. (10)]	Fuel and emissions target (CVT) [Eq. (11)]
0.7 m	2.07	1.98	1.74
	Improvement:	4.38%	15.6%
	Time consuming:	12 min	18 min
	4.3	4.27	3.72
1.4 m	Improvement:	0.656%	13.5%
	Time consuming:	18 min	30 min
	7.39	6.55	5.55
2.1 m	Improvement:	11.3%	24.8%
	Time consuming:	24 min	48 min
	8.6	8.45	7.3
2.8 m	Improvement:	1.71%	15.1%
	Time consuming:	36 min	66 min
	10.7	10.7	9.12
3.5 m	Improvement:	0%	14.6%
	Time consuming:	42 min	90 min
	14.8	13.1	11
4.2 m	Improvement:	11.3%	25.4%
	Time consuming:	48 min	102 min
	18.9	15.5	12.9
4.9 m	Improvement:	17.7%	31.6%
	Time consuming:	54 min	120 min

listed in Table 7, in a field of 700 m length for some digging sets (as case studies). As seen in Table 7, the CVT transmission (the third column) can improve the fuel consumption and emissions targets up to 17.7% in comparison with the conventional gearbox bulldozer (the second column) in these digging cases. In both the second and third columns, it is assumed that the minimum digging time is important, and the optimization problem is assumed as Eq. (10). If the minimum digging time is not so important, Eq. (11) can be used. In this case (the fourth column), the fuel consumption and emissions targets can be improved up to 31.6% in comparison with the conventional gearbox bulldozer (the second column). However, the number of stages and hence the excavation time may increase up to twice or even more.

Conclusions

A hybrid GA and ILP optimization method is developed in this paper to manage excavation programs of a bulldozer, especially when the digging target is more than the maximum digging depth of the blade. The transmission ratio flexibility of CVT is used, incorporated with the proposed method to shift engine operating points from low efficiency zones to operating zones ensuring optimal fuel rate and exhaust emissions. The proposed optimization procedure helped improve the fuel rate and emissions (HC, CO, and NOx) target function of a bulldozer by more than 31% in five case studies for digging depths less than the maximum digging depth of the bulldozer blade. The terrain type of this research was assumed as sandy loam. Bekker's formula was used for the vehicle–terrain interaction. Finally, integer linear programming was used to solve the excavation program problem, the target of which was to find the optimum combination of digging steps for a specific digging depth program. The results showed that the CVT transmission can improve the fuel consumption and emissions targets up to 17.7% with the same excavation time, and can improve the targets up to 31.6% without excavation time constraint, in comparison with the conventional gearbox bulldozer. The proposed optimization formula can be redefined for other off-road vehicles and terrain types. The approach provides a powerful solution to modeling and control of off-road and construction vehicles that can be implemented in dynamic control methods such as fuzzy controllers to reduce environmental impacts of heavy vehicles.

In addition, the proposed methodology of this paper can be used for fuel consumption optimization and emission reduction in other commercial and off-road vehicles, especially agricultural and construction vehicles. In this paper, a tracked bulldozer is considered. However, the same methodology can be used in future research for optimization of a pneumatic wheeled bulldozer, loader, or excavator. Furthermore, the concept of drawbar pull in this research work is considered the force acting on a vertical bulldozer blade. In other agricultural and construction vehicles, the drawbar pull can be replaced by other forces that should be produced by the vehicle, with respect to their missions, soil and terrain types, and applications.

Data Availability Statement

All data generated or analyzed during the study are included in the published paper. Information about the *Journal's* data sharing policy can be found here: https://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

Acknowledgments

The authors wish to express their gratitude for the scientific and financial support from the Automotive Engineering Research Center (AERC) of Iran University of Science and Technology (IUST).

References

Bekker, M. G. 1960. *Off-the-road locomotion*. Ann Arbor, MI: Michigan University Press.

Bekker, M. G. 1969. *Introduction to terrain-vehicle systems*. Ann Arbor, MI: University of Michigan Press.

Caterpillar. 2018. "The cat d6t dozer: Caterpillar-D6TDozer." Accessed March 20, 2017. https://www.cat.com/en_US/products/new/equipment/dozers/medium-dozers/1000028472.html.

Chong, D., Y. Wang, L. Chen, and B. Yu. 2016. "Modeling and validation of energy consumption in asphalt mixture production." *J. Constr. Eng. Manage.* 142 (12): 04016069. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001189.

Cutini, M., and C. Bisaglia. 2016. "Development of a dynamometric vehicle to assess the drawbar performance of high-powered agricultural tractors." *J. Terramechanics* 65: 73–84. https://doi.org/10.1016/j.jterra.2016.03.005.

Giakoumis, E. G., and A. Alysandratou. 2016. "Performance and emissions of a heavy-duty truck during the UDDS driving cycle: Simulation analysis." *J. Energy Eng.* 142 (2): E4015011. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000320.

Greiner, J., M. Grumbach, A. Dick, and C. Sasse. 2015. Advancement in NVH- and fuel-saving transmission and driveline technologies. *SAE 2015 World Congress & Exhibition*. Warrendale, PA: SAE International.

Houck, C. R., J. Joines, and M. G. Kay. 1995. *A genetic algorithm for function optimization: A MATLAB implementation*. NCSU-IE TR 95-09. Raleigh, NC: North Carolina State Univ.

Howard, C. N., M. F. Kocher, R. M. Hoy, and E. E. Blankenship. 2013. "Testing the fuel efficiency of tractors with continuously variable and standard geared transmissions." *Trans. ASABE* 56 (3): 869–879. https://doi.org/10.13031/trans.56.10222.

Kumar, A. A., V. Tewari, C. Gupta, and C. Pareek. 2017. "A device to measure wheel slip to improve the fuel efficiency of off road vehicles." *J. Terramechanics* 70 (Apr): 1–11. https://doi.org/10.1016/j.jterra.2016.11.002.

Markel, T., A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik, and K. Wipke. 2002. "Advisor: A systems analysis tool for advanced vehicle modeling." *J. Power Sources* 110 (2): 255–266. https://doi.org/10.1016/S0378-7753(02)00189-1.

Mastinu, G., and M. Ploechl. 2014. *Road and off-road vehicle system dynamics handbook*. London: CRC Press.

Mata, C., W. de Oliveira Leite, R. Moreno, J. R. Agudelo, and O. Armas. 2016. "Prediction of NOx emissions and fuel consumption of a city bus under real operating conditions by means of biharmonic maps." *J. Energy Eng.* 142 (4): 04016018. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000363.

Pan, M., J. Yan, Q. Tu, and C. Jiang. 2015. "Fuzzy control and wavelet transform-based energy management strategy design of a hybrid tracked bulldozer." *J. Intell. Fuzzy Syst.* 29 (6): 2565–2574. https://doi.org/10.3233/IFS-151959.

Park, Y.-J., H.-S. Gwak, and D.-E. Lee. 2017. "Dozer workability estimation method for economic dozing." *J. Constr. Eng. Manage.* 143 (2): 04016096. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001228.

Praticò, F. G. 2017. "Metrics for management of asphalt plant sustainability." *J. Constr. Eng. Manage.* 143 (4): 04016116. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001253.

Rossi, C., D. Pontara, and D. Casadei. 2014. "e-CVT power split transmission for off-road hybrid-electric vehicles." In *2014 IEEE Vehicle Power and Propulsion Conf.*, 1–6. New York: IEEE.

Tsuji, T., Y. Nakagawa, N. Matsumoto, Y. Kadono, T. Takayama, and T. Tanaka. 2012. "3-D DEM simulation of cohesive soil-pushing behavior by bulldozer blade." *J. Terramechanics* 49 (1): 37–47. https://doi.org/10.1016/j.jterra.2011.11.003.

Wang, G., X. Zhang, S. Zhu, H. Zhang, J. Tai, and N. Vanthinh. 2015. "Shift performance of tractor hydraulic power-split continuously variable transmission." *Nongye Jixie Xuebao, Trans. Chin. Soc. Agric. Mach.* 46 (10): 7–15. https://doi.org/10.6041/j.issn.1000-1298.2015.10.002.

Wang, H., and F. C. Sun. 2014. "Dynamic modeling and simulation on a hybrid power system for dual-motor-drive electric tracked bulldozer." *Appl. Mech. Mater.* 494–495: 229–233. https://doi.org/10.4028/www.scientific.net/AMM.494-495.229.

Wong, J. Y. 2008. *Theory of ground vehicles*. New York: Wiley.

Wong, J. Y. 2010. *Terramechanics and off-road vehicle engineering: Terrain behaviour, off-road vehicle performance and design*. Amsterdam, Netherlands: Elsevier.

Yokota, T., M. Gen, Y. Li, and C. E. Kim. 1996. "A genetic algorithm for interval nonlinear integer programming problem." *Comput. Ind. Eng.* 31 (3): 913–917. https://doi.org/10.1016/S0360-8352(96)00263-X.

Zhang, B. D., X. Zhang, L. Zhang, and L. H. Xi. 2016a. "Development and validation of a series hybrid electric bulldozer model on whole working condition." *Key Eng. Mater.* 693: 1811–1817. https://doi.org/10.4028/www.scientific.net/KEM.693.1811.

Zhang, H. 2015. "Simulation-based estimation of fuel consumption and emissions of asphalt paving operations." *J. Comput. Civil Eng.* 29 (2): 04014039. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000326.

Zhang, L., X. Wu, and M. J. Skibniewski. 2016b. "Simulation-based analysis of tunnel boring machine performance in tunneling excavation." *J. Comput. Civil Eng.* 30 (4): 04015073. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000542.

Zhang, Y., L. Ding, and P. E. D. Love. 2017. "Planning of deep foundation construction technical specifications using improved case-based reasoning with weighted k-nearest neighbors." *J. Comput. Civil Eng.* 31 (5): 04017029. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000682.