Optimization of gear ratios and gear-shifting strategy for enhanced efficiency in tracked vehicles

Stefan V. Milićević[a], *Ivan* A. Blagojević[b]

University of Belgrade, Faculty of Mechanical Engineering, Department for Motor Vehicles, Belgrade, Republic of Serbia,

[a]e-mail: stefanm9670@gmail.com, **corresponding author,**
ORCID iD: https://orcid.org/0000-0003-4837-9067

[b]e-mail: iblagojevic@mas.bg.ac.rs,
ORCID iD: https://orcid.org/0000-0002-5776-5990

DOI: 10.5937/vojtehg71-46133;https://doi.org/10.5937/vojtehg71-46133

FIELD: mechanical engineering
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: Tracked vehicles play a vital role across various domains, from military operations to construction and agriculture. This study focuses on improving the efficiency of tracked vehicles by optimizing both gear ratios and gear-shifting strategies while preserving other performance aspects.

Methods: The optimization process involves a genetic algorithm for determining optimal gear ratios, considering performance constraints. Furthermore, the paper introduces a gear-shifting optimization algorithm aimed at enhancing fuel economy to the maximum, while allowing for a valid comparison between two sets of gear ratios.

Results: Optimizing gear ratios leads to substantial reductions in fuel consumption, as the engine operates within more efficient regions. Additionally, the optimized gear-shifting strategy further enhances efficiency, resulting in a fuel consumption reduction exceeding 12%, when combined with the optimized gear ratios.

Conclusions: This paper offers a direct and robust approach for optimizing powertrain gear ratios and gear-shifting strategies in tracked vehicles. The results demonstrate significant improvements in fuel efficiency without compromising other critical vehicle performance parameters.

Key words: tracked vehicles, gear ratio optimization, gear-shifting strategy, genetic algorithm, fuel efficiency enhancement.

Introduction

Tracked vehicles encompass a wide range of applications, from construction and agriculture to military purposes. A defining characteristic of all tracked vehicles is their high fuel consumption (Jimenez-Espadafor et al., 2011). Reducing fuel consumption could significantly enhance vehicle design flexibility or extend operational range. Consequently, substantial attention is directed towards enhancing the energy efficiency of tracked vehicles. Recently, hybridization of tracked vehicles has gained significant attraction in the scientific community (Randive et al., 2021; Han et al., 2019; Bhatia, 2015). Many studies extensively analyze and optimize the propulsion systems of these vehicles, yielding considerably improved energy efficiency outcomes (Qin et al., 2018; Zhang et al., 2021).

In the context of the Serbian-made infantry fighting vehicle BVP M80A, initial investigations into hybridization and energy efficiency have emerged (Milićević & Muždeka, 2021; Milićević et al., 2021). Various hybrid propulsion configurations have been introduced, while retaining a manual five-speed gearbox. With the viability of hybridization established, optimization of both the powertrain and transmission has been demonstrated to yield optimal results (Zou et al., 2012). Hence, optimizing the gearbox becomes a logical pursuit. Also, most vehicle efficiency studies have employed a manual gearbox with predetermined gearshifting strategies (Milićević & Blagojević, 2022). So apart from optimizing gear ratios, it is wise to consider gearbox automation and the development of an appropriate gearshifting strategy. It is evident that each set of gear ratios corresponds to a specific gearshifting strategy capable of achieving optimal fuel economy (Ahssan et al., 2020). In other words, determining gear ratios and establishing an optimal gearshifting strategy are inherently intertwined when pursuing optimal fuel consumption.

The objective of this study is to optimize the transmission of a combat tracked vehicle by determining optimal gear ratios and an optimal gearshifting strategy, along with an analysis of enhanced energy efficiency. The reference vehicle chosen for this study is the BVP M80A.

Simulation model

A simulation model was developed to facilitate the optimization of the powertrain. This model encompasses all relevant motion resistances, which are mathematically formulated and subsequently integrated within the Simulink environment.

Drive cycle

A driving cycle represents the manner in which a vehicle is utilized, encapsulating its speed, acceleration, and path parameters (Achour & Olabi, 2016). At its simplest, it can be understood as the history of motion, specifically the history of a vehicle's speed, acceleration, and road gradient. Consequently, the energy efficiency and responsiveness of the vehicle and all its subsystems significantly depend on the chosen driving cycle. In contrast to wheeled vehicles, which have a set of standardized driving cycles, there is no standardized driving cycle for tracked vehicles. Hence, for the purposes of this study, a custom drive cycle was artificially synthesized, simulating a real-life road path that includes authentic turns and road grades. This drive cycle takes into account road gradient and frequent steering maneuvers, aiming to replicate real-life driving conditions. The speed, lateral acceleration, and grade are presented in Figure 1.

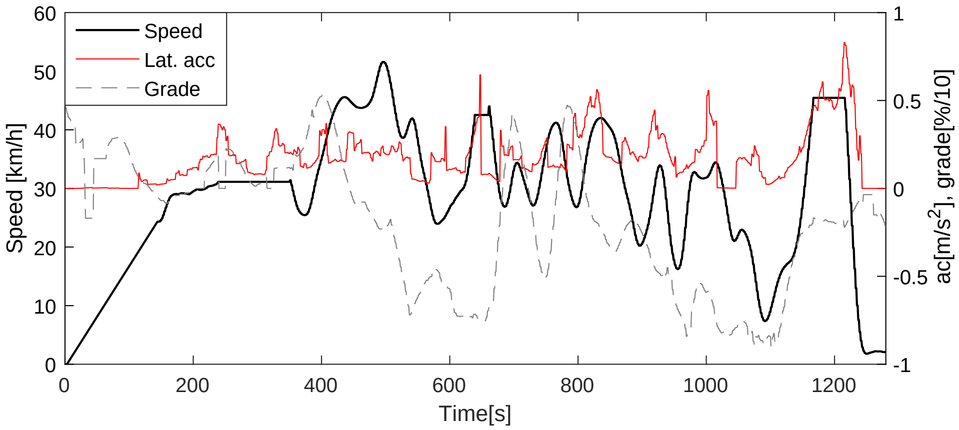

Figure 1 – Adopted drive cycle
Рис. 1 − Принятый приводной цикл
Слика 1 – Усвојени циклус вожње

Vehicle dynamics

An established vehicle dynamics model has been employed for external resistances (Milićević & Blagojević, 2023). The theoretical model covers resistances stemming from track-terrain interaction, grade, air resistance, centrifugal force, inertial forces, and turning resistance moments. An empirical formula was utilized for the coefficient of lateral resistance. The force on the outer track is defined as:

$$
\begin{aligned}
F_o = & \left[\frac{G\cos\alpha}{2} + \frac{h}{B}\left(\frac{G\cdot V^2}{g\cdot R} - G\cdot\sin\alpha\sin\psi\right)\right]\cdot f_r \\
& + \frac{1}{2}\frac{1}{(n+1)\cdot b^{\frac{1}{n}}\cdot(\frac{k_c}{b}+k_\phi)^{\frac{1}{n}}}\left(\frac{G\cos\alpha}{l}\right)^{\frac{1}{n}} \\
& + \frac{b}{2}\cdot\left(c\cdot\left(\frac{p}{\frac{k_c}{b}+k_\phi}\right)^{\frac{1}{n}}\cdot K_{pc} + 0,5\cdot\left[\left(\frac{p}{\frac{k_c}{b}+k_\phi}\right)^{\frac{1}{n}}\right]^2\cdot\gamma_s\cdot K_{p\gamma}\right) \\
& + \frac{G\cdot V^2\cdot s_o}{2g\cdot R'^2} + \frac{G\cdot\sin\alpha\cos\psi}{2} + \frac{\delta mga}{2} + \frac{C_D\cdot\rho}{4}\cdot A\cdot V^2 \\
& + \left(\frac{\mu\cdot G\cdot l}{4B}\cdot\left[1-\left(\frac{\frac{V^2}{g\cdot R}-\sin\alpha\sin\psi}{\mu\cos\alpha}\right)^2\right] - \frac{Iz\cdot\varepsilon}{B}\right),
\end{aligned}
\tag{1}
$$

and the force on the inner track is:

$$
\begin{aligned}
F_i = & \left[\frac{G\cos\alpha}{2} - \frac{h}{B}\left(\frac{G\cdot V^2}{g\cdot R} - G\cdot\sin\alpha\sin\psi\right)\right]\cdot f_r \\
& + \frac{1}{2}\frac{1}{(n+1)\cdot b^{\frac{1}{n}}\cdot(\frac{k_c}{b}+k_\phi)^{\frac{1}{n}}}\left(\frac{G\cos\alpha}{l}\right)^{\frac{1}{n}} \\
& + \frac{b}{2}\cdot\left(c\cdot\left(\frac{p}{\frac{k_c}{b}+k_\phi}\right)^{\frac{1}{n}}\cdot K_{pc} + 0,5\cdot\left[\left(\frac{p}{\frac{k_c}{b}+k_\phi}\right)^{\frac{1}{n}}\right]^2\cdot\gamma_s\cdot K_{p\gamma}\right) \\
& + \frac{G\cdot V^2\cdot s_o}{2g\cdot R'^2} + \frac{G\cdot\sin\alpha\cos\psi}{2} + \frac{\delta mga}{2} + \frac{C_D\cdot\rho}{4}\cdot A\cdot V^2 \\
& - \left(\frac{\mu\cdot G\cdot l}{4B}\cdot\left[1-\left(\frac{\frac{V^2}{g\cdot R}-\sin\alpha\sin\psi}{\mu\cos\alpha}\right)^2\right] - \frac{Iz\cdot\varepsilon}{B}\right).
\end{aligned}
\tag{2}
$$

In these equations, the first three terms on the right side represent the resistances arising from track-terrain interaction (with the normal reaction modified due to load transfer). The fourth and fifth terms are the longitudinal forces resulting from the effect of centrifugal force and the slope of the terrain, and the sixth and seventh terms are the acceleration and air resistance. The eighth term is the moment of turning resistance. The presented equations have been implemented in the Simulink environment with the drive cycle data as an input, and the forces on the tracks as an output.

Engine

The quasi-static model with no transient dynamics was adopted. Fuel consumption is defined as:

$$\frac{dm_f}{dt} = f(T_e, n_e), \tag{3}$$

where T_e and n_e are the effective torque and the rotational speed of the engine.

The total consumption is:

$$C = \int_0^t dm_f. \tag{4}$$

The ICE model is based on a fuel map of the reference vehicle (Hardenberg & Buhl, 1982).

Transmission

Transmission is modeled as a simple five gear mechanical transmission. All kinematical relationships are assumed to be ideal. The model takes into account 'negative' flow of power, i.e. power flowing from the tracks to the engine:

$$T_e = \begin{cases} T_w \cdot \frac{1}{i_{gb} \cdot \eta_{tran}}, & T_w > 0 \\ T_w \cdot \frac{\eta_{tran}}{i_{gb}}, & T_w < 0 \end{cases} \tag{5}$$

where T_w is the torque at the drive wheel, i_{gb} is the current gearbox ratio and η_{tran} is the efficiency coefficient of transmission.

Optimization procedure

This section introduces the optimization procedure applied to determine the optimal gearbox ratios and the most effective gear-shifting strategy for

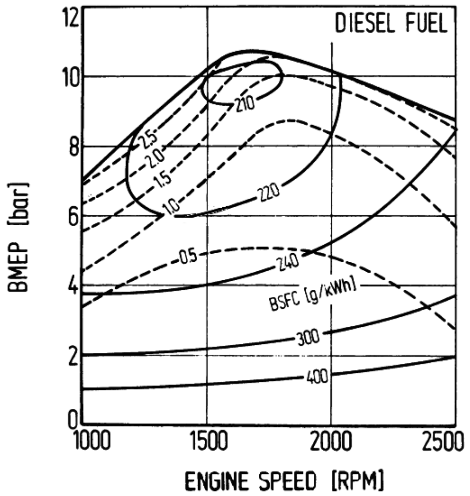

Figure 2 – Fuel map contour of the ICE (g/kWh)
Рис. 2 – Контур топливной карты ДВС (г/кВтч)
Слика 2 – Мапа потрошње мотора СУС (g/kWh)

a given drive cycle. The standard gear-shifting strategy for the reference vehicle is illustrated in Figure 3. However, this strategy remains effective only within specific gear ratios and is not applicable when gear ratios are altered. For that reason, focusing solely on optimizing gear ratios, without also optimizing or at least adjusting the transmission shifting strategy, fails to maximize the vehicle's efficiency and cost-effectiveness, not to mention the absence of a reference for comparison.

Consequently, this paper introduces not only optimization of gear ratios, but also a gear-shifting optimization algorithm, whose main usage is enhancing fuel economy to the maximum, while allowing for a valid comparison between two sets of gear ratios. This comparison is achieved by utilizing an optimal gear-shift strategy for both sets.

In this study, the optimizations of gear ratios and the gear shift strategy are carried out individually. Initially, gear ratios are determined through the utilization of a genetic algorithm and a Simulink vehicle model. Following this, an optimal gear shift strategy is established using an iterative algorithm, based on the predetermined gear ratios. Hence, it can be inferred that the optimization procedure encompasses the enhancement of two distinct problems: optimizing gear ratios and optimizing gear shift strategy.

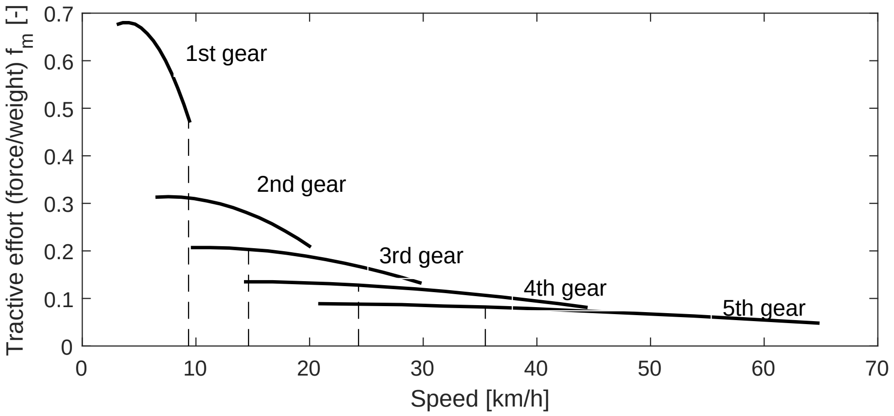

Figure 3 – Diagram of the reference vehicle dynamic coefficient with an example of gear-shifting instances
Рис. 3 − Диаграмма динамического коэффициента эталонного транспортного средства с примером переключения передач
Слика 3 – Динамичка карактеристика референтног возила са примером тренутака промене степена преноса

Furthermore, to ensure that the adopted gear ratios and the gear-shifting strategy can meet the demands of the driving cycle and prevent physically impossible outcomes during optimization, the Simulink model includes stopping criteria in the event of unmet torque or speed requirements.

Optimization of gear ratios

Gear ratio constraints

Gear ratios in the transmission significantly impact vehicle performance. Therefore, during the optimization of gear ratios, it is essential to either have a comprehensive driving cycle covering all possible scenarios and motion conditions, or introduce specific constraints. Ideally, a comprehensive driving cycle would help alleviate algorithm constraints, but since standardized driving cycles for tracked vehicles do not exist, certain limitations must be introduced in this case.

A high-speed tracked vehicle possesses key performance metrics, heavily influenced by transmission gear ratios: gradeability, maximum speed, and acceleration (Randive et al., 2019). Gear ratios of the first and fifth gears notably affect the vehicle's capability to move on slopes and achieve maximum speed. The adopted test vehicle is capable of operating on a slope of 60% and reaching a top speed of 65 km/h, achieved with the declared gear ratios for the first and fifth gears:

$$i_I = 3.97$$

$$i_V = 0.57.$$

Consequently, the gear ratio for the first gear can be larger but not smaller, whereas for the fifth gear, the situation is reversed. Hence, the constraints on the gear ratios for the first and fifth gears are:

$$\begin{aligned} i_I &> 3.97 \\ i_V &< 0.57. \end{aligned} \tag{6}$$

In principle, gear ratios of the other gears are allowed to vary. However, due to the vehicle's combat nature, performance must never be compromised, ensuring a sufficient power reserve for acceleration at all times. This constraint will be incorporated into the algorithm itself through a penalty function.

In the event of overhauling the entire transmission, even the gear ratio of the final drive could become a subject of optimization. In such a scenario, the product of the final drive gear ratio and the transmission gear ratio would be the optimized parameter. However, given the primary focus on the transmission, for the purposes of this study, the existing gear ratio of the reference vehicle's final drive will be adopted, which is $i_{fd} = 5.786$.

Genetic algorithm procedure

The genetic algorithm (GA) optimization procedure is applied. Among the heuristic-based optimization techniques, the genetic algorithm (GA) stands out, utilizing a population of solutions in its search process. Its application is often in enhancing energy efficiency (Eckert et al., 2016, 2021).

A genetic algorithm (GA) functions as a search heuristic that emulates the natural evolution process. This approach is a common choice for generating valuable solutions to optimization and search problems. By adjusting the optimization parameters, it is possible to modify both the algorithm exploratory capabilities and its convergence speed which makes the GA a very good choice for robust optimization.

The primary objective of optimization is to identify the minimum values of the objective function, corresponding to the designated set of gear ratios relative to the vehicle's drive cycle. To achieve this, a control-oriented Simulink model was developed, and it is executed during each iteration of the optimization process. The optimization's ultimate aim is to reduce fuel consumption across the entire drive cycle. The fuel consumption is expressed in liters per 100 km/h:

$$J_f = \frac{m_{fuel}}{d_{cycle} \cdot \rho_f} \cdot 100, \tag{7}$$

where m_{fuel} is the mass of fuel consumed during the drive cycle, d_{cycle} is the traveled distance and ρ_f is the fuel density. The mass of fuel consumed is obtained as:

$$m_{fuel} = BSFC \cdot \int_{i=1}^{N} P_{ei}, \tag{8}$$

where $BSFC$ is the brake specific fuel consumption of the engine, and P_e is the engine effective power which directly depends on the required torque and speed:

$$\begin{aligned} T_e &= \frac{T_{req}}{i_{tran}}, \\ \omega_e &= \omega_{req} * i_{tran} \end{aligned} \tag{9}$$

In this way, the objective function can be defined as:

$$\begin{aligned} & F = J_f \\ \textit{subject to:} \quad & T_e \leq T_{emax} \\ & \omega_{emin} \leq \omega_e \leq \omega_{emax} \end{aligned} \tag{10}$$

Given that the optimization of the combat tracked vehicle is being performed, the vehicles performance must never be compromised. In this case, the performance primarily refers to the reserve of power (torque) in the second, third, and fourth gear. This constraint is taken into account using a penalty function defined as:

$$P = \frac{1}{T_{res}}, \tag{11}$$

where T_{res} is the torque reserve, which is obtained as the difference between the current torque and the maximum available for the given speed:

$$T_{res} = T_{max}(\omega) - T_{current}(\omega). \tag{12}$$

Therefore, the final objective function for the optimization of gear ratios is obtained as follows:

$$\begin{aligned} & F = (w_1 \cdot J_f + w_2 \cdot P) \\ \textit{subject to:} \quad & T_e \leq T_{emax} \\ & \omega_{emin} \leq \omega_e \leq \omega_{emax} \end{aligned} \tag{13}$$

where w_1 and w_2 are weights whose values can be changed depending on optimization priority.

Selection, crossover and mutation

The entire driving cycle is considered as one instance in the optimization. The GA creates a vector of gear ratios $x(k)$ and evaluates its performance over the entire driving cycle:

$$x(k) = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix} \tag{14}$$

Each vector $x(k)$ in the population is evaluated. Then, mutation and crossover operations are performed over the entire population, creating modified populations which are then evaluated. Original and modified populations are then combined, reordered best to worst and re-sized.

The crossover function randomly selects two members of the original population via the MATLAB function randperm. This step ensures that two distinct parents are chosen for crossover. The uniform crossover is applied to the selected parents' positions. It takes two parent positions and a parameter γ as inputs and returns two child positions. The γ parameter controls the blending of genetic information from the parents.

The Mutate function is called for each child's position. The Mutate function takes the child position, mutation rate, and the mutation step size as inputs and returns the mutated child position. After mutation, the child's position is checked to ensure it remains within the specified boundaries. If the mutated value exceeds the defined boundaries, it is replaced with the boundary value to keep the solution within the feasible search space. The flowchart of the applied genetic algorithm procedure is shown in Figure 4.

As mentioned, the Simulink model is equipped with a stopping mechanism that halts the simulation if any physical constraints are violated. If the simulation duration is shorter than the length of the drive cycle, the value of 'Inf' is assigned for the given population.

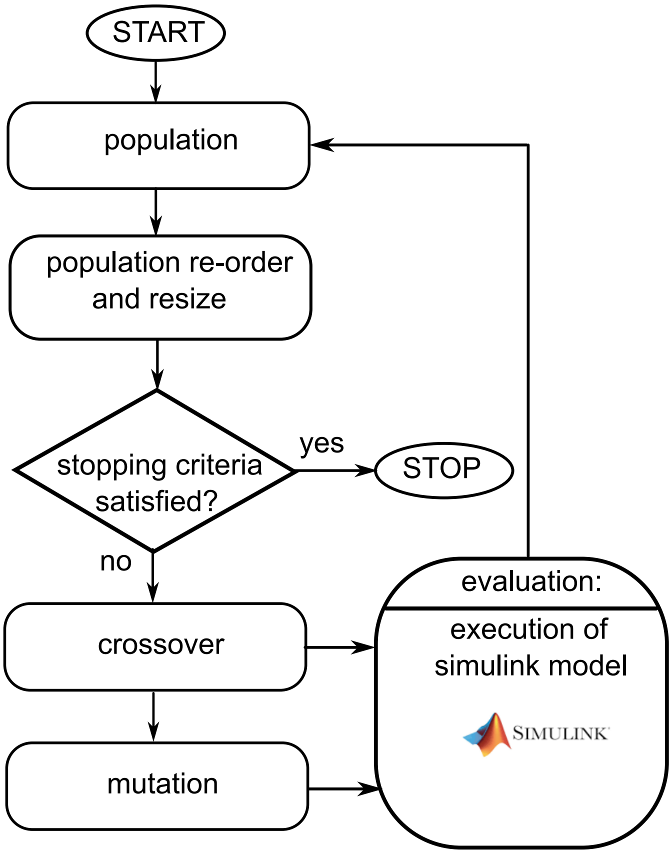

Figure 4 – Genetic algorithm flowchart
Рис. 4 − Блок-схема генетического алгоритма
Слика 4 – Графички приказ генетичког алгоритма

Gear selection optimization

In order to minimize fuel consumption while maintaining the adequate performance of the vehicle, it is not enough to determine only the optimal gear ratios; it is also necessary to define the appropriate gear-shifting strategy, i.e., to select the appropriate gear ratio.

This problem constitutes a gear selection optimization challenge. It entails discovering the most efficient gear-shifting strategy for a given drive cycle. Since one must independently select the optimal gear for each drive cycle instance, it qualifies as a discrete optimization problem. This problem is addressed through an iterative process (see Figure 5).

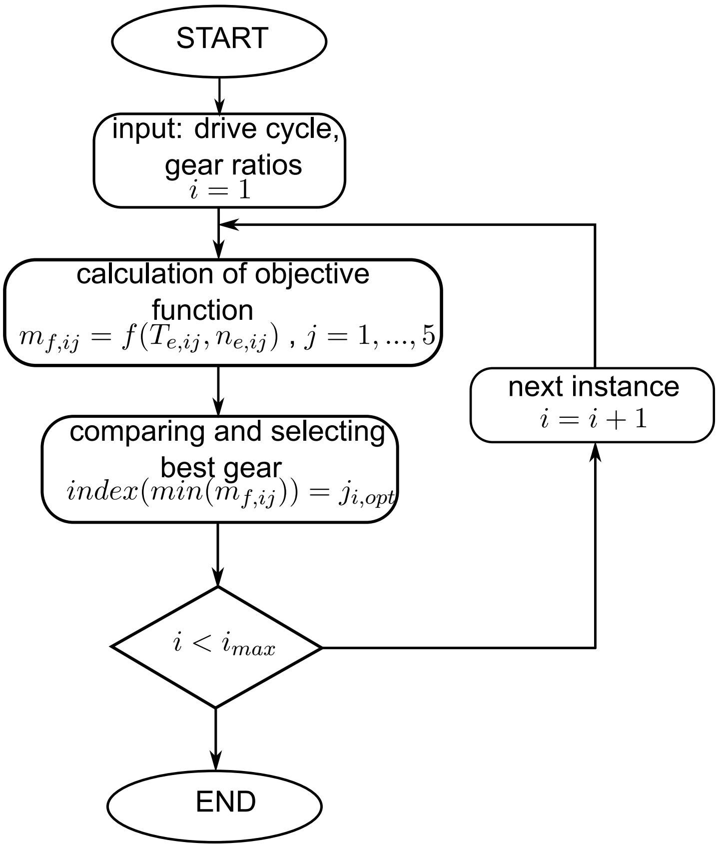

Figure 5 – Iterative gear-shifting optimization procedure
Рис. 5 – Итеративная процедура оптимизации переключения передач
Слика 5 – Итеративна процедура оптимизације стратегије промене степена преноса

The iterative process involves checking each gear (indexed as j) for every instance i in the drive cycle to find the most fuel-efficient gear-shifting strategy for the vehicle.

Minimizing fuel consumption while maintaining optimal reserve torque may lead to a higher frequency of gear shifts which could drastically increase mechanical wear. For that reason, the durability function L needs to be included. The function gives a predefined penalty value of 1 if the gear was changed compared to the previous instance, and 0 if it was not:

$$L = \begin{cases} 0, & j_i = j_{i-1} \\ 1, & j_i \neq j_{i-1} \end{cases} \tag{15}$$

The objective function which is evaluated for every gear is defined as:

$$f = w_1 \cdot Jf + w_2 \cdot P + w_3 \cdot L \tag{16}$$

where w_1, w_2 and w_3 are the weight factors, J_f is the fuel consumption, and P_1 is the reserve power.

Results

Applying the genetic algorithm to the optimization problem of gear ratios results in significantly lower fuel consumption. The change in the objective function value is depicted in Figure 6.

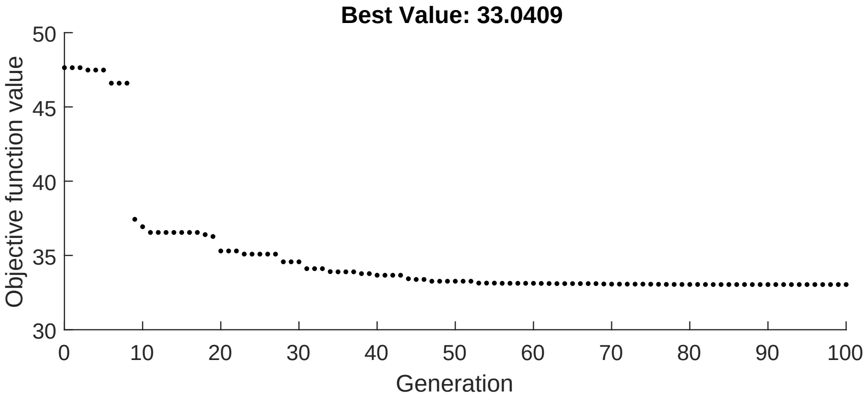

Figure 6 – Fitness function value
Рис. 6 − График изменения значений целевой функции
Слика 6 – Дијаграм промене вредности циљне функције

The new gear ratios lead to the shifting of the engine operating points towards more efficient regions of engine operation (Fig. 7).

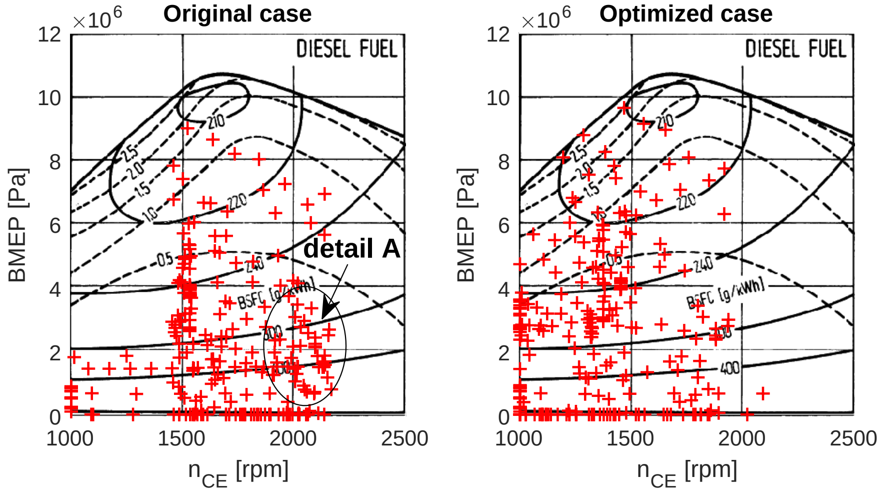

Figure 7 – Distribution of the engine operating points for the original and the optimized case
Рис. 7 − Распределение рабочих точек двигателя в оригинальном и оптимизированном случаях
Слика 7 – Расподела радних тачака мотора за оригинални и оптимизовани случај

Figure 7 illustrates that, with the new gear ratios, the engine operates in a more efficient region. For instance, it is noticeable that numerous operating points in the highly inefficient region (detail A) are eliminated in the optimized scenario.

The original and optimized gear ratios are compared in Table 1. Due to the close proximity of the gear ratios of the third and fourth gears, consideration can be given to eliminating one gear, effectively resulting in a four-

Table 1 – Gear ratios - original and optimized values
Таблица 1 – Передаточные числа − исходные и оптимизированные значения
Табела 1 – Преносни односи - оригиналне о оптимизоване вредности

Gear	Original	Optimized
i_1	3.91	3.91
i_2	1.84	1
i_3	1.241	0.7693
i_4	0.833	0.7475
i_5	0.571	0.5412

speed transmission. However, comprehensive analyses of the required performance are necessary for making such a decision.

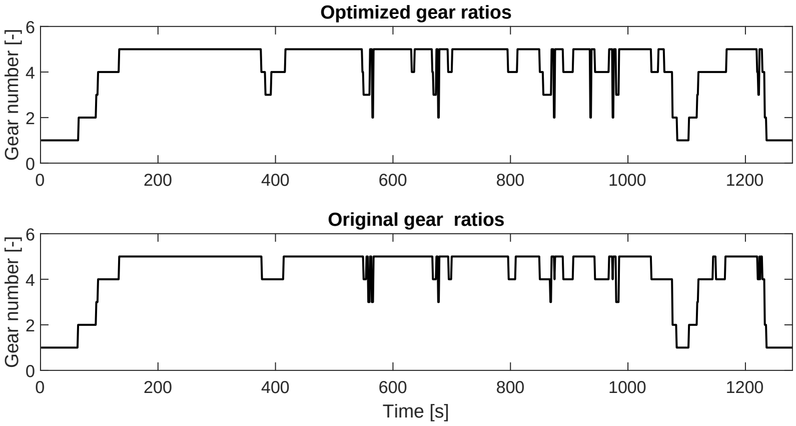

Figure 8 – Comparison of gear-shifting strategies for original and optimized gear ratios
Рис. 8 − Сравнение стратегий переключения передач для исходных и оптимизированных передаточных чисел
Слика 8 – Поређење стратегија промене степена преноса код оригиналних и оптимизованих преносних односа

After optimizing the gear ratios, the optimization of the gearshift strategy was undertaken. First, the gearshift strategy was optimized for the original gear ratios, followed by the optimization for the optimal gear ratios. The optimization of gear shifting enabled the comparison of two transmissions with different gear ratios, as presented in Table 2. The comparison of the gearshift strategies is illustrated in Figure 8.

Table 2 – Fuel consumption comparison
Таблица 2 – Сравнение расхода топлива
Табела 2 – Поређење потрошње горива

Case	Relative fuel consumption [-]	Improvement [%]
Original gear ratios	100	**-**
Optimized gear ratios	87.32	**12.68**

Uniform weights were applied to gear-shifting optimization for both the initial and optimized gear ratios. The highest weight was assigned to fuel consumption ($w_1 = 0.4$), while the remaining two weights were set to $w_2 =$

$w_3 = 0.3$. This alignment in weight distribution led to notable similarities in the gear-shifting strategies, attributable to the resemblance in gear ratios.

Conclusion

This paper introduces a study and an analysis focused on improving the efficiency of tracked vehicles by optimizing gear ratios while maintaining other performance aspects. The motivation for this research arises from the existence of previous investigations where modernized powertrains were hybridized, yet the gear ratios remained unchanged, which adversely affected their overall efficiency. In this context, it was natural to explore the potential for efficiency improvement in terms of gear ratios.

A genetic algorithm was employed to optimize the gear ratios. The Serbian IFV named BVP M80A, which had already been studied, was adopted as the reference vehicle. For comparison purposes and to achieve maximum efficiency, optimization of the gear-shifting strategy was also implemented. During the optimization of both the gear ratios and the gear-shift strategy, care was taken not to compromise other crucial vehicle performances. A penalty function was introduced for the preservation of reserve torque, and weight factors for optimizing gear-shift strategies were also considered to ensure torque reserves and gearbox durability.

Using a model created in Simulink, optimization was conducted, yielding results that demonstrated fuel efficiency increase exceeding 12%. It is important to note that weight factors are variable, and the penalty functions magnitude can vary. The method described in this paper offers a direct and robust approach to optimizing powertrain gear ratios for vehicles. In the future, the focus will be on developing forward-looking models to assess vehicle performance, as well as on creating hybrid optimization approaches that encompass weight factors.

References

Achour, H. & Olabi, A.G. 2016. Driving cycle developments and their impacts on energy consumption of transportation. *Journal of Cleaner Production*, 112, pp. 1778–1788. Available at: https://doi.org/10.1016/j.jclepro.2015.08.007.

Ahssan, M.R., Ektesabi, M. & Gorji, S. 2020. Gear ratio optimization along with a novel gearshift scheduling strategy for a two-speed transmission system in electric vehicle. *Energies*, 13(19), p. 5073. Available at: https://doi.org/10.3390/en13195073.

Bhatia, V. 2015. Hybrid tracked combat vehicle. In: *2015 IEEE International Transportation Electrification Conference (ITEC)*. Chennai, India, pp.1–23, August 27-29. Available at: https://doi.org/10.1109/ITEC-India.2015.7386862.

Eckert, J.J., Corrêa, F.C., Santiciolli, F.M., Costa, E.d.S., Dionísio, H.J. & Dedini, F.G. 2016. Vehicle gear shifting strategy optimization with respect to performance and fuel consumption. *Mechanics Based Design of Structures and Machines*, 44(1-2), pp. 123–136. Available at: https://doi.org/10.1080/15397734.2015.1094669.

Eckert, J.J., da Silva, S.F., de Menezes Lourenço, M.A., Correa, F.C., Silva, L.C. & Dedini, F.G. 2021. Energy management and gear shifting control for a hybridized vehicle to minimize gas emissions, energy consumption and battery aging. *Energy Conversion and Management*, 240, p. 114222. Available at: https://doi.org/10.1016/j.enconman.2021.114222.

Han, X., He, H., Wu, J., Peng, J. & Li, Y. 2019. Energy management based on reinforcement learning with double deep Q-learning for a hybrid electric tracked vehicle. *Applied Energy*, 254, p. 113708. Available at: https://doi.org/10.1016/j.apenergy.2019.113708.

Hardenberg, H.O. & Buhl, H. 1982. The MERCEDES-BENZ OM 403 VA-A Standard Production, Compression-Ignition, Direct-Injection Multifuel Engine. *SAE transactions*, 91, pp. 93–120 [online]. Available at: https://www.jstor.org/stable/44631933 [Accessed: 20 August 2023].

Jimenez-Espadafor, F.J., Marín, J.J.R., Villanueva, J.A.B., García, M.T., Trujillo, E.C. & Ojeda, F.J.F. 2011. Infantry mobility hybrid electric vehicle performance analysis and design. *Applied energy*, 88(8), pp. 2641–2652. Available at: https://doi.org/10.1016/j.apenergy.2011.02.010.

Milićević, S. & Muždeka, S. 2021. Modelling and performance analysis of the BVP M-80A hybrid drive. *Vojnotehnički glasnik/Military Technical Courier*, 69(1), pp. 64–87. Available at: https://doi.org/10.5937/vojtehg69-28232.

Milićević, S.V. & Blagojević, I.A. 2022. Component sizing and energy management for a series hybrid electric tracked vehicle. *Vojnotehnički glasnik/Military Technical Courier*, 70(4), pp. 877–896. Available at: https://doi.org/10.5937/vojtehg70-39762.

Milićević, S.V. & Blagojević, I.A. 2023. Theoretical Model of High-Speed Tracked Vehicle General Motion. *FME Transactions*, 51(3), pp. 449–456. Available at: https://doi.org/10.5937/fme2303449M.

Milićević, S.V., Blagojević, I.A. & Muždeka, S.R. 2021. Advanced rule-based energy management for better fuel economy of hybrid electric tracked vehicle. *FME Transactions*, 49(3), pp. 711–718. Available at: https://doi.org/10.5937/fme2103711M.

Qin, Z., Luo, Y., Zhuang, W., Pan, Z., Li, K. & Peng, H. 2018. Simultaneous optimization of topology, control and size for multi-mode hybrid tracked vehicles. *Applied energy*, 212, pp. 1627–1641. Available at: https://doi.org/10.1016/j.apenergy.2017.12.081.

Randive, V., Subramanian, S.C. & Thondiyath, A. 2019. Component Sizing of Single and Dual Drive Series Hybrid Electric Powertrain for Military Tracked Vehicles. In: *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*. Hanoi, Vietnam, pp.1–6, October 14-17. Available at: https://doi.org/10.1109/VPPC46532.2019.8952308.

Randive, V., Subramanian, S.C. & Thondiyath, A. 2021. Design and analysis of a hybrid electric powertrain for military tracked vehicles. *Energy*, 229, p. 120768. Available at: https://doi.org/10.1016/j.energy.2021.120768.

Zhang, B., Guo, S., Lv, Q., Zhang, X., Ouyang, M. & Teng, L. 2021. Quantitative analysis of the energy saving mechanism of a hybrid electric tracked vehicle by an analytical method. *Energy Conversion and Management*, 237, p. 114067. Available at: https://doi.org/10.1016/j.enconman.2021.114067.

Zou, Y., Sun, F., Hu, X., Guzzella, L. & Peng, H. 2012. Combined optimal sizing and control for a hybrid tracked vehicle. *Energies*, 5(11), pp. 4697–4710. Available at: https://doi.org/10.3390/en5114697.

Повышение эффективности гусеничной машины за счет оптимизации передаточных чисел и стратегии переключения передач

Стефан В. Миличевич, **корреспондент**, *Иван* А. Благоевич

Белградский университет, машиностроительный факультет,
кафедра моторных автомобильных транспортных средств,
г. Белград, Республика Сербия

РУБРИКА ГРНТИ: 78.25.09 Военная автомобильная техника,
78.25.10 Бронетанковая техника
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Гусеничные транспортные средства играют весьма важную роль в различных областях − от военных операций до строительства и сельского хозяйства. Данное исследование сосредоточено на повышении эффективности гусеничных транспортных средств путем оптимизации как передаточных чисел, так и стратегий переключения передач при сохранении других аспектов производительности.

Методы: Процесс оптимизации включает генетический алгоритм для определения оптимальных передаточных чисел с учетом ограничений производительности. Помимо того, в статье представлен алгоритм оптимизации переключения передач, направленный на максимальное *повышение топливной экономии, позволяющий проводить достоверное сравнение двух наборов передаточных чисел.*

Результаты: Оптимизация передаточных чисел трансмиссии приводит к значительному снижению расхода топлива, что обусловлено более эффективной работой двигателя внутреннего сгорания. Помимо того, оптимизированная стратегия переключения передач еще больше повышает эффективность, что приводит к снижению расхода топлива более чем на 12%.

Выводы: В данной статье предлагается прямой и надежный подход к оптимизации передаточных чисел силовых агрегатов и стратегий переключения передач гусеничных машин. Результаты показали значительное повышение топливной экономии без ущерба для других важнейших эксплуатационных характеристик автомобиля.

Ключевые слова: гусеничная техника, оптимизация передаточных чисел, стратегия переключения ступени в трансмиссии, генетический алгоритм, повышение эффективности расхода топлива.

Повећање ефикасности гусеничног возила оптимизацијом преносних односа и стратегије промене степена преноса

Стефан В. Милићевић, **аутор за преписку**, *Иван* А. Благојевић

Универзитет у Београду, Машински факултет, Катедра за моторна возила, Београд, Република Србија

ОБЛАСТ: машинство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Гусенична возила имају значајну улогу у различитим областима, од борбених операција до грађевинске индустрије и пољопривреде. Рад је фокусиран на повећање ефикасности гусеничних возила оптимизацијом преносних односа и стратегије промене степени преноса, уз задржавање захтеваних перформанси.

Методе: Процес оптимизације укључује генетски алгоритам за одређивање оптималних преносних односа, узимајући у обзир ограничења перформанси. Осим тога, рад уводи алгоритам за оптимизацију промене степена преноса који *има за циљ максимизацију економичности возила, уз обезбеђивање валидног поређења два сета преносних односа.*

Резултати: Оптимизација преносних односа доводи до значајних смањења потрошње горива, што је узроковано ефикаснијим радом мотора са унутрашњим сагоревањем. Поред тога, оптимизована стратегија промене степена преноса додатно повећава ефикасност, што је довело до смањења потрошње горива већем од 12%.

Закључак: Представљен је системски приступ оптимизацији односа преноса и стратегија промене степена преноса код гусеничних возила. Резултати показују значајна побољшања у ефикасности возила и смањење потрошње горива без угрожавања осталих критичних параметара перформанси возила.

Кључне речи: гусенична возила, оптимизација преносних односа, стратегија промене степена преноса, генетски алгоритам, повећање ефикасности потрошње горива.

Paper received on / Дата получения работы / Датум пријема чланка: 23.08.2023.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 29.11.2023.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 30.11.2023.