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A SIMULATION MODEL OF DAMAGE-INDUCED CHANGES IN THE FUEL CONSUMPTION OF A WHEELED TRACTOR

MODEL SYMULACYJNY ZMIAN ZUŻYCIA PALIWA CIĄGNIKA KOŁOWEGO W ASPEKCIE USZKODZEŃ*

The existing diagnostic systems are applied to monitor and optimize a tractor's performance and effectiveness, while there is no consumption monitoring systems in terms of damage. A malfunction can be analyzed at different levels of complexity, including systems, kinematic pairs and components. Based on the generated consequences, defects can be classified into the following groups. Are the following classes of damage: damage to functional, emission, unsafe deteriorating dynamics, which are assigned to certain effects. The study was prepared simulation model wheeled tractor, which incorporates traction characteristics describe physical phenomena associated with the operation of the tractor and having an impact on the process of degradation under certain loading cycles. An algorithm for determining fuel consumption during simulated defects in a wheeled tractor is presented in this paper. Most tractor malfunctions affect fuel consumption. Fuel consumption is one of the key diagnostic parameters in evaluations of a vehicle's technical condition. The magnitude of changes in fuel consumption varies subject to the type of defect. The effects of simulated malfunctions of a wheeled tractor on its fuel consumption are discussed in this paper.

Keywords: *wheeled tractor, model simulation, damage, fuel consumption.*

Stosowane obecnie elektroniczne systemy w ciągnikach kołowych służą do monitorowania i optymalizacji efektów pracy pod kątem jego wydajności i efektywności, natomiast brak jest systemów monitorujących zużycie paliwa w aspekcie uszkodzeń. Uszkodzenie można rozpatrywać na różnych poziomach złożoności maszyny, np. układów, zespołów węzłów konstrukcyjnych lub elementów. W pracy przyjęto klasyfikację uszkodzeń ze względu na ich skutki. Wyróżniono następujące klasy uszkodzeń: uszkodzenia funkcjonalne, emisyjne, zagrażające bezpieczeństwu, pogarszające dynamikę, którym przyporządkowano określone skutki. W pracy przygotowano model symulacyjny ciągnika kołowego, w którym uwzględniono charakterystyki trakcyjne opisujące zjawiska fizyczne związane z funkcjonowaniem ciągnika i mające wpływ na proces jego degradacji w określonych cyklach obciążeń. Przygotowano algorytm służący do określania zmian zużycia paliwa przy symulowanych uszkodzeniach ciągnika kołowego. Większość z uszkodzeń ciągnika kołowego ma wpływ na zużycie paliwa. Zużycie paliwa może być jednym z podstawowych parametrów diagnostycznych podczas oceny stanu technicznego pojazdu. W zależności od rodzaju uszkodzenia zmiany zużycia paliwa mogą być różne. W pracy przedstawiono przykładowe przebiegi symulacyjne niektórych uszkodzeń ciągnika kołowego na zużycie paliwa.

Słowa kluczowe: *ciągnik kołowy, model symulacyjny, uszkodzenie, zużycie paliwa.*

1. Introduction

The agricultural tractor is rather a heavy machine and is used for a variety of operations from tillage to haulage and under diverse conditions. Whatever the case may be, one of the most important considerations is to ensure safety in operation or in other words a hazard free operation [8]. Statistical data shows tractor-related accidents cause approximately 300 fatalities each year [17].

This paper proposes a simulation model for diagnosing defects in a wheeled tractor's components and evaluating the consequences of the resulting damage. A simulation model of a wheeled tractor should support evaluations of:

- tractor's functionality during transport and operation,
- performance parameters,
- operating safety in field and road driving modes,
- exhaust gas emissions.

A tractor has to be maintained in good operating condition during seasonal field works in farming and forestry. The technical condition of a wheeled tractor has to be regularly monitored to ensure its full functionality, to lower repair costs and minimize down time. The existing diagnostic systems are applied to monitor and optimize a tractor's performance and effectiveness, and they are often limited to analyzing engine performance and comparing the measured parameters with standard values [1, 16, 18].

In this study, a simulation model was developed on the assumption that defect diagnosis in a wheeled tractor is a process of detecting, isolating and describing malfunctions:

- detection of defects (determining the moment of damage),
- localization of defects (determining the type and place of damage),
- identification of defects (determining the magnitude and variability of diagnostic parameters over time).

The physical, chemical and mechanical properties of arable soil in north-eastern Poland vary significantly. For this reason, the efficiency of tractor performance is an important and a complex consideration. Tractor performance is determined by various dynamic input

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** functions that change over time. At present, there are no methods for continuously monitoring tractor efficiency that account for all energy losses. In order to support the optimization of tractor performance, the above indicators have to be determined on-line [7].

Tractor performance on actual soil conditions differs substantially from the results of laboratory track testing. The physical laws governing movement and behaviour in general vary from one surface to the other, while constant changes in terrain and drawbar pull generate ongoing variations in the dynamic load on each wheel. [3].

Traction properties of a wheeled tractor largely depend on the interaction between the wheel and the ground. The optimal use of a wheel consists of ensuring maximum efficiency of a wheel, not exceeding the permissible values of wheel slip, and obtaining the maximum tractive effort [15, 19].

A new approach to simulations of wheeled vehicle operation needs to be adopted to ensure compliance with environmental protection requirements and to reduce fuel consumption. Harmful substances emitted with exhaust gas have a highly detrimental effect on plant production and the environment, and they create serious environmental risks [4, 5, 9].

In the past decades, significant advances have been made in intelligent machine diagnostic systems. Modern wheeled tractors are highly complex vehicles which have to be monitored in real time with the involvement of automatic damage detection systems [6].

2. Classification of defects in a wheeled tractor

A defect is reported when at least one of the measurable or immeasurable features characterizing the tractor's technical condition ceases to support correct functioning of the machine [14]. A defect is defined as the loss of the tractor's ability to perform the assigned functions [PN-93/N-50191]. A malfunction can be analyzed at different levels of complexity, including systems, kinematic pairs and components [12].

Based on the generated consequences, defects can be classified into the following groups [10]:

- functional defects (u_f) which inhibit performance (torque, towing force, working speed, fuel consumption),
- exhaust defects (u_e) which increase toxic emissions (and noise) and fuel consumption due to a malfunction of the fuel supply system, layout of the diesel engine and the power transmission system,
- defects that jeopardize driving safety (u_s) can affect the following tractor systems: brake, suspension, steering and lights.
- defects that affect engine performance (u_d) and driving parameters in a tractor, including decreased acceleration, delayed response to changes in movement parameters, unequal power levels, significant loss of power and moment of force.

The presence of defects and malfunctions should be signaled in the monitoring system. The operator should be provided with information about the type and location of the malfunction.

In a wheeled tractor, the following symptoms are associated with the discussed categories of defects:

- **functional defects (u_f):** overheating or slipping of friction clutch, gearbox overloading and overheating, damage to gearbox bearings which increases system temperature, damage to reduction gear shaft bearings which increases system temperature, overloading of the final drive which causes overheating and seizing of differential satellite gear, damage to ring gear and shaft bearings which increases system temperature, overloading of rear portal axle which causes overheating, damage to reduction gear housing, bearing damage which increases system temperature, uncontrolled loss of air in front and rear axle tires, leak in induction system, turbocharger failure, engine overheating, cooling system failure, engine overload, wear of cylinder liners, wear of piston rings, loose sockets and valves, engine wear, unequal power levels in cylinders, oil pump damage, incorrect oil pressure reading, significant bushing clearance in the crankshaft and piston assembly, abnormal oil pressure drop in the engine lubrication system,
- **exhaust defects (u_e):** damage to gear housing, loss of gear oil, damage to reduction gear housing, loss of gear oil, damage to final drive housing, uncontrolled loss of air in front and rear axle tires, leak in induction system, engine overheating, cooling system failure, loss of coolant, wear of piston rings, loose sockets and valves, engine wear, unequal power levels in cylinders, fuel injector leak, combustion problems, malfunctioning fuel dosing system, injector failure, loss of engine oil, engine oil burning,
- **defects that jeopardize safety (u_s):** excessive clearance in steering system, light bulb damage in the lighting system, wiper malfunction, horn malfunction, loss of brake fluid, reduced brake force, reduced pressure in brake system, air in brake system, damaged brake pump, worn-out brake lining, uncontrolled loss of air in front and rear axle wheels, tire puncture, loose valve stem, oil pump damage
- **defects that affect performance (u_d):** overheating or slipping of friction clutch, gear tooth damage, damage to reduction gear teeth, damage to portal axle teeth, leak in induction system, turbocharger failure, wear of cylinder liners, wear of piston rings, loose sockets and valves, engine wear, unequal power levels in cylinders, fuel injector leak, combustion problems, malfunctioning fuel dosing system, injector damage.

3. Model for simulating defects in a wheeled tractor

A system for simulating damaged-induced changes in a tractor's fuel consumption has been proposed for the identified categories of defects: (u_f), (u_e), (u_s) and (u_d). The presented model of a wheeled tractor relies on traction values describing physical phenomena which are associated with a vehicle's operation and which determine its wear in a given load cycle (Fig. 1).

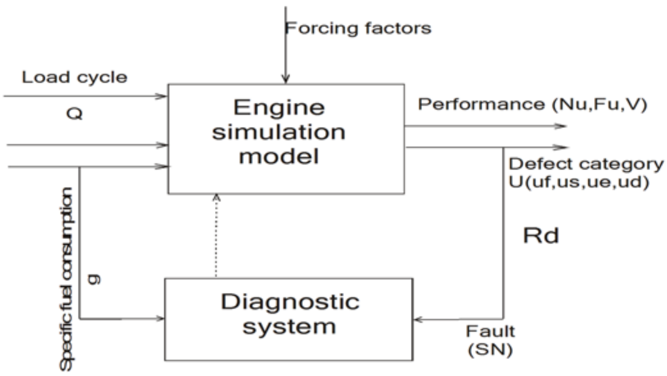

Fig. 1. Diagnostic diagram of a wheeled tractor based on the proposed mechatronic system for monitoring the condition of wheeled tractor (MSMC), where: g – specific fuel consumption, N_U - pulling power; pulling power; FU – pulling force; V – speed; SN - fault, Q – load; u – defect category [13]

A tractor's operating status is determined by: driving speed, resistance to motion (of the tractor and implements), mass, gear ratio in the power transmission system, layout of the power transmission system, rolling radius of drive wheels, etc. The severity of damage to a tractor's parts and assemblies is determined by the load cycle and material strength.

A simulation model of a wheeled tractor was developed based on a system of functional correlations presented in Figure 2. A structural diagram of a wheeled tractor is presented in Figure 3.

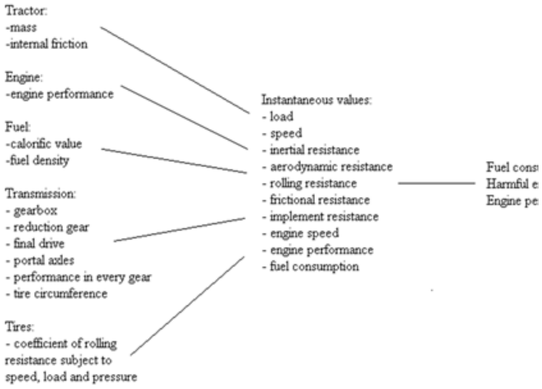

Fig. 2. Correlations between a tractor's technical parameters in a defect simulation model

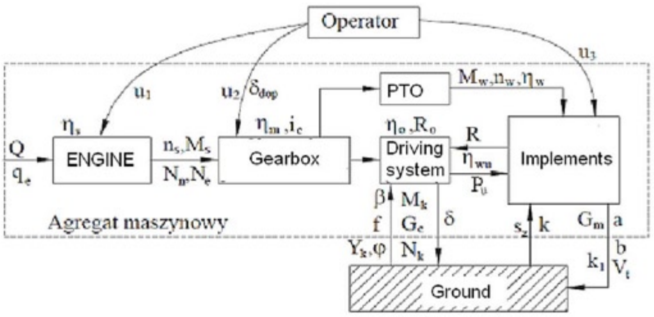

Fig. 3. Structural diagram of a wheeled tractor in the process of monitoring operating parameters [11]: β – ground inclination (slope), δ – slip ratio of drive wheels, ϕ – coefficient of tractive adhesion, η_m –mechanical efficiency, η_o – tractive efficiency (total), η_s – engine efficiency, η_u – traction efficiency, η_{wu} – traction efficiency rating, a – width of implement, b – depth of implement, f – coefficient of rolling resistance, M_w – PTO torque, n_w – PTO rotational speed, η_w – PTO efficiency, g_e –specific fuel consumption, G_c – tractor mass, G_m – implement mass, i_c –overall gear ratio, k – soil strength, k_1 –rolling resistance of implement, M_k – driving torque, M_s – net torque, N_e – effective power, N_k – driving power, N_n – nominal power output, n_s – engine rotational speed, P_n – driving force, Q – fuel consumption per hour, s_z – presence of field stones, u_1 – fuel dose, u_2 –applied gear ratio, u_3 – operating mode, Y_k – load on drive wheels, V_t – operating speed of implement operation, R – resistance of implement, R_0 – resistance in the drive , PTO – power takeoff

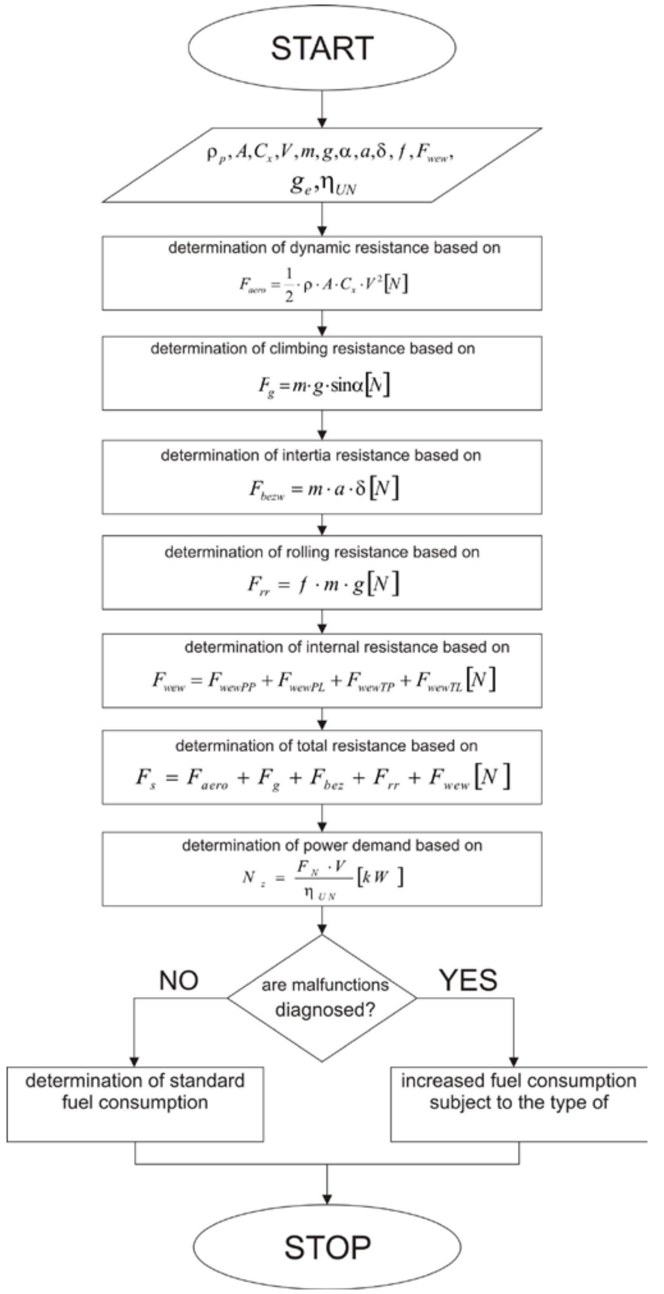

Fig. 4. An algorithm for determining fuel consumption in simulated tractor malfunctions g_e – specific fuel consumption, ρ_p – fuel density, ρ – air density, A – area of the tractor's front face, C_x – coefficient of aerodynamic drag, V – velocity, m – mass, g – gravitational acceleration, α – ground inclination, a – acceleration, δ – rotational mass coefficient, f – rolling resistance coefficient, F_{wew} – internal resistance on each wheel, η_{UN} – power transmission efficiency.

An algorithm for determining fuel consumption during simulated defects in a wheeled tractor is presented in Figure 4.

The model for simulating malfunctions in a wheeled tractor supports the identification of defects in view of their consequences (fuel consumption), as illustrated by the following relationship:

$$G_V = \frac{g_e}{1000 \cdot \rho_p}\left(\frac{1}{2}\cdot\rho\cdot A\cdot c_x\cdot V^2 + m\cdot g\cdot\sin\alpha + m\cdot a\cdot\delta + f\cdot m\cdot g + F_{wewPP} + F_{wewPL} + F_{wewTP} + F_{wewTL}\right)\cdot\frac{V}{\eta_{UN}} \quad (1)$$

Based on the analysis of the relationship defined by formula (1) can see the effect of specific resistance to motion (aerodynamic, resulting from the slope of the road, inertia, and internal resistance of rolling wheels) changes in fuel consumption.

New generation tractors are equipped with automatic control systems which replace the operator. This solution supports effective vehicle operation, reduces fuel consumption and optimizes torque and engine power settings required to perform the tasks of agricultural. The system rapidly detects any vehicle malfunctions to prevent damage and an increase in long-term fuel consumption [2].

4. The use of a simulation model to evaluate the effect of vehicle malfunctions on fuel consumption

Most tractor malfunctions affect fuel consumption. Fuel consumption is one of the key diagnostic parameters in evaluations of a vehicle's technical condition. The magnitude of changes in fuel consumption varies subject to the type of defect. Certain malfunctions significantly increase fuel consumption in a wheeled tractor, including induction system leaks, turbocharger failure, combustion problems and fuel injector damage. Defects such as engine overheating result in a medium increase in fuel consumption. Malfunctions which lead to a minor increase in fuel consumption include incorrect oil pump pressure, significant bushing clearance in the crankshaft and piston assembly, loss of gear oil. Some defects increase fuel consumption subject to engine load, including wear of piston rings, loose sockets and values, oil pump damage, overheating or slipping of friction clutch. The effects of simulated malfunctions of a wheeled tractor on its fuel consumption are discussed in this part of the paper.

Gear tooth damage can be identified based on the following symptoms: deteriorating performance of the gearbox and the power transmission system, increased fuel consumption during attempts to maintain the same wheel torque and identical performance parameters (Fig.5 and 6).

$$\eta_{UN} = \eta_{sprz.} \cdot \eta_{skrz.pl.} \cdot \eta_{skrz.przek.} \cdot \eta_{red} \cdot \eta_{przek.gl.} \cdot \eta_{zwol.}$$

$$G_V = \frac{g_e}{1000 \cdot \rho_p} \left(F_{aero} + F_g + F_{bez} + F_{rr} + F_{wew} \right) \frac{V}{\eta_{UN}}$$

Fig. 5. Formula presenting the effect of gear tooth damage on changes in fuel consumption

Fig. 6. Diagnostic symptoms of gear tooth damage

Induction system leaks and turbocharger failure are identified based on the following symptoms: reduced engine performance, lower torque values, increased specific fuel consumption and increased fuel consumption during attempts to maintain the same wheel torque and identical performance parameters (Fig. 7–9).

Malfunctions of the fuel dosing system are diagnosed based on the following symptoms: reduced engine performance, reduced torque, increased specific fuel consumption and increased fuel consumption during attempts to maintain the same wheel torque and identical performance parameters (Fig. 10 and 11).

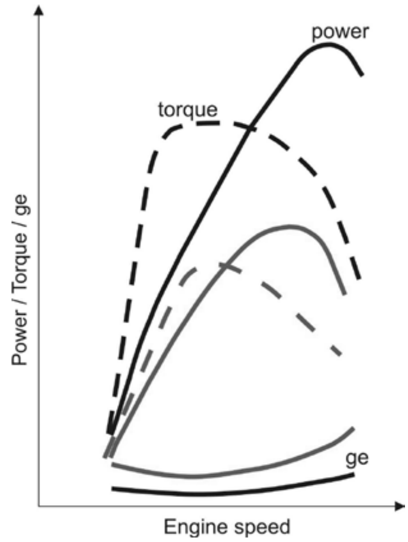

Fig. 7. The effect of induction system leaks and turbocharger failure on engine performance

$$G_V = \frac{g_e}{1000 \cdot \rho_p} \left(F_{aero} + F_g + F_{bez} + F_{rr} + F_{wew} \right) \frac{V}{\eta_{UN}}$$

Fig. 8. Formula presenting the effect of induction system leaks and turbocharger failure on engine performance

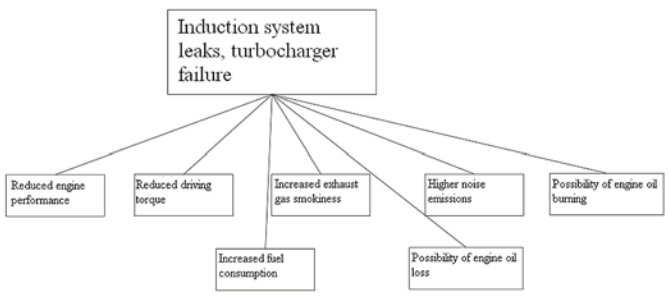

Fig. 9. Diagnostic symptoms of induction system leaks and turbocharger failure

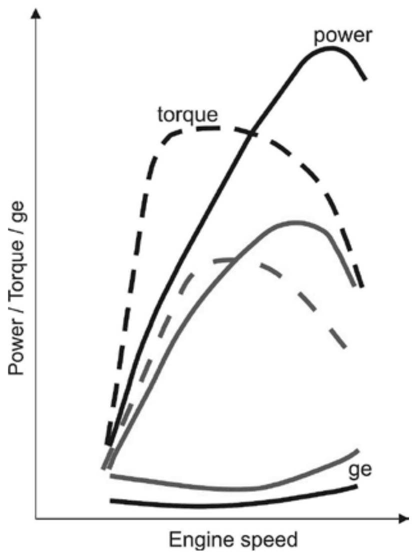

Fig. 10. The effect of fuel dosing system malfunctions on engine performance (black – optimally functioning engine, red – malfunctioning engine)

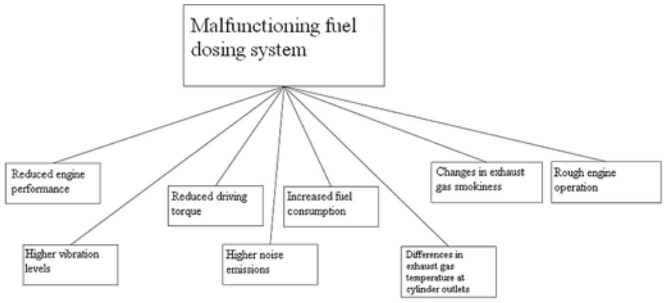

Fig. 11. Diagnostic symptoms of fuel dosing system malfunctions

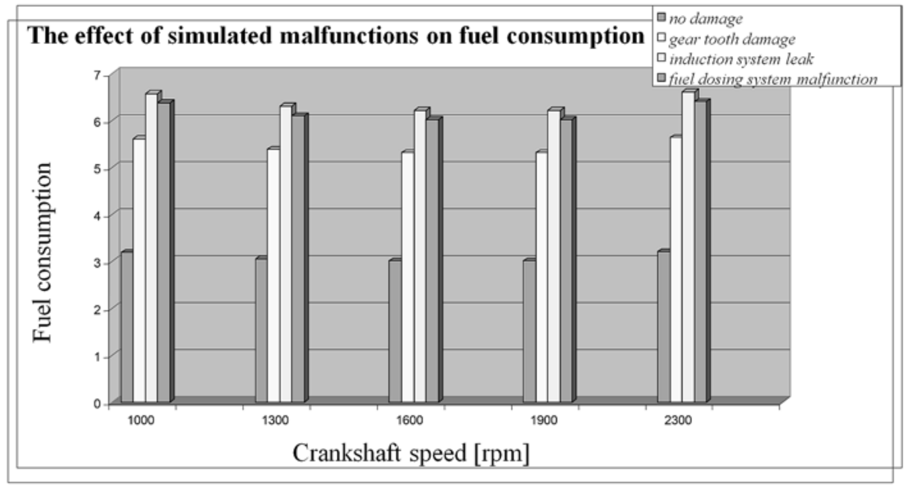

Fig. 12. Correlations between changes in fuel consumption and the simulated malfunctions: no damage, gear tooth damage, induction system leak, fuel dosing system malfunction.

Changes in hourly fuel consumption at different engine speeds during the simulated malfunctions are presented in Figure 12.

6. Conclusions

The presented simulation model supports the development of a diagnostic system which identifies four categories of defects in a wheeled tractor.

Simulation models can identify functional defects, exhaust defects, defects that jeopardize safety and defects that affect performance. The above has been illustrated on the example of several simulations.

Developed diagnostic model enables the identification of the technical condition of wheeled tractors by identifying changes in fuel consumption which can be used to control operation of the vehicle. Fuel consumption is the primary diagnostic parameter in identifying the condition of the vehicle.

Simulation models support the selection of the most appropriate software and hardware for a wheeled tractor's diagnostic system.

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