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Mathematical Modeling and Efficiency Evaluation of A Hydrostatic Regenerative Braking System in Quarry Dump Trucks

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Abstract:

This article examines the issues of improving energy efficiency in dump trucks operating under quarry conditions. The importance of hydrostatic regenerative technologies based on the recovery of kinetic energy lost during braking is scientifically substantiated. The study analyzes energy flows by considering vehicle operating modes, load levels, and driving conditions. The potential for reducing energy losses through the application of regenerative systems is identified. The processes of energy storage in hydraulic accumulators and its efficient utilization are evaluated. The results demonstrate the potential to reduce fuel consumption, improve environmental performance, and decrease exhaust emissions.

Keywords: Regenerative Systems, Energy-Saving Technologies, Hydrostatic Transmission, Fuel Efficiency, Energy Recovery, Hydraulic Accumulator, Environmental Performance, Mathematical Modeling.

Introduction

At present, the rational use and conservation of energy resources have become one of the most pressing global challenges. In particular, the high level of energy consumption in industrial and transport sectors necessitates the introduction of advanced and efficient technologies [1], [2], [3]. Dump trucks operating in quarry conditions function under heavy loads and are characterized by substantial fuel consumption. This not only increases operational costs but also has a negative impact on the environment.

Literature analysis

The specific characteristics of motion in quarry transport, namely frequent stopping and starting, descending from elevated positions, and ascending with heavy loads, lead to increased energy losses. In particular, during braking, a significant portion of kinetic energy is dissipated as thermal energy [4], [5]. However, there are opportunities to recover this energy, and in this context, regenerative technologies are of particular importance. Figure 1 illustrates a hydrostatic regenerative braking system [1].

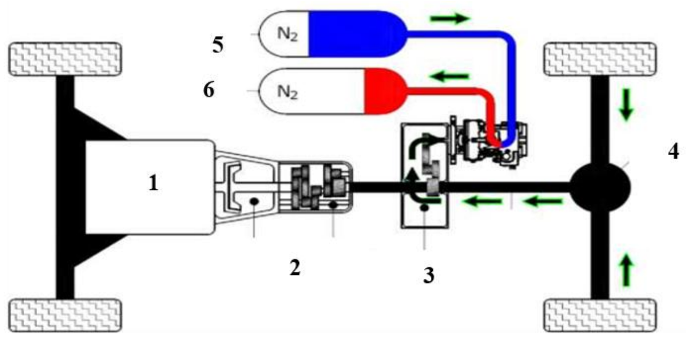


Figure 1. Schematic diagram of regenerative braking in a hydrostatic energy recovery system: 1 – internal combustion engine; 2 – clutch and transmission; 3 – coupling between the system and the driveline (cardan shaft); 4 – differential; 5 – low-pressure hydraulic accumulator; 6 – high-pressure hydraulic accumulator.

Materials and Methods

In hydro-regenerative systems, energy exchange occurs between mechanical and hydraulic energy forms. During the braking process, the kinetic energy of the vehicle is converted into hydraulic energy by means of a hydraulic pump. As a result, the working fluid is compressed, generating high pressure within the system, which is stored in the hydraulic accumulator [6]. In the subsequent stage, when the vehicle starts moving or undergoes acceleration, this stored energy is reused. Through the hydraulic motor, the pressure energy is converted back into mechanical energy, thereby reducing the load on the internal combustion engine. Consequently, fuel consumption is reduced and the overall energy efficiency of the system is improved. Figure 2 shows the installation of the hydro-regenerative braking system on a dump truck [2].

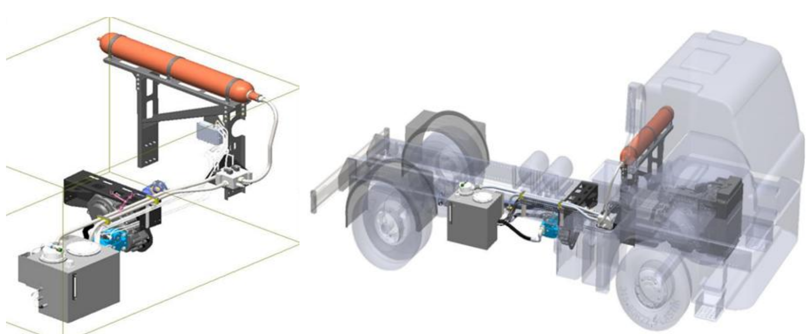


Figure 2. Hydrostatic regenerative braking system and its integration into a dump truck.

In recent years, particular attention has been paid to the investigation of energy-saving technologies through mathematical modeling. This approach makes it possible to evaluate system performance without conducting complex experiments under real operating conditions [7], [8]. At the same time, modeling results enable the determination of optimal system parameters.

Results and Discussions

Forces acting on the vehicle

During motion, a vehicle is subjected to various resistive forces. These forces act in the direction opposite to the vehicle's movement and arise due to different factors. The main resistive forces acting on a vehicle include rolling resistance, aerodynamic drag, and gravitational forces. These forces are illustrated in Figure 3 [9].

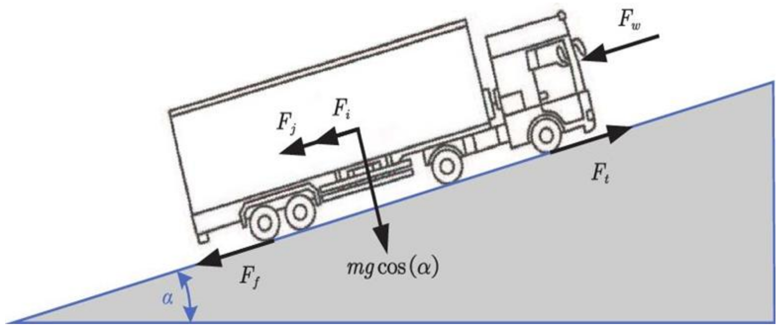


Figure 3. Dynamic model of a dump truck operating under quarry conditions.

The resultant force acting on the vehicle is expressed by Equation (1) as (F_D).

$$F_D = F_r + F_a + F_y \quad (1)$$

In Equation (1), (F_r) represents the rolling resistance corresponding to the rotational motion of the wheel. Rolling resistance, associated with the elastic structure of the wheel, is a resistive force generated ahead of the contact patch and acts in the direction opposite to the wheel's rotation. The coefficient (C_r) denotes the rolling resistance coefficient, which characterizes the resistance возникая (arising) between the vehicle's wheels and the road surface. It depends on several parameters, including vehicle mass, tire type, tire inflation pressure, and road conditions. The material properties and structural design of the tires significantly influence the magnitude of resistance. Tire inflation pressure is also a critical factor, as lower pressure leads to increased resistance [10], [11]. Additionally, road conditions, such as surface roughness and slipperiness, affect rolling resistance. The rolling resistance coefficient is typically taken as (C_r = 0.8), based on experimental data, and plays an important role in evaluating the energy efficiency of many types of vehicles. The rolling resistance corresponding to the rotational motion of the wheel can be calculated using Equation (2).

$$F_r = mgC_r\cos\alpha \quad (2)$$

In Equation (2), (g) denotes the acceleration due to gravity, while (α) represents the slope angle of the surface on which the vehicle is moving. During motion, the airflow encountered by the vehicle generates a force acting in the opposite direction to its movement. This force is referred to as aerodynamic drag, as it opposes the vehicle's motion. The aerodynamic resistance force acting on the vehicle, denoted as (F_a), is calculated as shown in Equation (3).

$$F_a = C_d\frac{\rho V^2}{2}A \quad (3)$$

In Equation (3), (C_d = 0.8) denotes the aerodynamic drag coefficient, (ρ) is the air density, (V) represents the vehicle velocity, and (A) is the frontal (cross-sectional) area of the vehicle. For the considered dump truck, the frontal area is given as (A =2.17*1.815=3,93 m^2). Grade resistance is the force resulting from the component of the vehicle's weight acting along the slope when the vehicle is moving on an inclined surface. This resistance is directly related to the vehicle's mass and the slope angle of the road. The grade resistance force, denoted as (F_y), is calculated as shown in Equation (4).

$$F_y = mg\sin\alpha \quad (4)$$

For the calculations, a MATLAB–Simulink model is employed, and the resistive forces acting on the vehicle are illustrated in Figure 4.

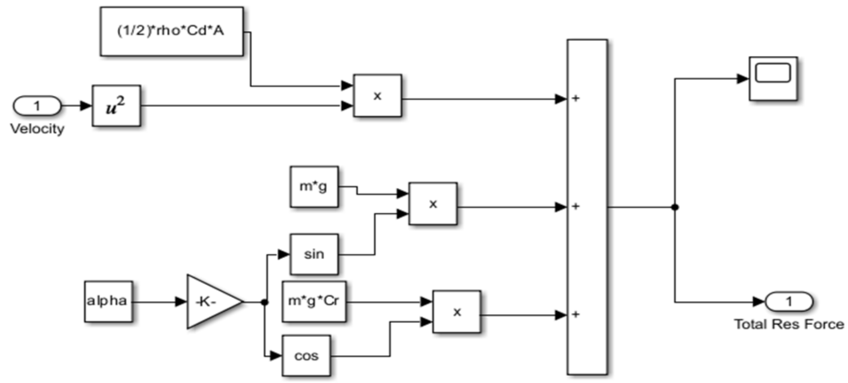


Figure 4. MATLAB–Simulink model of resistive forces.

Figure 5 presents the graph of the total forces acting on a dump truck with a mass of (m = 10) tons, plotted as a function of velocity variation [7].

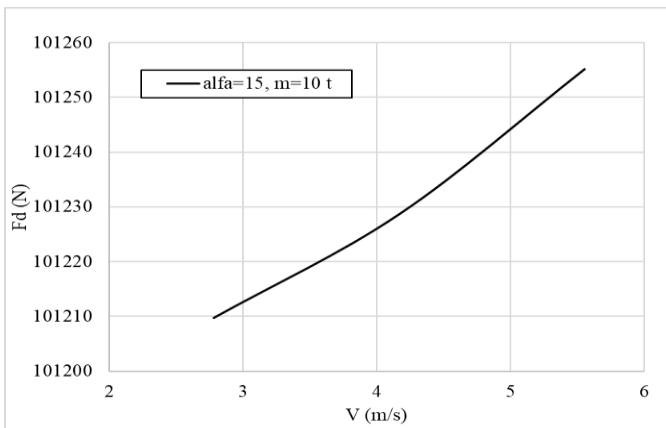


Figure 5. Total forces acting on a dump truck with a mass of (m = 10) tons.

Figure 6 presents the graph of the total forces acting on a dump truck with a mass of (m = 28) tons, plotted as a function of velocity variation.

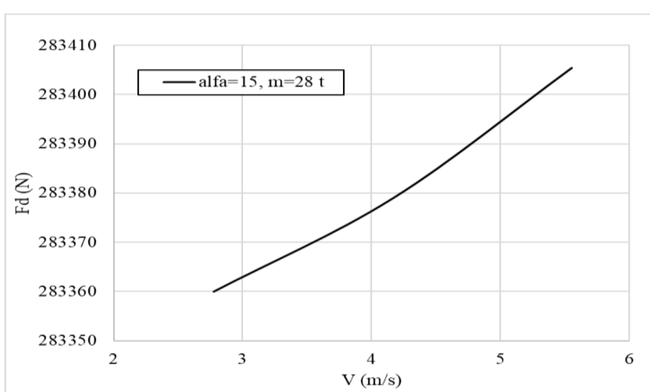


Figure 6. Total forces acting on a dump truck with a mass of (m = 28) tons.

Figure 7 presents the graph of the total forces acting on a dump truck with a mass of (m = 40) tons, plotted as a function of velocity variation.

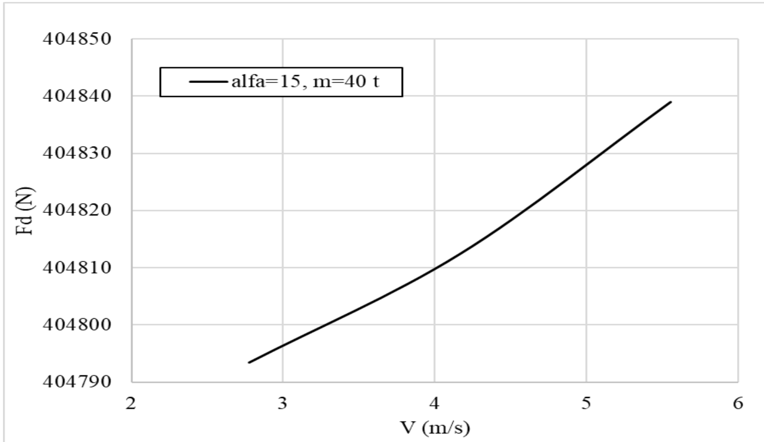
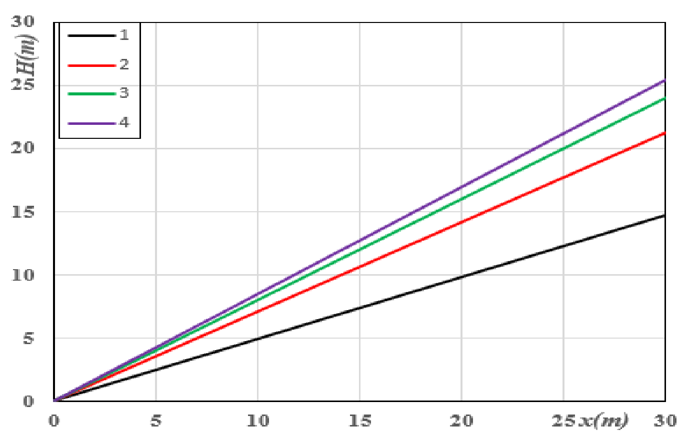


Figure 7. Total forces acting on a dump truck with a mass of (m = 40) tons.

The conducted studies show that the operating mode of vehicles has a significant impact on energy efficiency. During downhill motion, the braking intensity is high, and it is precisely in this phase that the potential for energy recovery reaches its maximum. Therefore, regenerative systems demonstrate the highest efficiency under such conditions [12], [13]. Figure 8 presents the graph of the height (in meters) that can be achieved using the recovered stored energy [7].



1 – 5^0; 2 – 10^0; 3 – 15^0;4 – 20^0;

Figure 8. Energy utilization in terms of achievable height.

Figure 8 illustrates the height that can be achieved using the stored energy. It can be observed that the maximum lifting height is obtained when the slope angle is 20^0, reaching up to 26 m.

Mathematical Model of the Hydrostatic Regenerative System for Quarry Dump Trucks

Using the MATLAB package, a mathematical model of the vehicle was developed. In constructing the model, both the resistive forces acting on the vehicle and the force generated by the hydraulic system were taken into account. The acceleration of the vehicle can be determined using Equation (5).

$$ma = F_H - F_D \tag{5}$$

In Equation (5), (m) denotes the mass of the vehicle, (a) represents the acceleration, (F_H) is the force applied by the hydraulic system, while (F_D) corresponds to the resultant of the resistive forces acting on the vehicle [14].

After determining the vehicle acceleration from the force balance, the velocity and position variations can also be obtained by taking the time integral of the corresponding expressions. The acceleration of the vehicle considering its mass is modeled in MATLAB–Simulink, as shown in Figure 9 [9].

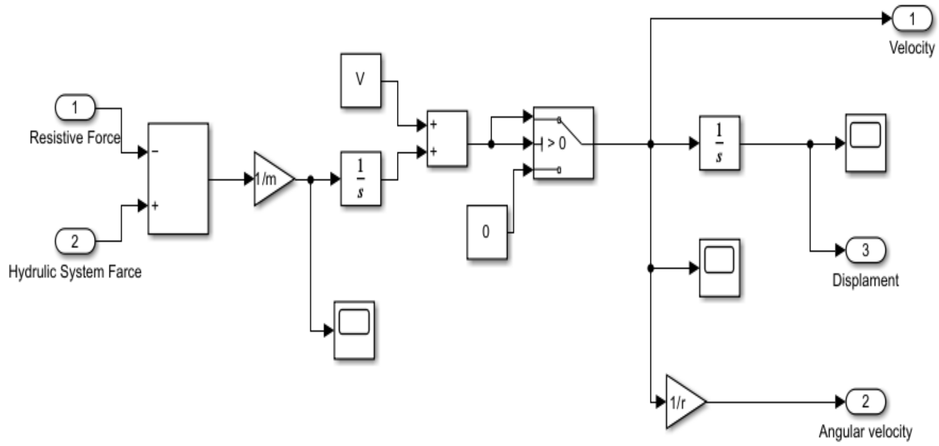


Figure 9. MATLAB–Simulink model of vehicle acceleration, velocity, and position.

Mathematical modeling is an important tool in the study of such systems. Through modeling, it is possible to predict the behavior of the system under various operating conditions. This, in turn, enables the determination of optimal design and operational parameters [15], [16]. As a result, the overall efficiency of the system can be maximized. Moreover, modeling results allow for comparison of different design alternatives and selection of the most appropriate solution, thereby increasing the practical significance of scientific research. In particular, modeling methods are highly effective in cases where experimental studies under real conditions are difficult to perform.

Conclusion

The introduction of energy-saving technologies in quarry transport has not only economic but also strategic importance. Given the limited nature of energy resources, their efficient use and conservation represent a priority task for any country. The conducted research has demonstrated the feasibility of recovering energy lost during braking in quarry dump trucks through hydrostatic regenerative systems. The application of such technologies makes it possible to reduce fuel consumption and improve the overall efficiency of vehicles. In addition, regenerative systems reduce the wear of braking components and decrease maintenance costs, thereby enhancing operational efficiency. Furthermore, the reduction in fuel consumption also leads to lower exhaust emissions, which is of significant environmental importance.

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