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DYNAMIC MODEL OF A HYBRID ARTICULATED TRUCK FOR ENERGY MANAGEMENT

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Abstract. *The purpose of this work is to develop a strategy of energy management of a hybrid articulated heavy truck by using longitudinal vehicle dynamic modeling. This study is focused on the torque management offered by the engine of an articulated heavy truck that is based on the use of a four-stroke internal combustion engine (ICE) of the tractor and one electric motor coupled directly to the axle of its trailer. The articulated vehicle has an independent drive axle to assist in maintaining its speed, both on hills and downhills. Equations of motion for these dynamic systems are solved in the MATLAB® environment, where a road profile is introduced as an input mode observing the 3% maximum slope National Department of Transport Infrastructure (DNIT) restriction for roads with a limit of 80 km/h. The results have shown that this type of strategy can be an important tool for fossil fuel savings as well as mitigating polluting gas emissions.*

Keywords: *Longitudinal dynamics, articulated heavy truck, electric motor, hybrid powertrain.*

1. INTRODUCTION

The automotive and road transportation industries have been increasingly trying to add autonomy and efficiency in the execution of its tasks, both in passenger transport as well as heavy loads. Heavy truck vehicles play an important role in the economy, particularly in Brazil, where the railway network is still incipient. Although the Brazilian rail network has been growing recently, the road modal transportation will continue to have an expressive participation in cargo transportation. It is thought that of all the energy consumed in the transportation sector, around 75% is spent on road transportation [1].

As well as passenger cars, which have been undergoing environmental policies that should be implemented in the coming decades, heavy truck vehicles may undergo similar restrictions. To meet the various environmental restrictions imposed by mostly European countries, conventional vehicles with internal combustion engines (ICE) are being replaced by electric vehicles (EV) or hybrid electric vehicles (HEV). In this context, the development trends in the automotive industries have switched from the traditional mechanical powertrain to an electric or hybrid powertrain. The implementation of hybrid powertrains has proven to be a very interesting choice in vehicle performance as it allows better management of the power available in the vehicle's wheels. Furthermore, the HEVs can provide fossil fuel savings and mitigate polluting gas emissions.

Articulated vehicles or tractor-trailer vehicles have been the focus of several recent articles. The performance simulation of this type of vehicle through dynamic modeling has been conducted for the analysis of handling stability, emergency braking, autonomous systems, trajectory control, maneuverability and many others [2-6]. For example, these vehicle dynamic models are basically used for studies involving fuel consumption, gas emission, propulsion layout, etc., employing a longitudinal vehicle model; steering system and tire behavior with a lateral vehicle model, and suspension system and comfort with a vertical vehicle model [7-8].

In several review articles involving the subject of hybrid electric vehicles (HEV), they primarily address topics such as: energy management strategies or energy optimization and powertrain architecture [1, 9-11]. The main issues related to HEV include: a) the recovered energy storage while downslope or braking, b) the search for the maximum efficiency point of ICE, c) the power flow optimization to obtain best fuel economy or low polluting gas emission.

Even though there may be many kinds of HEV, its concept in this study is composed of ICE and an electric motor on each wheel. Thus, the concept of energy management in this study should be understood as the HEV design to get an effective result with controlling conversion of energy on the powertrain of an articulated heavy truck.

The objective of this study is to develop an energy management strategy focused on a hybrid articulated vehicle to assist in maintaining the vehicle's speed, both on hills as well as downhills. For this purpose, a longitudinal dynamic modeling of a tractor-trailer vehicle with a new independent drive axle on the trailer is developed. This proposition is based on the use of a four-stroke internal combustion engine on the tractor and one electric motor coupled directly to the trailer's axle. The developed dynamic model focuses on managing the torque that will be applied by the electric motor to promote a greater load capacity of the truck and reduced fuel consumption, considering that optimal torque management allows the work of the internal combustion engine mostly in its optimum operating regime. Equations of motion for this dynamic system in the time domain are solved in the MATLAB® environment, where a road profile with a hill and a downhill is introduced as the input mode. The results have shown that the introduction of a torque provided by the electric motor can provide a smoother ride to the articulated vehicle.

2. DYNAMIC MODEL OF THE HYBRID ARTICULATED VEHICLE

The mathematical model of the hybrid articulated vehicle is based on the longitudinal vehicle dynamics of a trailer attached to a tractor. The tractor is composed by a front axle (1), without a propulsion, and a rear axle (2), with an internal combustion engine (ICE) propulsion. The trailer is the element of the truck that carries the heavy load and has an independent axle with an electric motor on each wheel. The basic features of the hybrid articulated truck are shown in Fig 1.

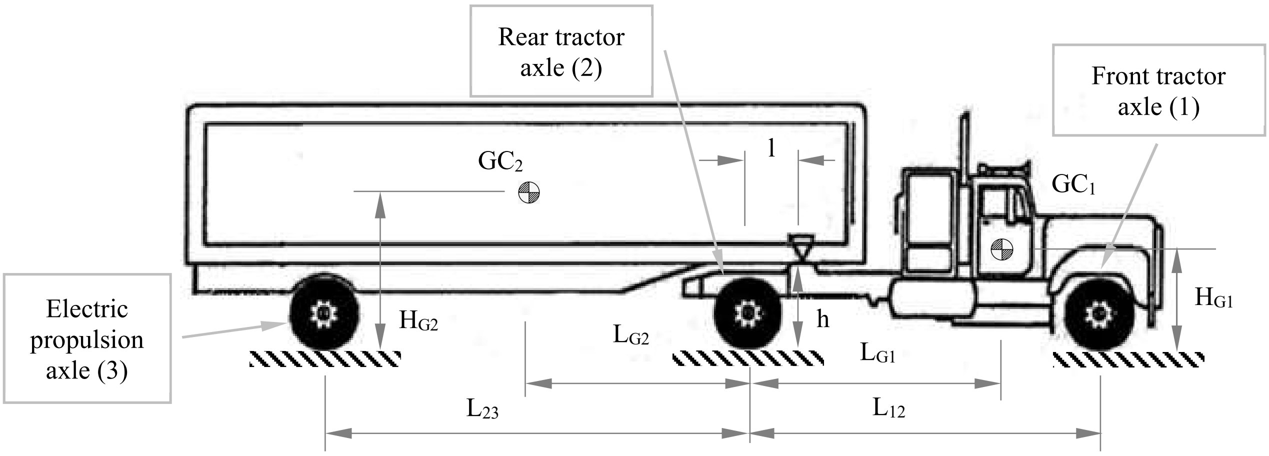


Figure 1. Articulated heavy truck basic dimensions.

The normal and longitudinal actions on the hybrid articulated truck bodies moving over a sloped track are shown in Fig 2.

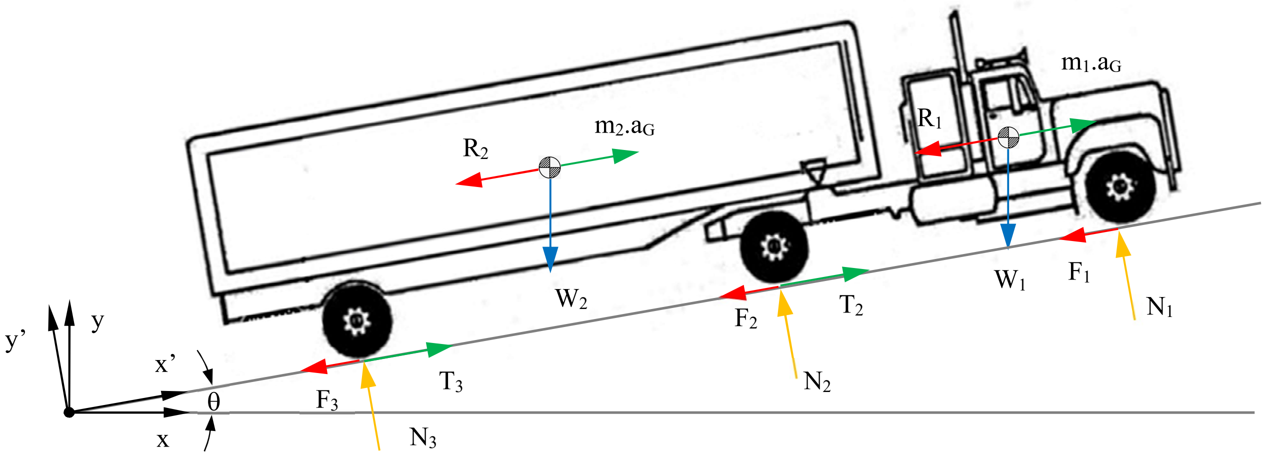


Figure 2. Model of an articulated truck moving on an inclined plane.

Where:
W_1 – Tractor weight;
W_2 – Trailer weight;
R_1 – Aerodynamic drag force of the tractor;
R_2 – Aerodynamic drag force of the trailer;
T_2 – Longitudinal tire force of the rear tractor axle (2);

T_3 – Longitudinal tire force of the trailer axle (3);
N_1 – Normal force on axle (1);
N_2 – Normal force on axle (2);
N_3 – Normal force on axle (3);
F_1 – Rolling resistance on axle (1);
F_2 – Rolling resistance on axle (2);
F_3 – Rolling resistance on axle (3).

According to Leal, da Rosa and Nicollazi, the equation of motion that describes the articulated truck behavior is deduced as a function of the resistances involved while running, as shown below [12]:

$$(W_1 + W_2).a_v = Q_m + Q_a + Q_s + Q_r + Q_i \quad (1)$$

Where a_v is the acceleration of the truck, Q_m is related to mechanical torque transmission resistances from the engine up to the wheels, Q_a is the aerodynamic drag force, Q_s is slope resistance, Q_r is rolling resistance from tire/road contact, and finally, Q_i is related to rotational inertia resistance of the truck's components.

As previously described, the objective of this study is the energy management provided by the electric motor installed on the trailer axle to maintain a constant velocity of the truck. Thus, the resistances Q_m and Q_i can be neglected.

The aerodynamic drag force can be admitted as follows:

$$Q_a = q \times C_x \times A \quad (2)$$

Where q is the dynamic pressure, C_x is the drag coefficient and A is the frontal area of the tractor. The expression of q is:

$$q = \frac{1}{2} \times \rho \times V_r^2 \quad (3)$$

Where ρ is the air density and V_r is the real velocity of the truck. The slope resistance can be admitted as:

$$Q_s = (W_1 + W_2) \times g \times \sin \Theta \quad (4)$$

Where g is the gravity acceleration. And finally, the rolling resistance can be admitted as:

$$Q_r = f \times (W_1 + W_2) \times g \times \cos \Theta \quad (5)$$

Where f is the frictional coefficient of rolling and can be expressed as:

$$f = a + b \times \left(\frac{V_r}{100}\right)^2 \quad (6)$$

In Table 1, the values for constants *a* and *b* for different types of tires are shown.

Table 1. Tire constants *a* and *b*.

Types of tires	***a***	***b***
Normal tires	0.0150	0.052
High hysteresis tires	0.0258	0.052

This study seeks to manage the electric motor operation only for the assistance of slopes without the driver's actuation varying the combustion engine rotation or the gear used. Thus, considering the power supplied by the internal combustion engine P_m constant and equal to the power needed to move the truck on a flat stretch. The power supplied by the motor can represent the power available in cube P_c allowing for its mechanical losses.

$$P_c = P_m \times (\eta_{cx} \times \eta_{diff}) \quad (7)$$

Where η_{cx} is the gearbox mechanical efficiency, and η_{diff} is the mechanical efficiency of the differential.

By definition, the power dissipated by the resistance forces must be in balance with the power available in the cube, being represented by the following equations:

$$P_c = P_a + P_s + P_r \tag{8}$$

$$P_a = Q_a \times V_r \tag{9}$$

$$P_s = Q_s \times V_t \tag{10}$$

$$P_r = Q_r \times V_t \tag{11}$$

Where V_t is the tangential velocity of the wheel and related to the real velocity of the truck by:

$$V_t = \frac{V_r}{(1-e)} \tag{12}$$

Where e is the tire/road contact slip coefficient.

From the balance of powers, an expression can be found for the difference between the effective power P_e needed to transit any road profile and the power in cube P_c that is required to move on a flat stretch. Thus, the difference between them is the resulting power that should be applied by the electric motor P_r.

$$P_r = P_e - P_c \tag{13}$$

Applying Eqs. (2), (4) and (5) to Eqs. (8), (9) and (10) follow that:

$$Pc = (q \times C_x \times A) \times V_r + \big((W_1 + W_2) \times g \times \sin\theta) + f \times (W_1 + W_2) \times g \times \cos\theta\big) \times V_t\,, \quad \Theta = 0 \tag{14}$$

$$Pe = (q \times C_x \times A) \times V_r + ((W_1 + W_2) \times g \times \sin\theta) + f \times (W_1 + W_2) \times g \times \cos\theta) \times V_t \tag{15}$$

3. ROAD PROFILE DESCRIPTION

The energy management strategy will be applied to a hypothetical situation where the hybrid articulated truck is running over a road profile containing flat stretches, a hill and a downhill as illustrated in Fig. (3).

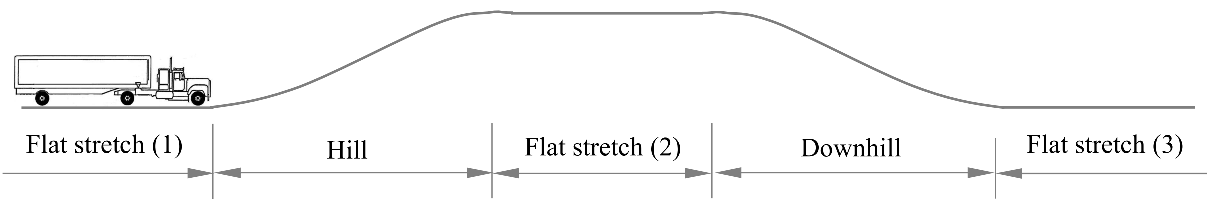


Figure 3. Road profile for energy management.

For the energy management of the hybrid articulated truck running over the road profile shown in Fig. (3), the mechanical propulsion of the tractor T_2 and the electric propulsion of the trailer T_3 are as presented below:

$$For\ flat\ stretch\ (1) \qquad T_2 = Constant\ and\ T_3 = 0 \tag{16}$$

$$For\ hill \qquad T_2 = Constant\ and\ T_3 = T_3(\Theta) \tag{17}$$

$$For\ flat\ stretch\ (2) \qquad T_2 = Constant\ and\ T_3 = 0 \tag{18}$$

$$For\ downhill \qquad T_2 = Constant\ and\ T_3 = T_3(\Theta) \tag{19}$$

$$For\ flat\ stretch\ (3) \qquad T_2 = Constant\ and\ T_3 = 0 \tag{20}$$

Where the road profile can be described by the following equations:

$$Hill: (\cos\gamma + 1) \times 0.3, \text{ where } \pi \leq \gamma \leq 2\pi \tag{21}$$

$$Dowhill: (\cos\gamma + 1) \times 0.3, \text{ where } 0 \leq \gamma \leq \pi \tag{22}$$

The road profile is adjusted according to the maximum inclination recommended by the Brazilian Design of Highways Norm (1973), which determines a maximum inclination of 3% for type III roads where the maximum speed is 80 km/ h [13].

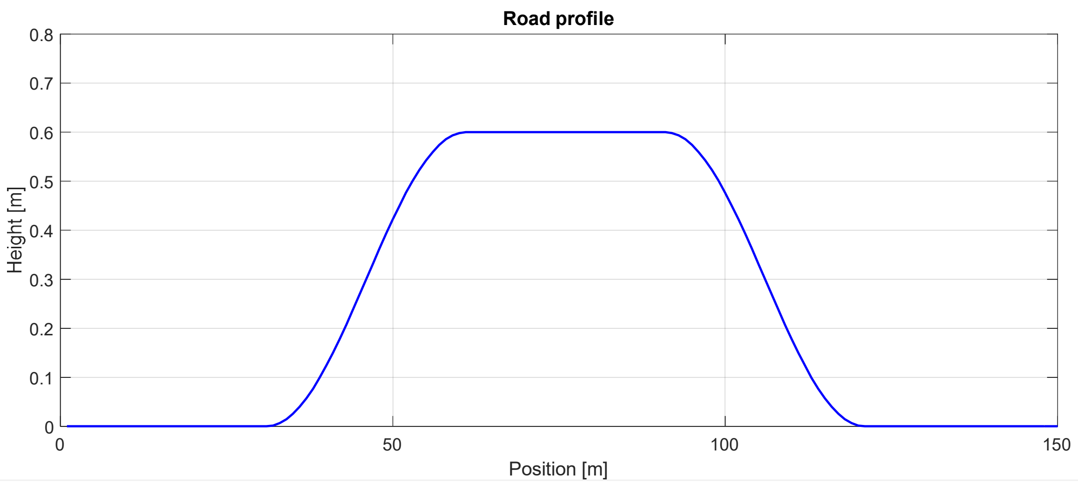
4. RESULTS

In this section, the previously presented hybrid articulated truck is used for energy management. The tractor and trailer propulsion data are shown in Table 2, [14].

Table 2. Tractor and trailer data.

Tractor	
Mass – m_1, kg	15000
Drag coefficient – c_x	0.9
Static frictional coefficient – μ_{s1}	0.015
Dynamic frictional coefficient – μ_{d1}	0.052
Dynamic rolling radius – R_d, m	0.5003
Frontal area – A, m^2	10
Trailer	
Mass – m_2, kg	25000
Static frictional coefficient – μ_{s2}	0.015
Dynamic frictional coefficient – μ_{d2}	0.052
Dynamic rolling radius – R_d, m	0.5003

A MATLAB® code to obtain the results is developed and presented below. Figure (4) exhibits the overall electric power response from the trailer axle along the path shown in Fig. (3).



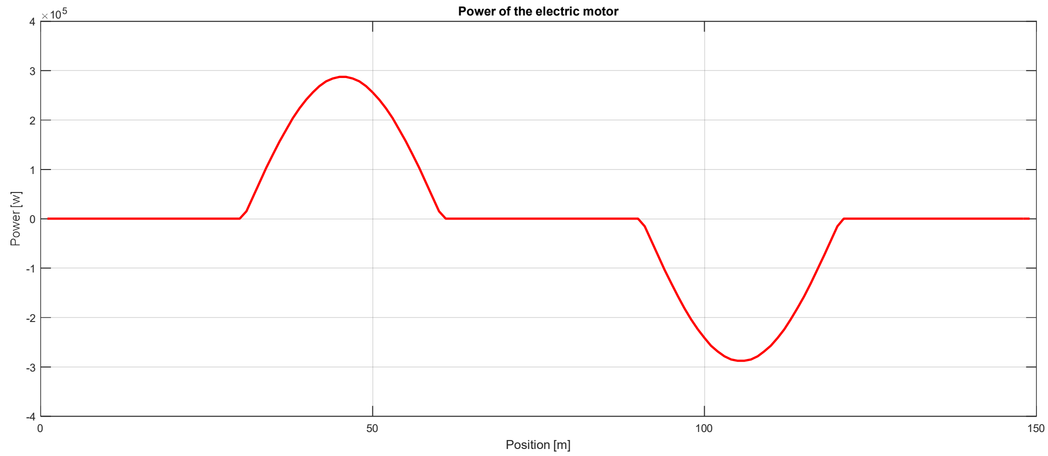


Figure 4. Road profile and electric power from trailer axle.

As observed in Fig. (4), the maximum intensity of the electric power to drive a truck on a hill is 280 kW, approximately 375 HP. From a brief internet search, it is verified that electric motor car chargers with power in this order of value are available on the market [15]. Therefore, it will soon be possible to find chargers with power greater than 280 kW for hybrid trucks.

The negative value of power while downhill only represents the energy consumed to assist the truck's braking and does not represent energy regeneration.

5. CONCLUSIONS

As presented in this study, knowledge regarding the energy management of a hybrid articulated truck running over a road profile containing flat stretches, a hill and a downhill is applied. As observed, a quantitative way of analyzing the difference in consumption and the variation in the autonomy of the truck is sought with the use of this system comparing the models of the original truck (without the electric motor on the trailer axle) and the truck with the use of the hybrid system.

Furthermore, the results have shown that the introduction of a torque from an electric motor installed on the trailer axle can provide a smoother ride for the articulated truck.

Regarding limitations, it must be addressed here that the results were obtained with a constant velocity of the truck without considering transitions between flat and sloped stretches. It is believed that considering accelerations and decelerations, it may achieve more reliable results.

6. ACKNOWLEDGEMENTS

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