# Design of the electric propulsion system for dumper trucks

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**ABSTRACT**

This article designs a high-efficiency electric propulsion system for industrial trucks, such as dumper trucks. This design proposes using an alternative energy storage system of green $H_2$ hydrogen to reduce emissions. This design determines the propulsion systems' technical and power requirements, starting with each vehicle's driving and duty cycles. For this analysis, a longitudinal dynamic model is created, with which the behavior of the energy conversion chain of the propulsion system is established. The evolutionary methodology analyzes the dynamic forces of vehicle interaction to size the propulsion system's components and the storage system. Using green $H_2$ as fuel allows an energy yield three times higher than diesel. In addition, using this green hydrogen prevents the emission of 264,172 kg of $CO_2$, which the dumper emits when consuming 1,000 daily gallons of diesel within its working day.



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## 1. INTRODUCTION

Vehicle mobility is moving towards cleaner and more sustainable technologies, using fewer polluting fuels [1]. Over time, research has been carried out to develop new designs with greater efficiency, better autonomy, and lower operating costs without sacrificing performance or the vehicle's useful life [2]. These unique designs reduce greenhouse gases from internal combustion, diesel, or gasoline cars. Consequently, cars with alternative propulsion systems are beginning to emerge, besides hydrogen vehicles [3]–[5].

Globally, the number of existing hydrogen-electric vehicles (FCEVs) is considerably lower than that of battery electric vehicles or plug-in hybrids vehicles. Nevertheless, according to the Global Electric Vehicle Outlook of the International Energy Agency (IEA), by the end of 2019, there were already 25,210 FCEV units. The main countries promoting this kind of vehicle technology are China, the United States, Canada, Japan, Korea, Germany, and other countries, mostly Europeans. These have focused on light vehicles but are currently implementing fleets for heavy vehicles [6]–[8]; these changes have been possible due to the great autonomy that gives hydrogen as a fuel in the transport sector and its several benefits against climate change. In addition, these countries invest heavily in FCEV for buses and trucks [9].

The growing interest in Europe is evident in the development of hydrogen as a fuel. The German government announced in July 2020 grants to 20 laboratories for hydrogen research for several years [10]. Hyundai's SUV, the Nexo with hydrogen fuel cell, is currently marketed in Spain. This vehicle is an evolution of commercial electric vehicles. Its great advantage is its range of 756 km and 123 kW (160 hp) of power, with no equal present. Moreover, the refueling time of the hydrogen tank is only 5 minutes, as if it were a conventional vehicle. In addition, this vehicle does not emit any pollution, only water.

On the other hand, Asian countries are also preparing to use fuel cells [11], [12]. For example, in Japan, the second-generation low-consumption Toyota Mirai has one more hydrogen tank with an extended range of 650 km. Additionally, its propulsion system develops 182 hp and 300 Nm, increasing its hydrogen capacity from 4.6 to 5.6 kg [8]. In South Korea, Hyundai contributes to adopting commercial vehicles powered by hydrogen fuel cells [13]–[16]. With this, the battery electric vehicle is beginning to be left behind.

The use of hydrogen vehicles in transportation continues to be restricted. Still, in trains and industrial trucks, an increase in hydrogen fuel cells has been generated [17]. The first hydrogen fuel cell trains started their test phase in Germany in 2018, and these tests ended in 2020 with positive results. Hydrogen fuel cell trains can seamlessly replace diesel-powered trains [18]. Moreover, the Swiss multinational electrical engineering and automation company ABB and Hydrogène de France (HDF) signed a collaboration agreement to manufacture megawatt-scale hydrogen fuel cells to power large ocean-going vessels. This technology will make it possible to propel large ships while powering their electrical systems. Furthermore, thanks to renewable energy generation, the hydrogen obtained will provide a clean energy chain [19].

ENGIE and the mining company Anglo-American announced a partnership for the joint development of the world's largest hydrogen dumper. It requires a custom-designed and manufactured hydrogen fuel dispenser. The hydrogen fuel cell-powered electric truck will be powered by a hydrogen cell consisting of eight 100 kW cells, and the total power output is 1,088 hp. Modifying the dumper includes replacing the diesel fuel tank with 22 hydrogen tanks and the diesel engine with hydrogen fuel cells and batteries [20]. This technology is also being implemented in 220X 20-ton excavators powered by hydrogen fuel cells in the construction industry, achieving zero and low carbon emissions [21]–[24]. In South America, politics will point toward obtaining green and blue hydrogen based on its opportunities for energy sources. For example, Chile is considered one of the Meccas of solar energy and was the first country to present a "national green hydrogen strategy" in November 2020; it is also the only Latin-American country with two projects under development [25].

In Colombia, strategies have been advancing since 2014 with the Renewable Energy Law 1715. By 2021, the energy transition law 2099 was issued, which together seeks to massify and align with the commitments made by Colombia in the Paris agreement, which establishes the reduction of carbon dioxide emissions. This energy transition law establishes clear goals regarding the use and generation of green hydrogen, intending to replace industrial processes in Colombia and massify its use by 2030 as a fuel source for heavy and light vehicles. Although Colombia currently produces gray and blue hydrogen due to the lower production costs of this type of hydrogen, it is expected that by 2030 the production of green hydrogen will reach a competitive price of 1.7 US/kg of $H_2$. Blue hydrogen has an average production cost of 2.4 US/kg.

## 2. METHOD

The proposed methodology consists of three steps. First, determine the low-order longitudinal model of the vehicle, which will allow sizing of the car's energy consumption, starting from the dynamic forces of interaction on the vehicle chassis. Second, define the propulsion system components, which are reliably determined from the study of the vehicle dynamics, taking the driving cycle for tests as a reference. So, it determines the peak power and its energy consumption within the propulsion cycle. Lastly, sizing the required capacity of the green hydrogen storage system.

### 2.1. Determine the low-order longitudinal model of the vehicle

Initially, the necessary forces interacting with the truck to achieve its displacement under arbitrary conditions are determined based on classical Newton's laws. Subsequently, the longitudinal Gillespie model is determined from the free body diagram. For this purpose, the free-body diagram is shown in Figure 1. The main forces, resistive and tensile, are determined according to (1) to (4). This diagram associates the resistive and traction forces during the truck's travel.

$$F_x = T_e \, N_{tf} \, \eta_{tf} / r \tag{1}$$

$$R_x = R_{xf} R_{xr} = f_r \, W \tag{2}$$

$$D_a = 1/2 \, \rho \; V^2 \, C_D \, A \tag{3}$$

$$M \, a_x = F_x - R_x - D_a - W \sin \theta \tag{4}$$

where $F_x$ [N] is the tractive force, $T_e$ [Nm] is the engine torque, $N_{tf}$ is the mechanical reduction, $\eta_{tf}$ is the mechanical efficiency, $r$[m] is the wheel radius, $R_x$[N] is the rolling resistive force, $f_r$[-] is the rolling coefficient, $W$[kg m/s$^2$] is the gross vehicle weight, $D_a$[N] is the aerodynamic force, $\rho$ is the air density,

$C_D$ is the aerodynamic coefficient, $A$ [m$^2$] is the cross-sectional area of the vehicle, $M$ [kg] is the mass of the vehicle, $a_x$ [m/s$^2$] is the acceleration, $\theta$[rad] is the terrain inclination, and $V$[m/s] is vehicle speed.

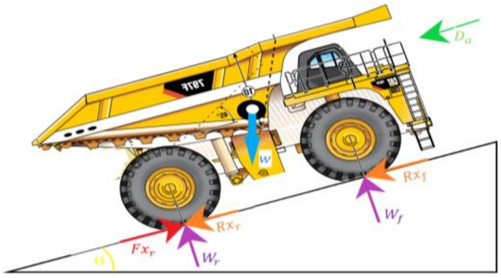


Figure 1. Forces acting on the dumper

### 2.2. Define the propulsion system components

For the vehicle power model, it is sufficient to determine the instantaneous power produced by the vehicle, versus speed versus time data, according to (5). This truck's power consumed (greater than 0 W) or generated (negative) is calculated from a velocity cycle. A velocity cycle consists of a series of velocity versus time data, which a GPS data logger easily determines with a sampling rate equal to or greater than 10 Hz [26].

$$P = Fx * V \quad (5)$$
$$P > 0 \; consumed$$
$$P < 0 \; generated$$

where $P$ [W] is the engine power.

For the selection of the components, namely the engine, the mechanical reduction system, and the energy storage system, it is considered: i) the electric motor must comply with the maximum power generated by the driving cycle, i.e., $P_m \geq Max\ (P)$. The electric motor must deliver the maximum power according to the driving cycle. An oversizing of 20% of the maximum power is proposed to guarantee this; ii) in addition, the engine must ensure an adequate coupling between engine speed and wheel speed. For this purpose, a mechanical reduction must be dimensioned since the electric motor always has higher RPMs than the wheel. It must consider that it $V_x = \omega r$ must be fulfilled. Where $V_x$ [m/s] is the linear velocity of the vehicle, ω [rad/s] is the angular velocity of the wheel, and r [m] is the radius of the wheel, assuming a wheel without any deformation. The reduction $N_{tf}$ [-] is determined by the engine and wheel revolutions fraction; and iii) the wheel torque is determined by model $T_e = Fx\frac{N_{tf}\eta_{tf}}{r}$, where $T_e$ [Nm] is the motor torque, $Fx$ is the longitudinal force, $\eta_{tf}$ is the mechanical efficiency of the transmission, which can be assumed to be 95%. The other parameters are previously in this section.

### 2.3. Sizing the required capacity of the green hydrogen storage system

This point determines the energy storage system. For this using (6), it is possible to decide on the amount of energy needed for the vehicle to meet the speed requirements of the driving cycle. It is important to note that this storage system must complete the daily working hours of the truck. Once the energy value [Js] is obtained, its equivalence in [Wh] is determined. Thus, considering the specific energy of green hydrogen, it can determine the required amount of fuel in m$^3$.

$$E_V = \int_0^t P\,dt = \sum_{t=0}^{t_f} P_t \Delta t \quad (6)$$

where $E_V$ [Ws] is the instantaneous energy of the dumper.

## 3. RESULTS AND DISCUSSION

Initially, the data from the technical specification sheet of the C797F CAT truck are considered for the dynamic force calculations. Table 1 shows the main mechanical and technical characteristics of the dumper truck. It is important considering the dumper gross weight without any energy storage system because its weight could reduce the truck autonomy.

Table 1. Technical specifications mining truck CAT 797F

| Characteristic | Value |
|---|---|
| Overall length | 15.08 m |
| Total width between tires | 9.52 m |
| Gross power SAE J1995 | 4.000 hp @ 1750 rpm |
| Cylinder | 106 Lt |
| Torque | 16277.45 Nm @ 1750 rpm |
| Gross weight of the machine in working order GMV | 623.690 kg |
| Rated Payload Capability | 363-Tons metrics |

### 3.1. Driving cycle

The driving cycle is a profile of speeds vs. time, representing a driving style on main roads or in cities. A driving cycle considers traffic, type of road, climate, and geography, including altitude, among the most important data and the type of driving style. The study is based on the worldwide harmonized light vehicle test cycle (WLTC) Class 1 driving cycle applied to the Dumper truck. The WLTC cycle for a class 1 vehicle is divided into low and medium speeds. If $Vmax < 70\ km/h$, the medium-speed part is replaced by the low-speed part [5]. Figure 2 shows the WLTC Class 1 driving cycle used as the basis for the mathematical development of the dumper truck. Although the distance traveled is 8,091 meters according to the WLTC Class 1 test cycle, it constantly took the terrain inclination angle at 15°. This angle is defined because it is the one that most closely resembles the actual operation of the truck in a mine.

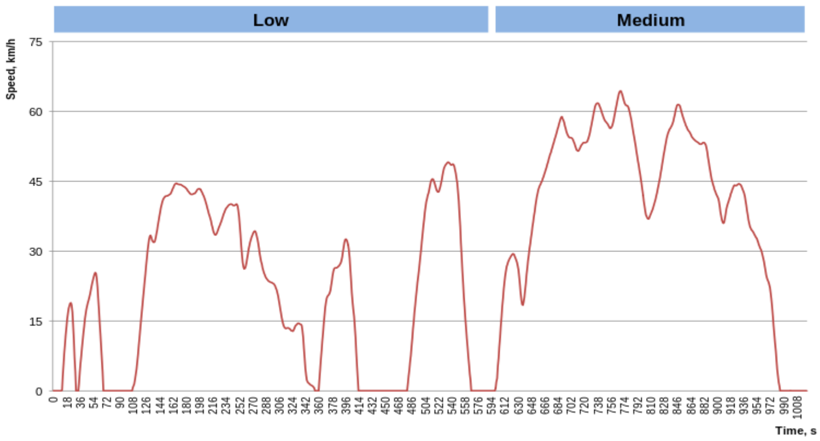


Figure 2. WLTC Class 1 driving cycle

### 3.2. Simulation results

Figure 3 shows the acceleration data determined from the selected driving cycle. As can be seen, the vehicle's acceleration is within the expected range [-2, 2] $m/s^2$. We estimate the traction power required to define the electric motor with this data. By subtracting the traction force (Fx), its instantaneous value is obtained during the travel. It is shown in Figure 4.

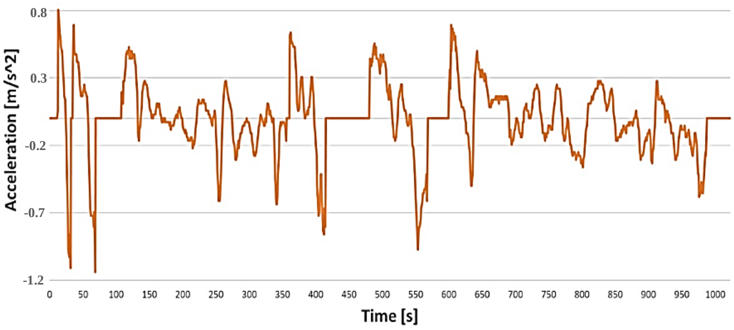


Figure 3. Truck acceleration

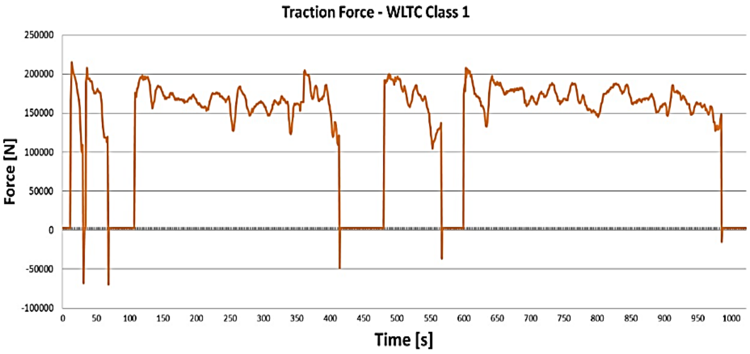


Figure 4. Traction force

Then, each interaction force is multiplied by the speed to determine the maximum power of the electric motor, as represented in (5). Figure 5 shows the aerodynamic forces present on the dumper truck during the driving cycle. On the other hand, the traction force is multiplied by the speed, obtaining the electrical power. Regenerative braking occurs naturally and is represented on the negative side of Figure 6.

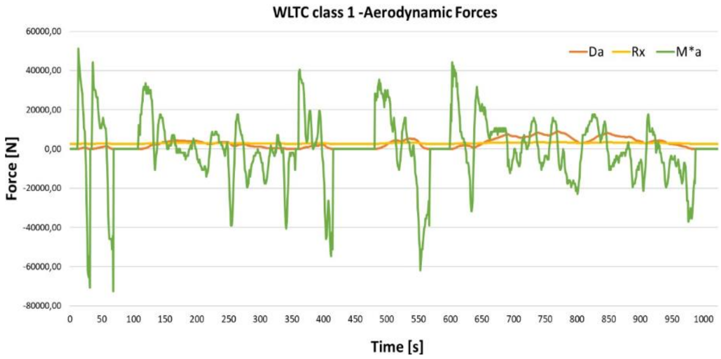


Figure 5. Interactive resistive forces over the truck

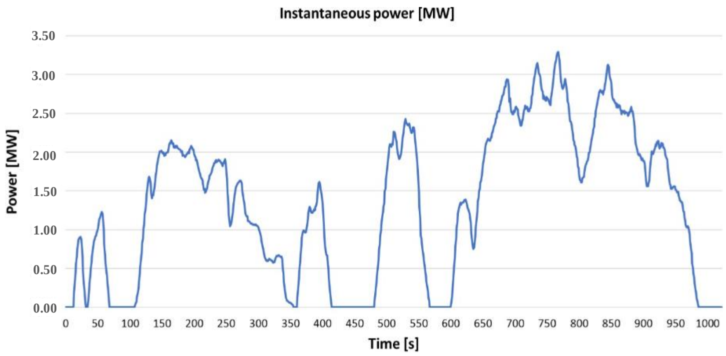


Figure 6. Instantaneous power of the truck

### 3.3. Determination of the electric motor

The peak power obtained is 2.5 MW; under design criteria, this power must be increased by 20% to contemplate any additional power requirement not considered. Thus, 3.1 MW is required to be supplied. Once the motors have been selected, it can determine the motor torque by clearing $T_e$ given in $Nm$ from (1). Finally, the wheels' characteristics and the truck's maximum speed, listed in Table 2, must be considered to determine the transmission ratio of the motor to the wheels.

After determining the wheel's angular velocity as $\omega = 18.77\, m/\frac{2.010\, m}{s} = 9.34$ rad/s, we seek the maximum rpm, and the mechanical reduction is shown in Table 3. This mechanical reduction is the ratio between both angular velocities (wheel and electric motor), and its efficiency energy is around 95%. Then, the maximum value of the traction force is obtained, and it can determine as the torque related in section 2.2 obtaining $T_e =$ 16,927.01 Nm.

Table 2. Determination of motor torque CAT 797f

| Maximum speed | 67.6/18.77 | [km/h]/[m/s] |
|---|---|---|
| Wheel Radius 59/80R63 - BRIDGESTONE | 79.1/2.010 | inches/m |

Table 3. Selection of electric motor characteristics

| Motor - RPM max | 2400/251.33 | rpm /rad/s |
|---|---|---|
| Mechanical reduction | $N_{tf} = \frac{9.34}{251.33} = 26.91$ | - |

Four permanent magnet motors are selected for an all-driven traction vehicle (we use one motor for each wheel) with the highest efficiency in the market; this motor has been specifically developed for heavy-duty vehicles. The power and nominal torque characteristics are fulfilled in Table 4, where the technical features of a unit are presented.

Table 4. Electric motor - Danfoss EM-PMI 540-T4000-1200DA

| Characteristics | Value | Units |
|---|---|---|
| Control voltage | 500 | VAC |
| Nominal power | 531 | kW |
| Nominal torque | 4229 | Nm @ 1200 rpm |
| Maximum torque | 5930 | Nm @ 2400 rpm |
| Nominal Current | 705 | A [ac] |

With the values determined, it can establish the capacity of the propulsion system. However, to obtain the power required for each motor, four electric motors will be used, one for each wheel; then, we must determine that the energy consumption for the route is 380.31 W/s (or 105.64 W/h). It is then divided over the distance of the test drive cycle, obtaining 13.05 Wh/km.

### 3.4. Determination of the energy storage system

The electrical energy to carry out the electrolysis process can come from a renewable source of solar, wind, hydro, or biomass energy, which is why hydrogen is green. Electrolysis has an electrical conversion efficiency ranging from 60% to 70%, translating into an approximate consumption of 50 to 60 kWh of electrical energy to produce 1 kg of $H_2$ [12]. Table 5 shows the main properties of hydrogen, where it can observe its upper and lower heating power point and its density in a gaseous state. Considering that each gallon of diesel has an average weight of 3,217 kg, it determines that 1,000 gallons of diesel fuel from the mining dump truck weight approximately 3.2 tons.

Table 5. Properties of hydrogen

| Properties | Values | Units | Properties | Values | Units |
|---|---|---|---|---|---|
| Gas density | 0.089 | kg/m³ | Ignition range | 4 a 77 | % in air |
| Liquid density | 70.76 | kg/m³ | Ignition energy | 0.2 | MJ |
| Boiling temperature | -252.76 | °C | Upper heating value | 33.880 | kcal/kg |
| Flame speed | 346 | cm/s | Lower heating value | 28.670 | kcal/kg |

Note: The upper and lower heating value may vary according to temperature

Replacing 1,000 gallons of diesel (with an approximate weight of 850 kg/m$^3$ and an energy density of 40 MJ/kg) requires an energy of 128,703.940 MJ. According to Pacific Northwest National Laboratory, replacing the diesel (in gallons) with green hydrogen (in kg) needs a conversion factor of 1.12. This parameter relates to the fuel cell and the internal combustion engine performance, as shown in Table 6. Thus, we needed 1,200 kg of green hydrogen to replace its energy storage system. That means that this quantity of hydrogen requires 10680 L of H2O (8.9 liters/kg $H_2$).

Table 6. Substitution of $H_2$ for diesel-comparison of calorific value and efficiency

| Item | $H_2$ | Unit | Diesel | Unit |
|---|---|---|---|---|
| Quantity of fuel required | 500 | kg | 1.000 | gal |
| Calorific value | 33.880 | kcal/kg | 11.000 | kcal/kg |
| Fuel cell performance | 50 a 70 | % | 40 to 45 | % |

The dumper truck will be powered by a hydrogen fuel cell module consisting of 30 Ballard FCmove-HD+ cells with 100 kW each. The total power output of the system is 4.023 hp. Table 7 shows the technical characteristics of one of the 100 kW hydrogen fuel cell modules. Five high-pressure gas cylinders between 500 and 700 bar are required for the high-pressure compressed hydrogen storage system with 1,120 kg of hydrogen and 224 kg/cylinder for the mining truck dumper.

Table 7. Fuel cell power module for the dumper truck

| Fuel Type | Gaseous hydrogen |
|---|---|
| Net system power | 100 kW |
| Operating current | 20 to 360 A |
| Operating voltage | 280 to 560 V |
| Dimensions (l x w x h) mm | 1996×802×440 |
| Module weight | 260 kg |
| Operating temperature | -30 °C - +50 °C |
| Maximum efficiency | 57% |
| Fuel supply pressure | 8 bars |

## 4. CONCLUSION

The methodology developed in this research applies to any ground terrain vehicle, including dumper trucks. This method analyses how energy is converted from the energy storage system until the mechanical power is transmitted to each wheel. So, all the general components are selected according to their technical characteristics. It is important to highlight that the inverter is not chosen because it is treated as a black box that requires converting the maximum power established by the driving cycle. However, the inverter could have any modulation and switching technique.

Also, the method employs the well-known Gillespie's longitudinal model (in the automotive world). With them, it is possible to establish the energy consumption in any vehicle and thus determine the production of green hydrogen required for an electric propulsion system. Within the design, it is observed that this type of electric propulsion system with a hydrogen fuel cell is technically feasible and can be implemented in any vehicle, from the largest to the smallest.

It is important to highlight that the high-compression cylinders for gaseous hydrogen must be co-designed with the manufacturers. Due to since the existing ones in the market only reach up to 200 bar and considering that the hydrogen fuel cell module works at 80 bar, steel cylinders that support from 500 to 700 bar are required to achieve the highest percentage of hydrogen compressed in these cylinders.

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