Understanding Horsepower

This document defines and explains what power is. It helps to understand the different loss mechanism associated with an internal combustion engine vehicle and how to minimize them to achieve better fuel economy and horsepower.

Definition of Power

Power is defined as the amount of work performed in a period of time, where the work is a measure of energy. Mathematically, power is expressed as

Power = Energy / Time.

In other words, power is the amount of energy (work) used (delivered) in a certain amount of time. The metric unit of power is the Watt which is equal to one Joule of energy per second. The Watt is named in honor of James Watt. Horsepower is another non-metric unit of power that was defined in the late 18th century by James Watt. The horsepower was invented to give an indication of how powerful a steam engine was compared to the pulling abilities of a single horse in a short period of time. The relation between Horsepower and Watt is

1 Horsepower = 745.7 Watts.

Power Balance for the Internal Combustion Engine (ICE) vehicle

The primary energy source of a vehicle with an internal combustion engine (ICE) is the potential chemical energy released from the air-fuel mixture combustion. The powertrain of the vehicle is the group of mechanical/electric components that transform the chemical energy into usable propulsion energy which accelerates the vehicle. The main energy conversations in an ICE are from chemical energy to mechanical and to electrical energy. Because the powertrain is far less than ideal, its overall efficiency is less than 100%. Therefore, a large fraction of the available power from the chemical reaction is lost throughout the powertrain via different mechanism and consumed by different vital accessories. The power flow in a conventional ICE vehicle powertrain is depicted in Figure 1. The individual power flows are described in Table 1. In this document, the driveline is defined as the components of an automotive vehicle that connect the transmission up to the wheels.

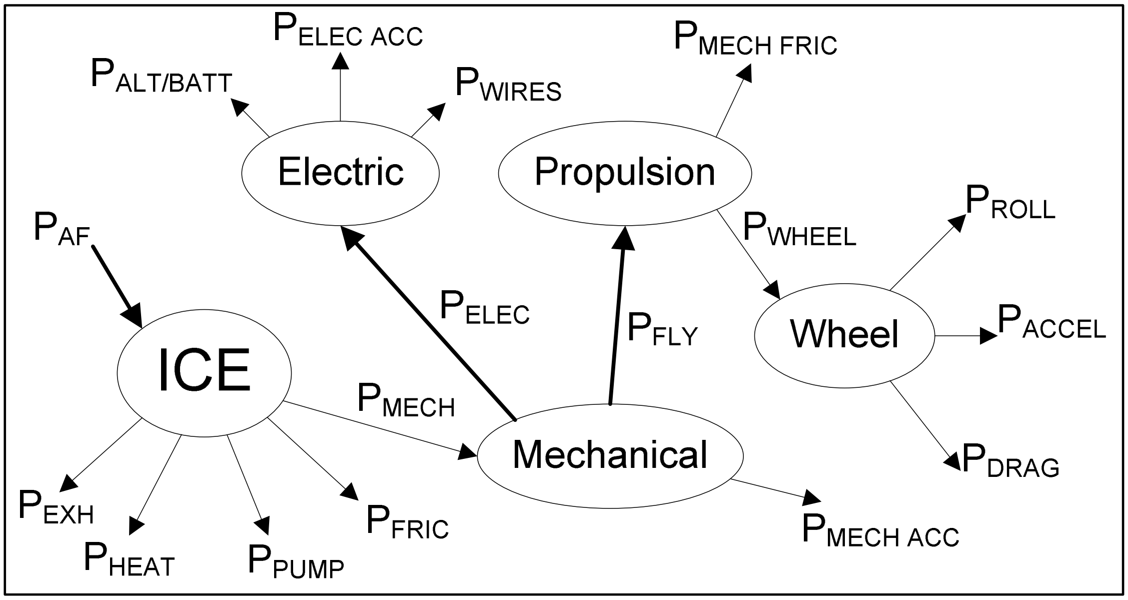

Figure 1: Power Flow in a Conventional ICE Vehicle Powertrain

Power Flow	Description
P_{AF}	Chemical power - power released by the air-fuel combustion
P_{EXH}	Power loss due to exhaust mass flow resistance - power consumed by expelling the exhaust gases through the exhaust system and the work done to open and close the valves
P_{HEAT}	Power loss due to combustion heat - heat released by the combustion (Not the heat due to friction)
P_{PUMP}	Power loss due to the air intake pumping – dependant on the throttle position and the work done to open and close the valves
P_{FRIC}	Power loss due to the mechanical friction within the engine
P_{ELEC}	Mechanical power converted to usable electrical power
P_{MECH}	Power converted to usable mechanical power
$P_{MECH\ ACC}$	Power consumed by accessories such as oil and water pumps, power steering, power braking, A/C compressor and the power lost in the belt system
P_{FLY}	Power available to the propulsion system at the fly wheel
$P_{ELEC\ ACC}$	Power consumed by the electrical accessories such as lights, radio, vehicle computers, Fans, etc
P_{WIRES}	Power loss due to wire resistance
$P_{ALT/BATT}$	Power loss in alternator and battery
P_{WHEEL}	Power available at the drive wheels
P_{ROLL}	Power loss due to rolling resistance (Deflated tires have a higher rolling resistance, compared to properly inflated tires)
P_{DRAG}	Power loss due to aerodynamic drag

$P_{MECH\ FRIC}$	Power loss due to the mechanical friction in the transmission and driveline (Includes the friction from the braking assembly).
P_{ACCEL}	Remaining power to accelerate the vehicle

Table 1: Input and Output Power Flows in the Powertrain

It is assumed in the previous diagram that the vehicle is traveling perpendicular to gravity (not going up or down hill), that there is no wind resistance (no wind flowing against or with the vehicle) and that all brakes are not engaged.

Vehicle Horsepower Rating

Figure 1 shows the importance of clearly defining which loss mechanisms are included in the rated horsepower value. In the early 1970s, the Society of Automotive Engineers (SAE) published the standard J1349 which defined a standard method of rating an engine's horsepower. In a few words, the horsepower rated under J1349 (or SAE net HP) is for a completely installed engine, including all accessories and standard intake and exhaust systems. In other words, it measures horsepower at the flywheel (See P_{FLY} in Figure 1) and excludes all transmission and driveline losses.

The J1349 standard was not without loopholes. Taking advantage of these loopholes, some car manufactures are able to inflate their engine horsepower ratings and therefore rendering the SAE net HP rating less accurate. This led the SAE to introduce in 2005, new test procedures (J2723) for engine horsepower and torque (See www.sae.org/certifiedpower).

This testing procedure is optional. Manufactures completing it can be advertised as "SAE-certified".

Transmission and Driveline Friction

The power lost in the transmission and in the driveline due to friction and resistance is where a large portion of power is lost (See $P_{MECH\ FRIC}$ in Figure 1). Compared to a manual transmission, an automatic transmission suffers more losses due to its mechanical complexity and weight (increased friction), the resistance/slip in the viscous coupling of the torque converter, the transmission oil pump and hydraulic system. Not surprisingly, a 4 wheel drive vehicle suffers even more losses compared to a 2 wheel drive vehicle. Also included in the driveline power loss are the friction from the braking assembly and the friction from the wheel bearings.

Average power losses for a typical vehicle are summarized in Table 2.

	Manual Transmission	Automatic Transmission
2 Wheel Drive	15 % of P_{FLY}	20 % of P_{FLY}
4 Wheel Drive	20 % of P_{FLY}	25 % of P_{FLY}

Table 2: Transmission and Driveline Losses

Rolling Resistance

The rolling resistance (See P_{ROLL} in Figure 1), is caused by the deformation of the tire itself and by the deformation of the rolling surface. The energy used in the deformation is converted into heat. This is the reason why a tire gets hot after rolling for a period of time. The rolling resistance is highly dependant on the material of the tire and the rolling surface. Harder and smoother tires and surfaces yield a lower rolling resistance. Therefore, an under inflated or overloaded tire will have a higher rolling resistance. This explains why it is important to have well inflated tires to achieve better fuel economy. As another example, a train with steel wheels rolling on steel rails has an extremely low rolling resistance.

The power loss due to rolling resistance is expressed as

$$P_{ROLL} = m \cdot g \cdot c_{rr} \cdot v \text{ [Watts]}$$

where c_{rr} is the dimensionless rolling resistance coefficient, m is the mass of the vehicle [Kg], g is the gravitational field intensity [N/Kg] and v is the speed of the vehicle [m/s]. P_{ROLL} is the power lost in Watts. Table 3 shows the rolling resistance coefficient for an automobile tire on different road surfaces.

C_{rr}	Tire and Surface Type
0.010 to 0.015	Properly inflated rubber tire on concrete and hard asphalt
0.030	Properly inflated rubber tire on softer asphalt (hot day)

Table 3: Rolling Resistance Coefficient

Figure 2 shows the power loss from the rolling resistance versus speed for a vehicle weighing 1000 [kg], with a rolling resistance coefficient of 0.015. Since the power loss is proportional to the rolling resistance coefficient (c_{rr}), a vehicle traveling on softer asphalt will suffer twice as much loss due to rolling resistance.

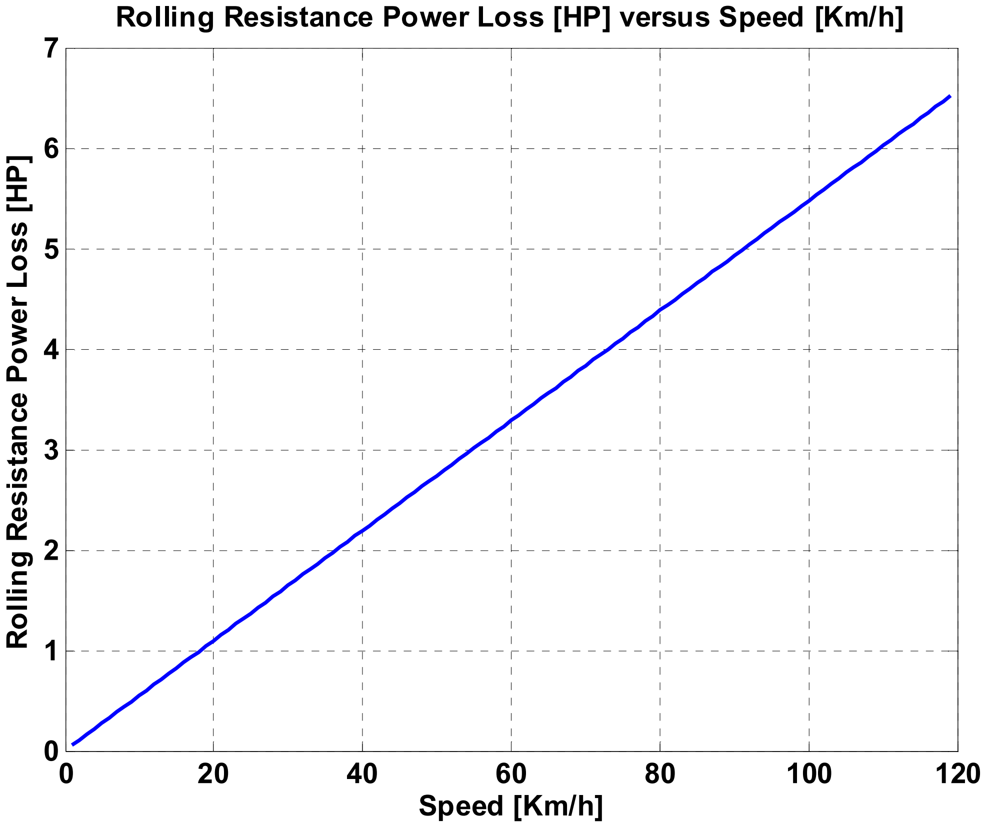

Figure 2: Rolling Resistance Power Loss versus Speed

Aerodynamic Drag

The aerodynamic drag is a force opposing the movement of an object in a fluid such as air. The aerodynamic drag is cause by the fluid flow around the object and is a function of the object shape only. It is not caused from the friction of the fluid rubbing against the object. For example, a sheet of plywood traveling perpendicularly to the direction of propagation has a much higher drag compared to a sheet traveling parallel to the direction of propagation. The aerodynamic drag is responsible for the terminal velocity attained by falling objects.

The power loss due to aerodynamic drag is

$$P_{DRAG} = \tfrac{1}{2}\rho \cdot v^3 \cdot C_d A \text{ [Watts]}$$

where ρ is the density of the air [Kg/m^3], v is the speed [m/s] and $C_d A$ is the drag factor of the vehicle [m^2]. P_{DRAG} is the power lost in Watts. The drag factor is the product of the aerodynamic drag coefficient C_d [dimensionless] and the frontal area of the object (or vehicle) A [m^2]. It is seen that the power loss due to aerodynamic drag increases with the cube of speed. Therefore, doubling the speed will increase the power loss by a factor of 8. Altering the shape of a vehicle, by installing a roof rack for example, will further increase the aerodynamic drag by increasing its $C_d A$ factor. Figure 3 shows the power loss from the aerodynamic drag versus speed for a vehicle weighing 1000 [kg], with a drag factor of 0.60.

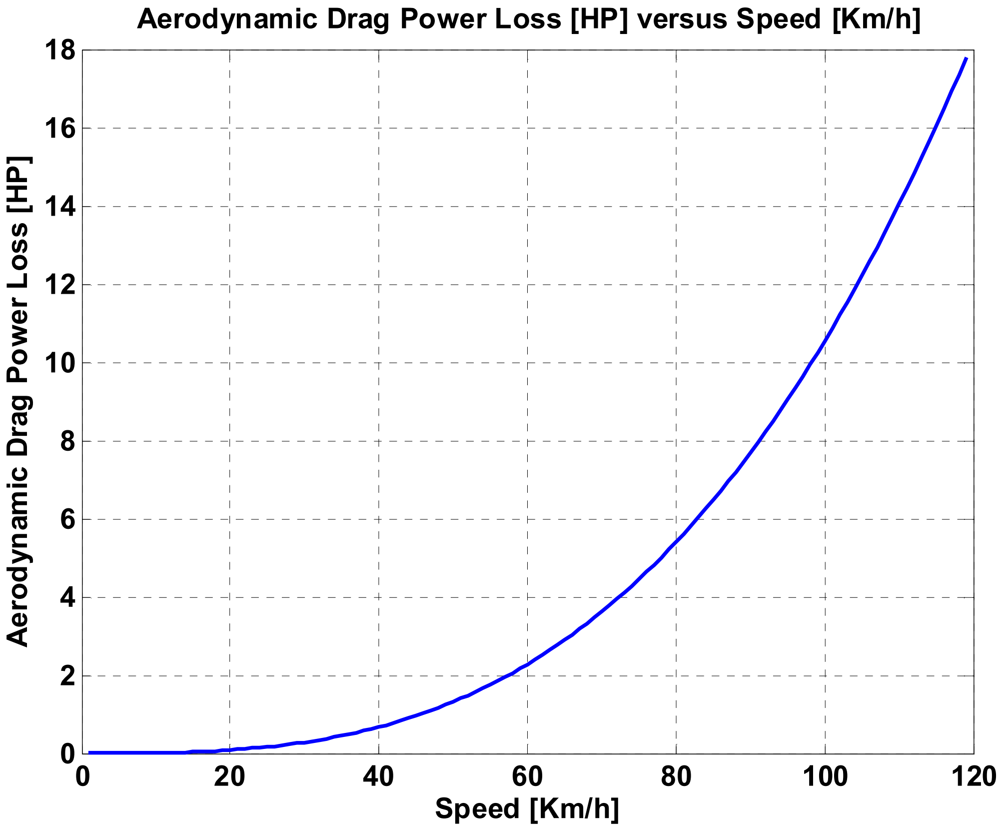

Figure 3: Aerodynamic Drag Power Loss versus Speed

Manufacturers will rarely list their Aerodynamic drag data. It can therefore be difficult to find a car's C_dA factor. However, it can be estimated quite accurately using a C_dA from a similar car design.

The Mayfield Motorsports Company have C_dA for some older cars.
http://www.mayfco.com/tbls.htm

My maximum horsepower measurement is higher than expected. How is this possible?

This erroneous value will occur under quick/hard shifting and is due to the kinetic energy stored in the spinning mechanical parts being transferred to the wheels in a short period of time. For the driver, this is the brief jerk felt while quickly releasing the clutch.

Here’s the explanation. Any rotating body has kinetic energy. The heavier the body and the faster it spins (RPM) the more kinetic energy it has. Under hard acceleration the engine is usually brought up to high RPM, the mechanical parts (flywheel) therefore acquires more kinetic energy. When the gear ratio decreases (shifting to a higher gear number) the transmission spins at a lower RPM. Therefore, when the clutch is released, the spinning engine parts suddenly transfer their kinetic energy to the transmission (wheels) until all the mechanical parts rotate at the same speed. The faster the clutch is released the faster the energy is transferred to the drive wheels. Since the power is the rate at which energy is transferred (Power = Energy / Time) it is possible for a very brief period of time (shifting jerk) that the accelerating power increases above the engines maximum accelerating power.

To avoid this problem, the user should perform a horsepower test over a single gear. For example, begin the run, lightly accelerate and shift to the second gear and then accelerate under WOT (Wide Open Throttle).