Chapter

Making the Most of the Energy We Have: Vehicle Efficiency

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Abstract

With global concerns over emissions from non-renewable sources and its dwindling global supplies. Optimization of our energy usage is highly important. Converting energy to various forms is usually an imperfect process with energy being wasted. Vehicle's convert on-board stored energy to a kinetic form to drive a vehicle. Understanding the sources of energy losses allow us to (a) reduce emissions created by combustion engines, and (b) improve driving range of electrified powertrains. Within this chapter energy losses across the vehicle will be explored for both non-powertrain and powertrain components. Modes of losses and test methods for vehicle components will also be outlined to highlight their significance in vehicle efficiency.

Keywords: vehicle efficiency, non-powertrain, powertrain, drag, combustion engines, electrification

1. Introduction

Energy is finite, as stated by the rules that govern the physical universe. It can neither be created nor destroyed, only stored in bonds between sub-atomic and atomic particles. Only when bonds are established or are broken is energy released. This occurs until a new near stable state is achieved. This is a universal rule, which has yet to be modeled any better.

Until the turn of the twenty-first century, fossil fuels have been the most practical way to power vehicles and most utilities in the world. These fuels were abundant in large quantities, could be transported with ease to all corners of the globe, the control of the exothermic was well understood and was considered a lot safer than other sources of power. For majority of the century it was the ideal energy carrier, but this was short sighted for two reasons. Firstly, the oil wells that are used are a finite supply. The vast fossil fuel reserves that we have been draining from were created by millennia of decomposed biomass that was present almost 650 million years ago. As current non-renewable supplies are being consumed at a faster rate, and the likelihood of finding new fossil fuel sources decrease. There will likely be a point where the once ideal energy carrier will be completely consumed. From recent studies, this is expected to occur in 50 years for crude oil and natural gas, while half a century more for coal [1, 2]. As we continue to consume this finite supply, the value of the fuel will increase with a large impact to all economic sectors. The only way to avoid this is by reducing our energy consumption or looking for alternatives energy sources.

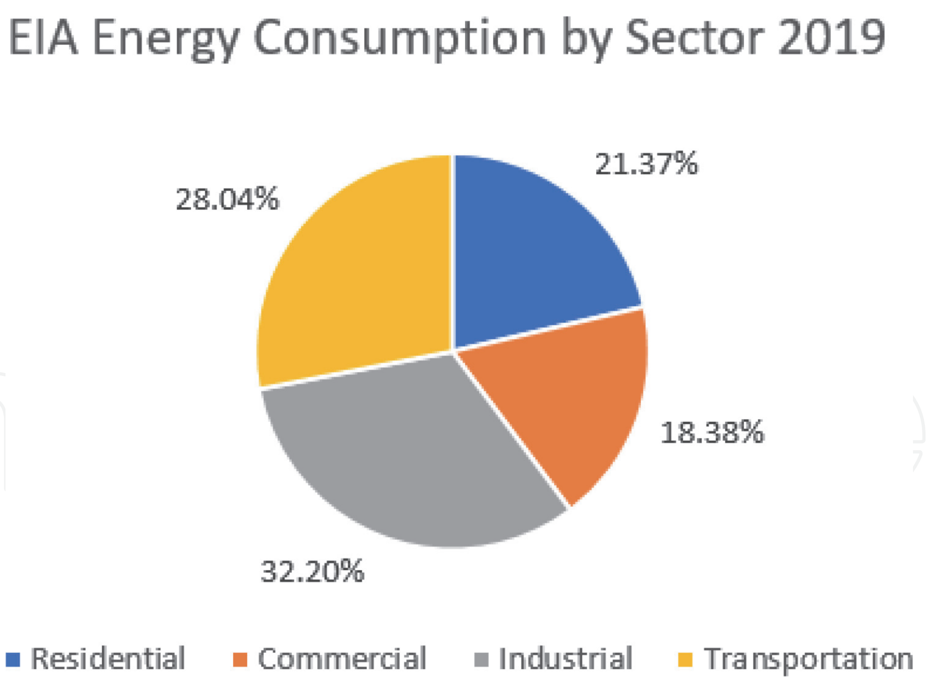

Figure 1.
The total US energy consumption by sector in 2019.

The transportation sector last year alone consumed an estimated 115.5 quadrillion Btu of energy [3]. As a prominent global energy consumer, improvements to transport energy efficiency can make a significant impact on a global scales (**Figure 1**). To act on this transport engineers have focused on improving current combustion technology, deployment of powertrain electrification and improvement to non-powertrain components.

2. The fundamentals of energy consumption for vehicles

Vehicle efficiency is generally defined by the distance traveled per use of a quantified energy. Most commonly, for the last century the vehicle metric for efficiency has been Mile per gallon of fuel (MPG). This metric was used universally among most countries due to legislation sharing. With refinements to emission impact measurements and alternate vehicle fuel source, new metrics such as CO_2 grams per kilometer and kilowatt-hours per kilometer have been adopted. With the introduction of electrification into vehicle power-trains the latter unit is used to quantify vehicle efficiency.

Breaking down to the basics of vehicle efficiency, we can explain the energy needed to move a vehicle using Newtonian mechanics. Using Eq. (1), we can deduce that variation in vehicle force can accelerate and decelerate the vehicle. A positive force on the left-hand-side (LHS) of the Eq. (1) means that the vehicle will be accelerating, a negative value means the vehicle is decelerating while a zero net force means the vehicle is in an equilibrium state (not moving or a constant velocity). The value of this force itself is a summation of the driving force provided by the vehicle's power-plant and the drag force that resists the vehicles motion. Vehicle force can be represented as power, which in turn can be used to calculate the energy required to move the vehicle.

$$Forces = Vehicle\ \ Mass \times Acceleration \tag{1}$$

In addition to the force produced by the vehicle, the vehicle mass has an influence towards how the transformation of energy is directed to the vehicle's motion. This is known as inertial mass. As an example, consider pushing a shopping trolley at the start of trip to the supermarket. When the trolley is empty it is easier push and as a result easier to accelerate, we can consider the trolley as having low inertia. In comparison at the end of the shopping trip when the trolley is full and has a higher mass it requires more force to reach the same acceleration and therefore described as having a higher inertia. The same principle occurs with vehicles, the heavier they are the harder it is for them to accelerate/decelerate. To overcome this requires either more power from the vehicle or a reduction vehicle inertia. Reduction in vehicle inertia has been a popular way to improve vehicle efficiency over the last several decades. The adaptation of light-weighting can be seen in the changes to chassis design and incorporation of new materials.

3. Forces acting on a vehicle

As previously mentioned a vehicle accelerates and decelerates by producing a net force. This net driving force is a combination of a propulsion force produced by the powertrain, and the drag forces that resists the vehicles motion Eq. (2). Both types of forces consume energy with the drag forces being parasitic in nature.

$$Driving\ \ Forces = Propulsion\ \ Force - Drag\ \ Force \tag{2}$$

3.1 Propulsion force

The vehicle powertrain provides the propulsion force needed to put the vehicle in motion as intended by the driver. Vehicle powertrains create this force by converting stored energy on-board to usable kinetic power providing force/torque. Typically with modern vehicles, hydro-carbon fuels or electro-chemical cells are used as the energy storage medium.

3.2 Vehicle drag forces

Vehicle drag is formed of numerous contributors across the vehicle. The nature of parasitic losses are frictional, viscous and inertial sourced. The absorbed energy is dissipated in impractical power that cannot be used to propel the vehicle. In this section, the losses across the tire, drive-train transmission and aerodynamic drag will be explored.

3.2.1 Tire drag

The wheels of a vehicle allow the powertrain to apply the driving force to the road surface. As the wheel has torque applied to it, a force output is transferred to the contact patch where the tire meets the road. This action can be represented by Eq. (3). The design of a wheel however incorporates the tire. The pneumatic tire commonly used on road vehicles are designed to not only transfer the driving force but also absorb shocks across the road. Because of this not all power is passed onto the road.

$$Tire\ \ Drag = \frac{Torque}{Tire\ \ Radius} \tag{3}$$

The primary reason for this energy loss is due to the deformation of the tire. It is mistakenly believed that the tire itself is perfectly circular when in contact with the road. With the overall weight of the vehicle acting on the wheel, the contact patch of the wheel is flattened disrupting the wheel's circular shape. As the tire rotates the contact patch moves across the wheel in relation to the ground. This motion requires the tread and sidewall directly in front of the contact patch to compress, then expand across the contact patch until it finally relaxes past the road surface [4, 5]. The tires rubber has elastic material properties and as it is compressed or expanded work is done, therefore consuming power provided by the driving force of the vehicle.

The drag produced by the tire is normally considered a function of the tires geometry, vertical load, pneumatic pressure and velocity. Furthermore, co-efficient can be established to capture influences from the tires construction, road surface and suspension settings. The drag force can be represented in a vehicle model by either maps or equations. A widely used tire drag model is the SAE J2452 equation Eq. (4) [6]. This equation utilizes five co-efficient that work in conjunction with the tire load, pneumatic pressure and velocity to provide the tire drag. The co-efficient for this model are achieved through physical testing.

$$Tire\ \ Drag = Load^{\alpha} \cdot Tire\ \ Pressure^{\beta} \cdot \left(A + BV + CV^2\right) \tag{4}$$

Component level drag testing for tires can be done in numerous ways. Tires are usually attached to a instrumented axle and then spun up to vehicle speeds while on a simulated road surface. The simulated road surface are the differentiating factor between most tire drag tests. Drum rigs where the tire sits upon a rotating drum and belt rigs that recreate the road using a conveyor style belt are the most common techniques for tire drag testing. Both provide highly controlled environments allowing for precise testing. However, the inclusion of simulated roads lead to some deviation in accuracy. Most visibly, the overestimation of tire drag through the drum method. This is due to the curvature of the drum imposed on the wheel, leading to a higher vertical deflection at the contact patch [4]. This deviation from the real life road conditions is the most significant draw back to most tire testing methods. More recently sophisticated mobile test tire trailer (MTTT) have been utilized to overcome the accuracy issues with simulated roads. This method of testing similarly uses an instrumented axle, but attaches it underneath an articulated trucks trailer. In this configuration the tire can be tested accurately to that of a real world case [7]. Though this method is the most accurate test method, it does sacrifice precision due to the reduced control of the test environment.

3.2.2 Drivetrain drag

All powertrains have regions in their operating windows where they provide power most effectively. Outside of these thresholds the powertrain unit can become inefficient. Typically this is dependent on the powertrains speed of operation. To overcome this, engineers and designers utilize gears and mechanical transmission devices to operate powertrain in their efficiency bands. The drivetrain's gearbox, differential and power-split devices share similar efficiency characteristics.

Drivetrain units suffer from two primary loss modes. The design of drivetrain components incorporate a multitude of gears, bearings and clutches to convert power. From the gears and bearings, natural imperfection at the individual component level can lead to friction that consumes the driving power. The lost power through friction is normally released as heat. In addition to this loss mode, transmission units also utilize oil to lubricate, cool and reduce wear around moving components. Because of this, viscous drag is experienced as the oil in the drivetrain units resist the motion of moving components [8]. Both of these drag modes are subject to the velocity and torque of the moving components. The higher both of the factors are, the higher the drag will be. Moreover, oil temperature will also have an influence on the viscous drag forces. As with most liquids including transmission oil, an increase in oil temperature leads to an increase of oil viscosity. Therefore at higher temperatures the viscous drag is reduced across the drive-train units. It is however not wise to operate drive-trains at high temperatures as it is to operate them at cold temperature. At high temperatures, design tolerances may be affected as parts expand and become weaker. While at cold temperatures viscous drag forces increase.

The calculation and estimation of drag losses are typically achieved either by computer-aided design/engineering (CAD/CAE) software or through physical testing [9]. Typical gearboxes, differential and power-split devices can include several bearings, clutches and various internal geometries that interact with lubricant flow making energy equations difficult to manage. With CAD/CAE tools, drive-train component drag can be estimated with the design and material choices known. This modeling technique for energy efficiency provides an adequate energy benchmark for rough assumptions. Though the actual component can be mocked up precisely in CAD/CAE, viscous and thermal interaction can be difficult to model accurately in simulations. Consequently, CAD/CAE efficiency results are limited to initial vehicle efficiency analysis before prototypes are built. On the other hand, physical testing can produce accurate energy characteristics of drivetrain components once prototype or production has been established. With the physical components, general energy consumption can be observed through analysis of power input and output. Dynamometers connected to the input and output shafts of the drive train unit are used to obtain these results. Steady-state tests are usually run with various set-points to obtain measurements of both input shaft velocity and torque inputs. The effect of temperature can also be included in component tests by either letting the component naturally soak thermal energy from a temperature controlled environment or by artificially controlling the oil temperature to desired levels. Results are constructed into tabulated maps indicating lost torque, lost energy or efficiency percentage.

3.2.3 Aerodynamic and hydrodynamic drag

Aerodynamic and hydrodynamic drag acts on the body of a vehicle moving through a volume of gas or liquid. Both aerodynamics and hydrodynamics share the same principles and are only separated by the medium that they are being propelled through. For the rest of this section we will look at the effects of drag on ground based vehicles, but the fundamental principles are directly transferable to marine vehicles.

Aerodynamic drag exists while a volume of air passes over the vehicle. As the air passes, it opposes the vehicle through various viscous drag dynamics. Over the last several decades energy efficiency optimization through aerodynamic drag reduction has been a noticeable through vehicle design. Majority of passenger road vehicles pre-1990 had a box-styled shape. As the understanding of aerodynamics grew and capability in vehicle body manufacturing expanded, passenger vehicles became sleeker. Not just for their improved esthetics, but also to utilize existing driving power without up-sizing power-plants. Today across all vehicle streams, manufacturers and designers try to exploit aerodynamics to reduce drag of vehicles using various tools.

Aerodynamic drag is a culmination of two primary interactions between the vehicle body and the fluid volume. To begin with a portion of fluid drag is produced across the surface of the vehicle body. This is known as skin friction and can be attributed to interactions of the fluid at the vehicles surface. Air is a viscous fluid, and behaves similar to that of its liquid counterparts which have lower viscosity. Viscosity of a fluid denotes the strength of the inter-molecular attraction between molecules in a fluid. As a fluid goes through a laminar flow over a surface, the immediate molecules at the surface can be assumed to have zero velocity. These molecules through their viscous properties exhibit a shear stress on the next layer of fluid molecules slowing them down from the free velocity stream. This occurrence of slowing down the next molecule layer continues until the next layer reaches the velocity of the free air-stream (**Figure 2**). This interaction is known as the boundary layer. With larger viscous forces acting between fluid molecules the distance at which the fluid layer return to free stream velocity grows. The increased size of this boundary layer contributes to a higher skin friction. The factors of control for designers and engineers on skin friction are limited. It is impractical and almost impossible to change the fluid's viscous properties. The only remaining factors that can alter skin friction are the body's overall surface area and the type of airflow over a surface. In the past aerodynamicists have experimented with the use of turbulent flow at the body's surface as an attempt to reduce skin friction drag. By introducing turbulence at the body's surface, boundary layers are disrupted therefore reducing boundary layer skin friction. The adoption of using turbulent flow to modify skin friction has however fallen out of favor due to the complexity of incorporating turbulence generating features in vehicle design and the additional pressure drag created by turbulence.

In addition to skin friction, the volume of the body and its interaction of displacing the fluid medium creates pressure drag. As the body displaces fluid, a volume behind the vehicle is left with low pressure as the air-stream attempts to return to an equilibrium state. With reduced pressure behind the vehicle, a pressure difference is created which results in drag. The key contributors for pressure drag is the body's shape, air stream velocity and the fluid properties. A large portion of aerodynamic drag is contributed by pressure drag, the typical aerodynamic drag equation is based around its properties. The first of which is the impact from of vehicle's co-efficient of drag (see Eq. (5)). As described previously the fundamental reason for pressure drag is the reduced volume of pressure created behind the

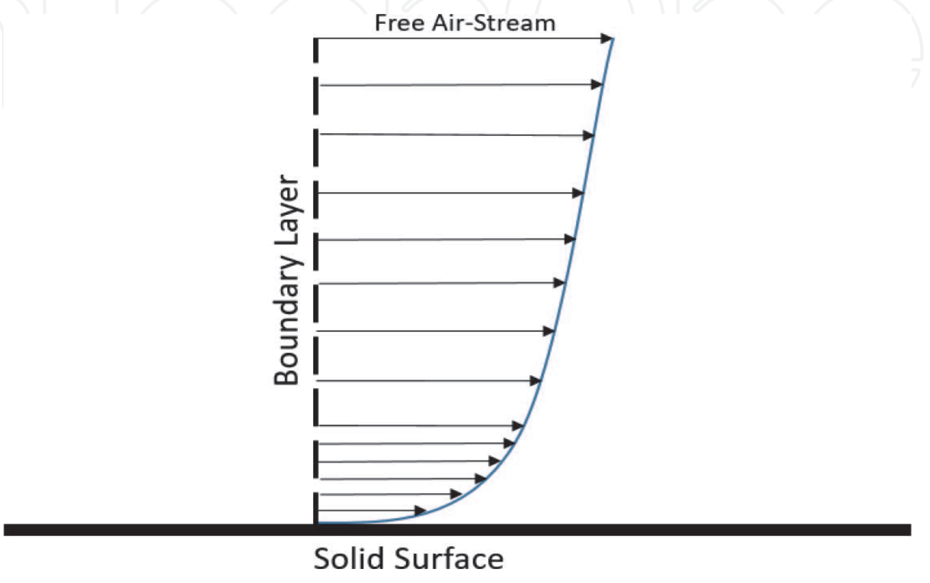

Figure 2.
Skin friction experienced at a vehicle's surface due to boundary layer interactions.

vehicle due to the displacement of the fluid medium. Vehicle designer can streamline the form of the vehicle to aid with the fluid returning to an equilibrium state behind the vehicle reducing the pressure differential on the vehicle. The streamline characteristic of the vehicle can be quantified in the co-efficient of drag metric and the frontal surface area of the vehicle.

The principle of aerodynamics emphasize the importance of drag reduction for high speed laminar flow vehicles. Vehicles at operating higher speeds will undergo a vast increase in aerodynamic drag. As seen with the aerodynamic equation, the velocity of the free-stream fluid increases drag at an exponential rate (see Eq. (5)). This characteristic of aerodynamic drag is a key focus for vehicle designers.

To quantify a vehicle's drag characteristics the co-efficient of drag and frontal surface area of a vehicle must be quantified. The frontal area can be found through physical measurements or design calculations. The co-efficient of drag however can only be quantified through physical testing or computational fluid dynamics (CFD). Through physical testing, wind/water tunnels and basins are used with models or actual vehicles to obtain this metric. The accuracy of these physical tests depend on the replication of environmental conditions. An example of such, is replication of moving roads and spinning wheels for on-road vehicles. Neglecting these factors could lead to inaccuracies in the co-efficient of drag measurement of the complete vehicle. Some vehicle specific aerodynamic test facilities have incorporated these features overcoming this potential issue, but with inclusion of such features, wind tunnel testing remains a costly option.

$$Aerodynamic\ \ Drag = \frac{1}{2} Cd\ \ Frontal\ \ Area\ \ \rho V^2 \tag{5}$$

As an alternative, aerodynamic testing can be achieved through computational means, using mathematical models based on Navier–Stokes and other models to represent turbulent interactions. Vehicle models are broken down to create a finite volume mesh and once that is achieved individual flow equations can be determined per cell. The accuracy of CFD simulations rely on the replication correct fluid dynamics and the resolution of the mesh created. With complex shapes, refined meshes are needed. With an increased number of mesh cells, an increased number of computations are needed and sufficient additional computation time to store and re-call the meshed data from memory. An example of this can be seen in **Figure 3**. As with this model of a light-weight race car, an increased mesh resolution is needed around the front wing where significant flow activity will occur. To overcome this, high resolution CFD simulations are run on supercomputers to reduce overall computational time.

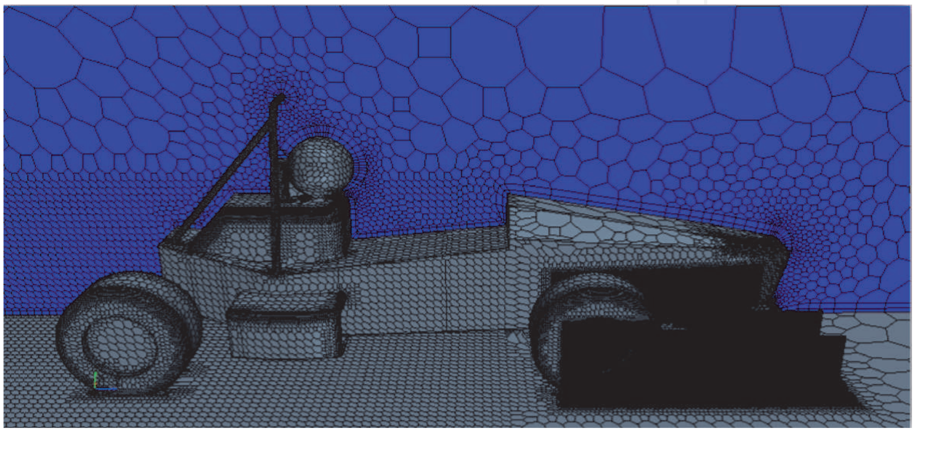

Figure 3.
A diagram displaying meshing resolution of a ultra-light-weight race vehicle.

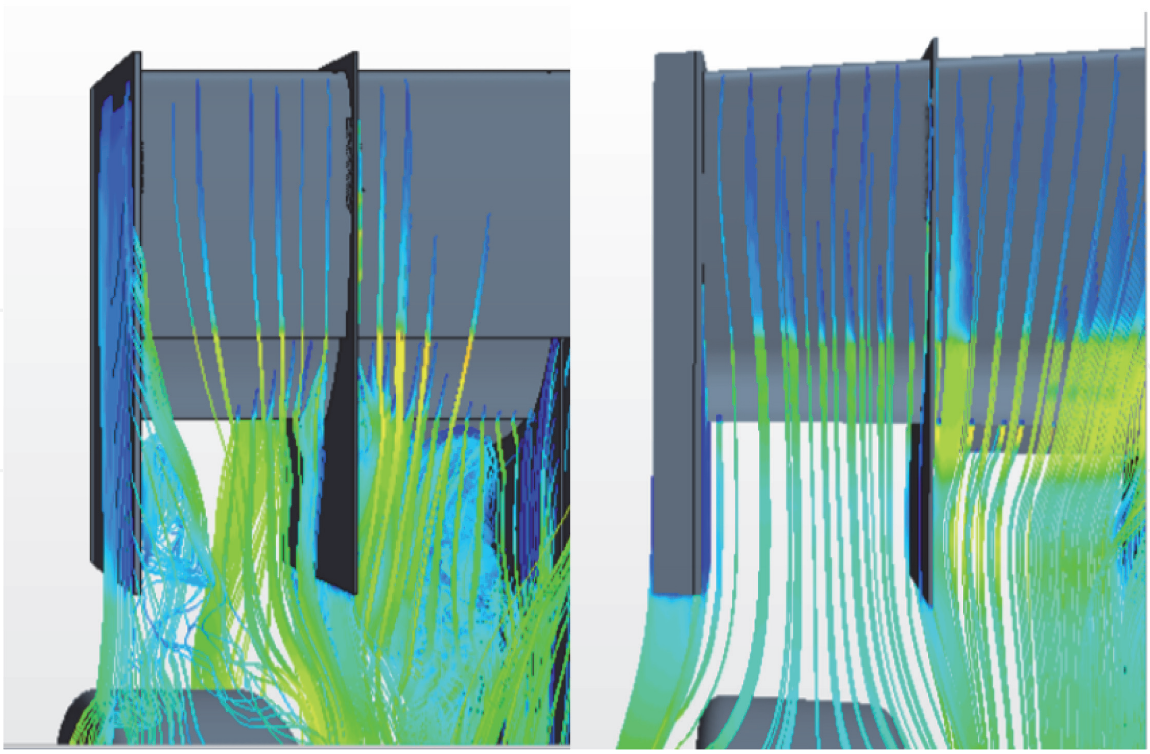

Figure 4.
The visualization of air stream flow over a front wing without an end-plate foot (left) and a front wing with an end-plate foot (right).

CFD has become a very popular technique due to its low costs and benefits in qualitative analysis. Tests can be repeated with little costs, allowing iterative design processes to be sped up. An example of such can be seen in **Figure 4** with the iterative design process used to implement end-plate foots on a race vehicle's front wing. In addition, various visualization techniques can be used to make improved analysis towards understanding fluid flow.

3.2.4 Summary of parasitic losses

The parasitic drag modes discussed can all be tested and represented in a single equation. As outline by the World Light vehicle Test Procedure (WLTP), a vehicles parasitic drag contribution can be tested during vehicle coast down tests. Through this procedure a vehicle is allowed to decelerate under its own drag. By measuring its deceleration at certain velocity points the drag force can be interpreted by Eq. (6). The formation of the equation captures the mechanical losses of the tires and drivetrain, and the aerodynamic losses. The aerodynamic portion of the equation differs from the typical aerodynamic equation as it incorporates the ability to measure the influence of crosswinds through the use of an anemometer.

$$Parasitic\ \ Drag = A_m + B_m v + C_m v^2 + \left(\frac{1}{2}\right)\rho A V_r^2 \left(a_0 + a_1 Y + a_2 Y^2 + a_3 Y^3 + a_4 Y^4 \right. \quad (6)$$

4. Energy losses across the powertrain

4.1 Combustion engines

Combustion engines have been the dominant power generation device for vehicles in the twenty-first century. Using the principles of the Otto-cycle, hydrocarbon fuel in the form of gasoline and diesel undergo combustion resulting in an exothermic reaction. The released energy is used to move a piston to provide kinetic power through a crankshaft. The popularity of this powertrain grew due to the low costs of gasoline and diesel but also thanks to the greater range in comparison to the electric vehicle (EV) powertrains and quickness in re-fueling vs. re-charging.

One of the short falls for combustion engines are their overall efficiency. These type of engines generally have an efficiency of 30–40%. The Otto-cycle relies on the expansion of gases through volume and pressure to create a driving force. The reaction itself suffers from inefficiencies, the energy released during combustion also gets released in the form of heat, light and noise. As a general rule of thumb a third of the energy is used for motive force, a third lost as heat and a another third through exhaust gases.

Moreover, energy is also lost to frictional, viscous and pumping losses. As an engine rotates, its motion is opposed by friction at the crankshaft bearings, piston rod connections and pistons sleeves; viscous interaction between the crankshaft and the oil in the lower engine block; and finally the pumping losses experienced in the combustion chamber as air needs to be sucked in or exhaust gases need to be expelled out [10]. Parasitic losses are also generated by most vehicles needing alternators and pumps to runs auxiliary systems.

Estimations around powertrain efficiency can be found from calculations based of design characteristics. Using assumptions of near perfect combustion and engine characteristics such as combustion chamber volume, and number of cylinders, power output of the engine can be estimated. With the abundance of test data from previous engines, these estimations can be refined to incorporate factors such as induction methods, engine layout and combustion timings. For absolute values of engine efficiency, physical testing of prototype or production engines are carried out. This is typically achieved through engine dynamometer testing. To measure efficiency, the energy of the fuel used is compared to the output power produced by the engine.

Efficiency characteristics of Otto-cycle engines are uniform across all variations. The output of steady state tests outline the peak torque across the engine speed and a gradient map outlining efficiency. Combustion engines in most cases have a single point of peak efficiency (OOP), this is normally located midway of the engine's capable speed and found close to wide-open throttle. The losses at certain portions of the maps are due to an increase in specific loss mode. At low engine speeds friction losses attribute to the main loss mode, while at higher speeds viscous drag becomes the overriding loss. This is illustrated by **Figure 5**. Following this, engine

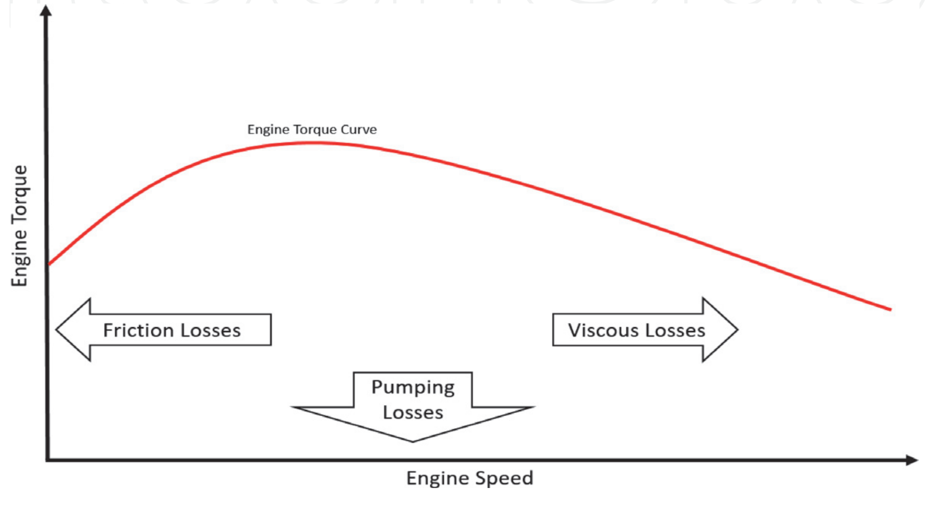

Figure 5.
Dominant losses across a combustion engines torque map.

efficiency only increases as it approaches wide open throttle due to a reduction in pumping losses resulted by a reduction in throttle restriction.

Diesel compression engines account for a large proportion of consumer and industrial vehicles. Like gasoline, diesel is made up of hydrocarbons but with a longer individual chain length. This alters the chemical properties, reducing volatility and increasing the ignition point of the fuel. As such ignition in diesel engines are achieved by auto-ignition through compression of the air-diesel fuel combo. Through high pressure fuel injection, and high compression ratios in the cylinder, combustion occurs more effectively due to the better air-fuel mixing. This is evident through the efficiency tests and reported MPG measurements from consumers. However, due to the combustion characteristics of diesel compression engines, additional emissions such as NOx and carbon particulates are increased. This is due to the leaner air-fuel mix creating a hotter combustion. Such emissions are harmful carcinogen to living creatures. Technologies to reduce these harmful emissions have been adopted, but with their inclusion the economic feasibility of diesel engines reduces.

4.2 Electric powertrains

Adoption of electrification in vehicle powertrains have grown in the last couple decades with the aspiration for energy efficient powertrains. In overall, on-road electric powertrains demonstrate energy efficiency measurements of 90%. This vast increase in efficiency is strong argument alongside with the zero immediate emissions for adoption of electrified powertrains [11].

Typically, electric powertrains have a broader range of efficiency across its operating window. As a general characteristic, EV powertrains produce large values of torque at lower speeds. At these lower speeds, electric powertrains are efficient due to reduced parasitic forces of the e-machine and low switching losses at the inverter. For vehicles that require transient power, especially at low speeds, electric powertrains are best suited.

All electrified powertrains utilize an e-machine to convert electrical energy to that of kinetic energy using magnets and electro-magnets. The control and supply of power is delivered through an alternating current. Energy storage for EVs are provided by chemical batteries. In today's adaptation of EVs, these cells usually consist of lithium electrolyte mixed with additives to improve discharge and health characteristics. By contrast, batteries typically supply only direct current, making the two components incompatible through direct connection. To overcome this, a switching device known as an inverter is used to convert the direct current (DC) of the battery to alternating current (AC) needed by the e-machine. Not only does the inverter facilitate current conversion, it also has the ability to control either the torque or speed of the e-machine. Each component of the electric powertrain suffer from individual loss modes.

4.2.1 Batteries

Though batteries are an energy storage device, an efficiency value can be attributed to ability to deliver the energy that was initially supplied to it. The primary loss method for batteries is through cell internal resistance. The cells internal resistance is a combination of the cathode, anode and electrolyte resistances [12]. As with the resistance losses of the other electrical components, a battery's power loss can be calculated through Eq. (7). The internal resistance of the battery cell is subjected to the cells temperature and its State of Charge (SOC). At cold temperatures and low SOC values the internal resistance rises rapidly (**Figure 6**). As a result to optimize

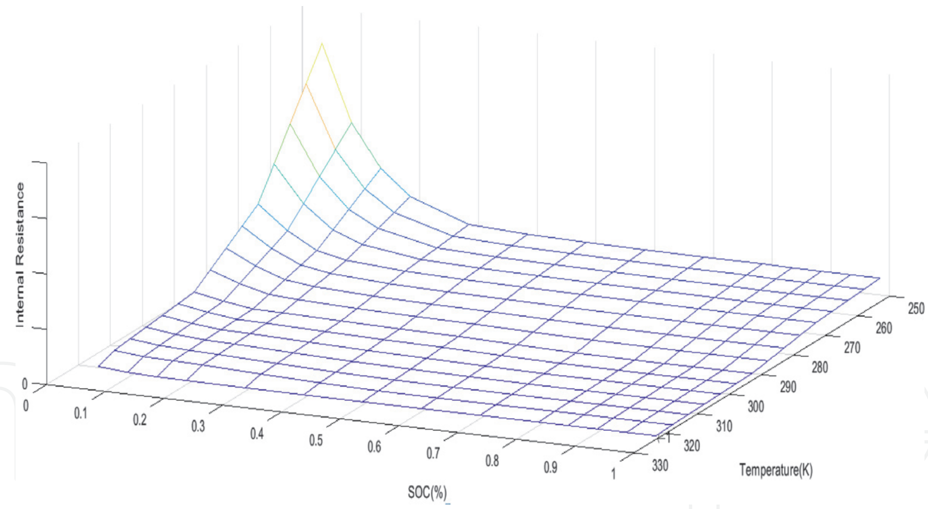

Figure 6.
The above map outlines the behavior of the internal resistance of the battery in relation to battery SOC and temperature.

efficiency, it is desirable to operate them at warmer temperature and greater SOCs. The energy lost through resistance losses are released in the form of thermal power.

$$Cell\ \ Resistance\ \ Losses\ \ (Watts) = I^2R_{anode} + I^2R_{cathode} + I^2R_{electrolyte} \tag{7}$$

The characterization of this power loss parameter is usually obtained through cell testing. Cell internal resistance can be found through either DC ohmic methods, AC pulse conduction or electro-chemical impedance spectroscopy. The specific method of choice is dependent on intended use of the battery cell. For vehicle applications, loads that are experienced by the battery are typically reactive and as a result AC pulse conduction methods are most suited. The AC method focuses on the impedance of the battery that includes not just the resistance but also the capacitance and inductance of the cell too.

A battery's capacity to store charge deteriorates over its lifespan. The measurement of available charge storage is quantified by State of Health (SOH). As a cell is charged and discharged, the quantity of useful lithium-ion electrolyte is diminished, due to decomposition of the electrolyte to Solid Electrolyte Interphase (SEI). The effect of these mechanism are outlined in **Table 1**.

The rate at which the electrolyte is lost is influenced by the depth of discharge, temperature and number of cycles experienced by the battery. Operating batteries at low SOCs, higher temperatures and large number of overall cycles will increase the rate at which the battery loses its capacity to store charge [14]. For automotive vehicles that rely on electrified powertrains, loss of stored energy capacity reduces the overall range that the vehicle can achieve on a fully charged battery. A conscious effort must be made by vehicle engineers to ensure a battery operates within a temperature window that neither degrades capacity or increases power loss (**Figure 7**).

Theoretical determination of the battery's SOH is extremely difficult. This is due to the difficulties of determining long-term physical models of internal chemical interactions. Models of battery SOH are usually achieved through experimentation. Data gathered from experiments can be utilized through regression analysis, n-term interpolation and statistical methods. The validity, computational time and effectiveness of data driven models can vary across the broad design characteristics of electro-chemical cell batteries [15].

Batteries are typically modeled theoretically in an equivalent circuit model. A battery in this model can be represented by the combination of resistors and capacitors in series and parallel. The individual resistance and capacitance values must be

Loss mechanism	Effect	Causes
Electrolyte decomposition	Power loss & capacity loss	High SoC & high temperatures
SEI growth on anode	Power loss	High SoC & high Temperatures
Contact loss of active material	Capacity loss	High cycling rate & high DoD
Current collector corrosion	Power loss	Over-discharge & low SoC
Lithium plating of the anode	Capacity loss	Low temperature, high cycling rates and poor cell balancing

Table 1.
Loss mechanisms and their effect in relation to electrolyte and anode interaction [13].

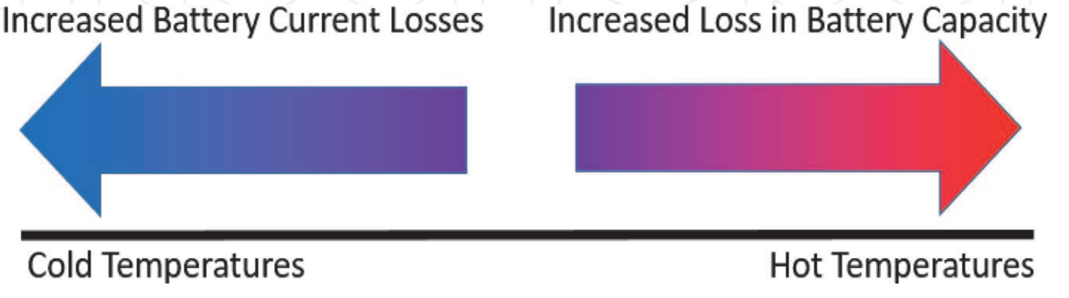

Figure 7.
Li-ion battery operation should avoid cold temperature where internal resistance losses increase or high temperatures where SOH degradation occurs.

derived from physical test data. From this configuration of the circuit, the SOC of the battery can be interpolated from the open-circuit-voltage (**Figure 8**) [16]. The model in this form can only provide representation of the battery's SOC. Any estimation of the battery's health would require adaptation of this basic model to incorporate the experimental SOH results to modify the components appropriately.

4.2.2 E-machines

The e-machines used for EVs suffer from electrical and mechanical losses. On the electrical aspects of an e-machine, power used to drive the device is lost through

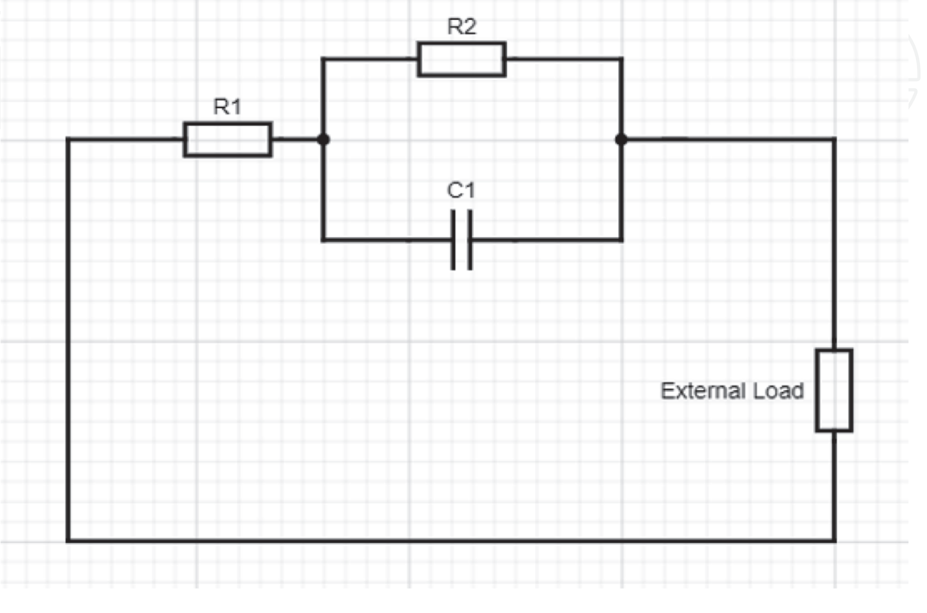

Figure 8.
An equivalent circuit model of a typical battery.

copper losses and eddy currents. Copper losses occur naturally in any current supplying conductor. Though conductors are chosen for their high conductance, they still suffer from some resistance. As current passes through, it experiences these internal resistances and power is lost. The power lost to copper losses relates to the current demanded, the losses itself can be calculated by Eq. (7).

$$Lost\ \ Power\ \ (Watts) = Current\ \ (Amps)^2 \times Resistance\ \ (\Omega) \tag{8}$$

Outside of current losses, eddy losses occur within the cores of the rotor and stator. As magnetic flux occurs across the stator and rotor, current is induced into the iron core conductors. As this is done, current loops within the core also produce their own countering magnetic field to the original as per Lenz' law [17]. As a product of the opposing magnetic field, some of the kinetic energy produced for the driving force is resisted and dissipated as heat. Mechanical losses for e-machine are very similar to losses for drivetrain components. Both viscous losses through the rotor drag (with air or coolant) and mechanical losses at the bearing will also reduce efficiency of the e-machine. The valuation of these losses can either be preliminary attained through CAD/CAE software or through physical coast-down tests. The significance of each loss varies across the operating window of the e-machine (**Figure 9**). Full characterization of motor efficiency are normally carried out through e-machine tests on dynamometers. Input power is calculated through the measurement of the AC waveform going into the motor and compared to output power derived from the torque and speed of the e-machine. In addition to powered tests, non-powered tests will also be done to breakdown mechanical losses. The combined results of which are usually represented by the use of efficiency maps.

4.2.3 Inverters

Inverters uses a H-bridge topology to switch the DC power provided by the battery to that of an AC waveform needed for the e-machine. Switching is achieved using transistors. In most cases these are an insulated-gate bipolar transistor (IGBT) or metal-oxide-semiconductor field-effect transistor (MOSFET). These type of transistors allow fast high power switching, that are controllable through low voltage signals, while operating at high efficiency values. Inverters lose energy most commonly from conduction, switching, and off state blocking losses, and are usually released as thermal energy at the transistor. Conduction losses are brought

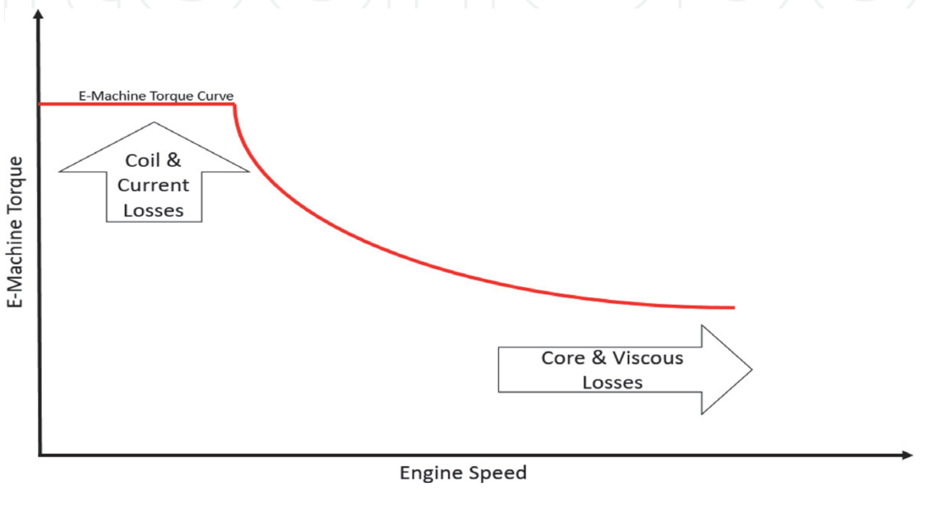

Figure 9.
Dominant losses across an E-machine torque map.

about due to forward saturation voltages and can be calculated in conjunction with the current passing through the inverter. Switching losses occur when the transistor switches states (on and off). During turn-on events capacitance between the gate and drain of transistor leads to an overlap of drain voltage and current resulting in lost energy. Turn-off energy loss behavior occurs after the gate voltage drops, during which the drain current naturally maintains until the drain voltage returns to peak. After which, the drain current logarithmically decays [18]. This overlap, as similar to that of the turn-on losses result in energy being lost. Switching losses are difficult to determine numerically and as a result loss characteristics are determined from test results. The balance of losses between modes are also a key design consideration for transistor choice. Solutions to overcome conductance losses may in fact increase switching losses. By increasing transistor size, conductance losses may be reduced, but consequently gate-drain capacitance would increase producing larger switching losses [19]. A balance must be met between the switching loss which dominates losses at high frequencies, in comparison to conductive loss dominance at low frequencies. In addition, transistors like most electrical components suffer from thermal influences. At increased temperatures, reduced efficiency can be expected from transistors. Thermal management of the inverter is important to ensure efficiency is maintained.

5. Improving energy efficiency

By understanding the mechanism from which energy is lost within automotive vehicles, we can identify trends for potential technology optimization to improve vehicle efficiency. Certain areas are optimization offer feasible opportunities that achieve the goals of regulators to reduce emission while keeping vehicles economical for consumer purchase and use.

5.1 Hybridization

Hybridization is currently a popular tool to improve vehicle efficiency. This is typically seen with a combination of a combustion engine and electric powertrain. By a combination of the two, emission produced by combustion engine can be reduced, energy management of the greater powertrain can be achieved and disturbance to current driver behavior can be minimized. Various configuration exist that vary depth of overall electrification and driving modes.

5.2 Recycling energy in combustion engines

Though the physics of combustion engines are inherent to their inefficiency, improved control of combustion characteristics and recycling lost energy can improve their efficiency. Improved design and simulation of intake and exhaust manifolds are common features on modern combustion vehicles [20]. The use of these tools help reduce the pumping losses, directly improving the cycle's efficiency.

In addition, the stability of exhaust gases can be used to alter combustion characteristics to improve efficiency. Exhaust gas re-circulation devices are now a standard feature on most diesel combustion engines. By diluting small amounts of the exhaust gas into the air intake post-throttle, allow engines to operate at wider throttle restrictions to reduce pumping losses but also reduce the overall temperature of the combustion in the engine [21]. The reduced combustion temperature aids in reducing the generation of NOx [22].

A popular method of increasing efficiency is through the use of charging the engine through turbochargers. This allows for downsizing of engines. Turbochargers use the energy of the exhaust gas to power an impeller that boost the air intake pressure. By increasing the intake pressure, the pumping losses can be further reduced as well as an increased amount of fuel-air in-cylinder leading to more power [23]. Alternatively, superchargers can increase intake pressures, but due to their reliance on the engine torque as their prime mover, increased parasitic losses are experienced. This reduces their overall impact on powertrain efficiency.

Moreover, some manufacturers have adopted selective cylinder deactivation as a method to reduce energy consumption. When the vehicle is operated in low power situations (low torque and low speed), only the necessary number of cylinders will receive fuel via their respective fuel injectors. An example of this can be seen by deactivation of four cylinders of a V8 engine developed by Daimler-Chrysler [24]. Using this approach, fuel is only needed for four cylinder over in normal situation where eight are typically used. Further, as an increased load is placed on the four active cylinders, the engine's throttle is opened further, thus reducing pumping losses [25].

5.3 Improvements in battery technology

Improvements in electric powertrain component efficiency are highly sort after. With a lower energy consumption, batteries on an electric vehicles can be reduced in size. Batteries size has a significant impact on the overall vehicle. Foremost, due to the relative recent advancement in battery technologies and their production methods, li-ion batteries seen in most electrified powertrain influence a large proportion of overall vehicle cost. In addition, with the reduced number of batteries the overall weight of the battery pack can be diminished. Majority of these advancements will come in the form of material choices for the electrolyte, cathode and anode of the battery cell. Most notably, innovative new solutions along solid-state type electrolytes have taken traction. Solid-state electrolytes provide opportunities for better power and capacity characteristics [26].

5.4 Next generation power inverter

Current inverter technology can be improved by innovations in power transistor design. As previously identified earlier transistors such as JFETs and MOSFETs suffer from on-state losses and reduction in efficiency at higher temperature. These losses are influenced by the material selection for the transistor gate. By facilitating the same voltage but with a thinner gate due to SiC semiconducting properties, on-state internal resistances can be reduced [27]. In conjunction, increased thermal conductance allows SiC MOSFETs to operate with elevated efficiency at higher temperature. Though better than its predecessor, SiC MOSFETs face barriers for mainstream adoptions due to defects seen through manufacturing.

5.5 E-machine optimization

In comparison to inverter and battery design, the fundamental technology of electromagnets are relatively mature for e-machines. Any improvements in e-machine efficiency are most likely to occur with control techniques. One such example is the research and application of switch-reluctance motors. Torque reluctance generated by electromagnets housed in the stator, allow for more simplistic design of the rotor. By doing so, overall rotational inertia can be optimized due to eradication of the electromagnets and commutation present on the traditional designs. Any development in mature products would require considerations of economic feasibility to substitute incumbent products. For motors, this would be the cost of production and materials. Without satisfying this criteria, adoption of new e-machine designs are unlikely.

An overall theme for vehicle energy optimization follows the stream of light-weighting components to reduce overall vehicle inertia. The reduction in either component weight or the number of components can have significant impact on vehicle performance. With a reduced overall mass, less torque is required to achieve the desired acceleration by the driver. Consequently, reduced energy consumption is achieved. With state-of-the-art design software, weight reduction through finite element methods/finite volume methods (FEM/FVM) can remove unnecessary materials from a product. By computing the structural loads going through a block of material, designers can remove excess material from their designs improving the overall weight of the component. This technique could be applied universally through a majority of most structural components of automotive vehicles, alongside developments in manufacturing techniques.

6. Conclusions

In conclusion, vehicle efficiency will be an important factor across all types of vehicles. With limited non-renewable fuel sources, pressure to reduce emissions and importance to bridge the gap between combustion and electric range concerns, energy optimization has become the prime focus to the transport industry. Analyzing the fundamentals of vehicle motion, various characteristic of vehicles can be targeted to improve vehicle efficiency. Reduction of vehicle inertia by weight reduction has been a popular stream that engineers and designers have pursued due to its significance with Newton's equation of motion.

Besides optimization of inertia, overall output of vehicle driving force can be as significant to improve vehicle efficiency. Vehicle drag, a natural commonality across all vehicles has more of a varied significance to a vehicle's efficiency. These loss modes tax vehicle power dependent on driving factors such as vehicle velocity and component temperatures. Optimization of these drag modes are subject to component characteristics.

In contrast, propulsion forces used to propel the vehicle are subjected more down to its efficiency of converting stored energy to useful kinetic energy for motion. As seen between combustion and electric powertrains, the latter method provides power at a greater efficiency. Propulsion methods that rely on combustion to convert stored energy into power waste large portions of energy. This results in 30–40% of actual useful power being used to drive the vehicle.

In comparison, electric powertrains provide tractive power at a high efficiency but rely on vehicle efficiency to maximize range off its limited energy storage. With no significant power conversion between energy mediums, electric powertrains can boast efficiency values of 80–90%. But with larger duration's needed to charge batteries, maximizing efficiency to gain range is currently sought after to ensure electric vehicles are as practical as combustion vehicles.

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Abbreviations

MPG	miles per gallon
LHS	left hand side
MTTT	mobile test tire trailer
4WD	four wheel drive
CAD/CAE	computer-aided design/computer-aided engineering
CFD	computational fluid dynamics
WLTP	world light-vehicle test procedure
EV	electric vehicle
OOP	optimum operating point
AC	alternating current
DC	direct current
IGBT	insulated-gate bipolar transistors
MOSFET	metal-oxide-semiconductor field-effect transistor
SOC	state-of-charge
SOH	state-of-health
DoD	depth-of-discharge
SEI	solid electrolyte interphase

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