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Report

Environmental Study of Off-Road Engine Technologies

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Project 54-F3844

Projet 54-F3844

Technical Report

Rapport technique

July 30, 2012

CSTT-HVC-TR-210

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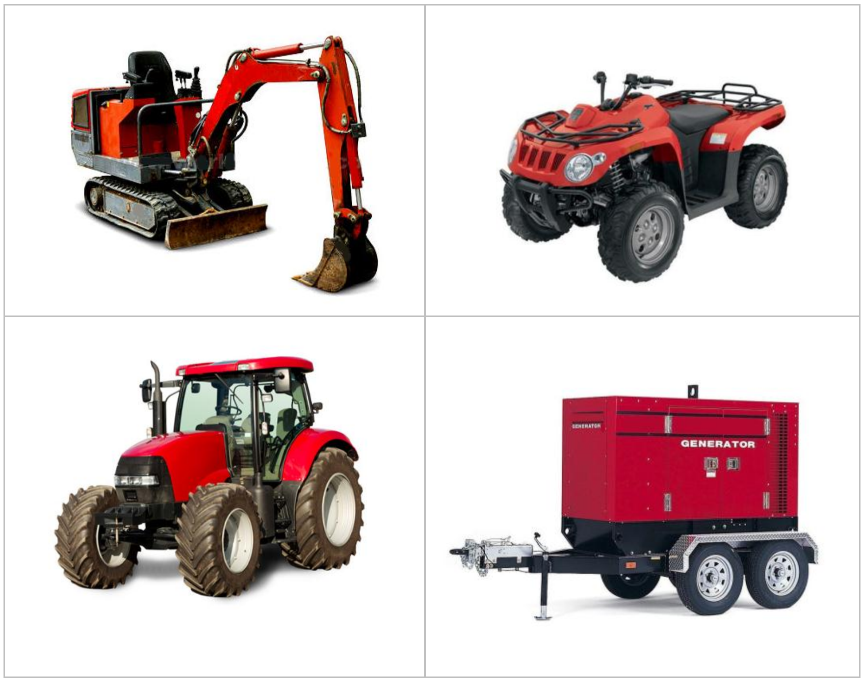
ENVIRONMENTAL STUDY OF OFF-ROAD ENGINE TECHNOLOGIES



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ABSTRACT

Environment Canada contracted NRC-CSTT to review the current fleet of off-road vehicles and equipment in Canada and to review their fuel consumption. NRC-CSTT was provided with a database containing census information of all the off-road equipment found in Canada. The equipment ranged from hand-held lawn trimming devices to mining haul trucks. A list of high fuel consumption fleets was identified as possible candidates for fuel consumption reduction strategies. From this sorted list, the top ten categories of greenhouse gas (GHG) emitters were identified. Technologies aimed at reducing fuel consumption, and therefore GHGs, were then studied to determine their applicability to each of the top ten fuel consuming fleets to quantify their potential to reduce fuel consumption. In addition, training, human factors, and real-time fuel consumption monitoring systems were reviewed.

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EXECUTIVE SUMMARY

Within the transportation sector, off-road vehicles and equipment are the second-largest source of greenhouse gas emissions in Canada, behind on-road vehicles, but ahead of air, rail and commercial marine sources.

NRC-CSTT was contracted to review technologies and strategies which offer potential greenhouse gas emissions reductions for vehicles and equipment in the off-road sector, and to assess the applicability and effectiveness of these technologies and strategies to the highest fuel consuming off-road vehicles and equipment in Canada.

Environment Canada provided NRC-CSTT with a database containing census information of all the off-road equipment found in Canada. The database provided powertrain specifications (fuel type, engine type, engine stroke, power rating, etc.), as well as estimated fuel consumption data, for each model of off-road vehicle and equipment in Canada. The database was used to identify the highest fuel consuming off-road vehicles and equipment. A primary analysis of the database revealed approximately 74,000 individual Product Models (or 37 million Product Model units, from 74 Applications) from model years (MY) 1985 and earlier through to MY 2010 in calendar year (CY) 2010, with a total fuel consumption of approximately 23.17 billion litres of fuel (diesel equivalent) per year.

A study of all 74,000 Product Models in the database was not within the scope of this project. Therefore, a limited MY range was selected (MYs 2006 through 2010) and a fleet-wide fuel consumption approach was taken, with a focus on specific Applications (Product Model groupings, e.g. tractors, generators, etc.), to identify potential off-road fuel savings. In the analysis, when fuel consumption rates were combined with fleet populations for each Application, it became quite evident which Applications should be targeted as candidates for fuel consumption reductions technologies/strategies, as these technologies/strategies would have the greatest overall resultant fuel consumption reduction at the national level.

Using this focused approach, the following Top 10 off-road Applications (corresponding to 72 Products and 7096 Product Models) were identified as the highest fleet-level, fuel consumers in Canada: motorcycles and ATVs, generator sets, pumps, agriculture tractors, snowmobiles, utility vehicles, off-highway trucks, forestry equipment, excavators, and forklifts.

A literature search was performed to gain insight into fuel consumption reduction technologies/strategies with potential application in the off-road sector. Any technology or strategy that could be legitimately applied to the Top 10 Applications was included in the study; a total of nine technology/strategy groupings were identified. To support the results of the final analysis, a summary of the theory of operation of all technologies/strategies was presented.

A tabular compilation of estimated percent fuel consumption and CO_2 reduction values resulting from the implementation of the technologies/strategies identified in the literature search was created. The percent fuel consumption reduction estimates for the identified technologies/strategies can be broadly summarized as follows: engine/transmission (1% to 15%); hybridization (5% to 70%); frictional/parasitic losses (0.3% to 5%); anti-idle (1% to 9%); human factors (1.5% to 20%). These percent reduction estimates were used to calculate reduction potentials for the Top 10 Applications.

The analysis included a qualitative matching exercise of the Top 10 Applications to each of the identified technologies/strategies. Some of the broad conclusions resulting from the qualitative matching exercise are as follows:

- Engine technologies/strategies can be universally applied, but their specific application will determine the level of effectiveness;
- Transmission technologies/strategies are limited in applicability to Applications that must accelerate repeatedly;
- Electrification/hybridization technologies/strategies are most applicable to vehicles or equipment with wide duty cycle ranges, where repetitive work functions create opportunities for energy recovery and storage;
- Friction control technologies/strategies can be applied universally, but the percent reduction potentials are low;
- Parasitic loss reduction technologies/strategies can be applied to all internal combustion engines (ICEs) with some form of accessory device being driven by the engine, and the full benefits may only be realized when combined with other complimentary technologies/strategies;
- Anti-idle technologies/strategies are very application-specific. Fully electrified engine and heating, ventilation, and air conditioning (HVAC) accessories will remove barriers to the implementation of anti-idle technologies/strategies;
- Intelligent controls are required for nearly all the technologies/strategies discussed in this report. Use of intelligent controls in the implementation of autonomous and semi-autonomous equipment controls will be important in some applications;
- Lightweighting can be universally applied in varying degrees, but the benefits seen in on-road applications may not be as great for off-road applications where equipment is often required to have high mass for operational reasons, or for equipment that rarely moves; and
- Human factor technologies/strategies can be universally applied, but the application, as well as operator compliance and acceptance, will determine the effectiveness.

A second analysis was performed which examined the technology/strategy-to-Application matches from a quantitative perspective. In total, 24 quantitative combinations of technologies/strategies-to-Applications (or Products) were identified, and a range of potential fuel consumption reductions were presented for each combination. These combinations were not ranked from highest to lowest potential fuel savings due to the large variation in estimated consumption reduction values and due to the fact that the example combinations represented an incomplete selection of Applications and Products from the database.

Both the qualitative matrix analysis and the example quantitative analysis aimed to demonstrate the applicability and effectiveness of matching specific fuel consumption reduction technologies/strategies with select Applications. A few observations resulted from these analyses:

(1) A small percentage reduction in fuel consumption applied to a fleet with a very large total fuel burn can equal or exceed the reductions resulting from more effective technologies applied to smaller fleets;
(2) Several technologies/strategies are not applicable to all Applications; and
(3) Several technologies/strategies have a very wide range of percent reductions; if the upper end of these estimates could be achieved, then even small fleets could realize significant fuel savings.

Recommendations

Based on the analysis of the data and the fuel consumption reduction technologies, NRC-CSTT has formed the following recommendations:

NRC-CSTT recommends that a more extensive application of the results of this report, in relation to the Environ/PSR database, be performed to determine the effect of applying the identified technologies/strategies to all of the Products in the database, regardless of fuel consumption. The goal would be to determine which combinations of technologies/strategies with Applications would provide the most fuel savings from the least amount of input to each individual Product. This analysis would identify the technology/strategy-to-Product matches that produce the greatest overall fleet fuel use reductions, and would also result in a Canada-wide fuel consumption inventory. When finalized, this fuel consumption inventory could be used to estimate total GHG emissions reductions for the CY 2010 Canadian off-road engine population.

Additionally, in this study, no consideration was given to comparing fuel consumption reductions to development and capital acquisition costs. NRC-CSTT recommends that costs be estimated for the identified technologies/strategies, and that these estimated costs be part of future analysis. Some consideration may need to be given to ranking potential results with consideration for cost and ease of implementation.

NRC-CSTT also recommends selecting one Application, or one segment, for further study to determine which technologies/strategies could be implemented to yield the greatest fuel consumption reduction across that entire Application or segment.

To assist original equipment manufacturers (OEMs) in deciding which technologies to implement, NRC-CSTT recommends that computer models of the powertrain systems be created, which will allow for the simulation of the vehicles/equipment with different technology scenarios and operating conditions. The simulation of the vehicles/equipment would allow for combinations of technologies and strategies to be investigated, and the results of the simulations would aid in identifying technologies and strategies to be further studied with prototype testing and limited field testing.

Ultimately, testing would be required to quantify the individual or additive effects of implementing specific technologies to existing vehicles/equipment operated in real-world conditions.

It is possible that human factor strategies for fuel consumption reduction could yield higher reductions, with less effort, and much sooner, than many of the technology-based methods. Operator training and on-board fuel consumption devices have all been shown, primarily in on-road applications, to reduce fuel consumption by a considerable amount. However, strategies to reduce fuel consumption via operator awareness and training may be better suited to applications that are industrial and commercial in nature, rather than for personal use.

NRC-CSTT recommends that studies be performed for specific segments to determine if the methods in which vehicles/equipment are being sourced and operated could be improved. The results of such a study could be a suggestion that acquisition and operator training be mandated to better educate fleet owners and users about fuel efficient practices. As well, instantaneous fuel consumption displays and fuel savings programs (similar to the 'SmartDriver' transit program) could be implemented for Applications, such as mining and forestry, to teach drivers to operate vehicles or machinery in a more fuel efficient manner. Ultimately, these near-term operator awareness programs could be combined with long-term equipment technology improvements, producing a compounding effect that could maximize fuel consumption reductions.

Finally, in the absence of regulations, such as the on-road corporate average fuel economy, the manufacturers of off-road equipment may have little incentive to voluntarily initiate or engage in the recommended fuel reduction strategies described in this report. Incentive programs may need to be developed that would financially compensate the OEMs for electing to install technologies and apply strategies that lower fuel consumption for their products, or to the end users who elect to purchase a product with technologies which reduce fuel consumption.

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1 INTRODUCTION

1.1 Purpose

Environment Canada (EC) retained the National Research Council of Canada (NRC), as represented by the Centre for Surface Transportation Technology (CSTT), hereafter known as NRC-CSTT, to perform a review of technologies and strategies which offer potential greenhouse gas (GHG) emissions reductions, via fuel consumption reductions, for vehicles and equipment in the off-road sector. In addition, the scope of this review included an assessment of the applicability and effectiveness of these technologies and strategies with regards to the highest fuel consuming off-road vehicles and equipment in Canada.

1.2 Background

Within the transportation sector, off-road vehicles and equipment are the second-largest source of GHG emissions in Canada, behind on-road vehicles, but ahead of air, rail and commercial marine sources [1].

There is a diverse range of applications in the off-road sector; Figure 1 provides a list of common off-road applications, grouped into nine categories: Lawn and Garden, Airport and Rail Service, Recreational, Recreational Marine, Portable Commercial, Mobile Industrial, Agriculture, Logging, and Construction and Mining.

Lawn & Garden	**Portable Commercial**	**Construction & Mining**
Trimmers/Edgers/Cutters	Generator Sets <50 hp	Asphalt Pavers
Lawn mowers	Pumps <50 hp	Tampers/Rammers
Leaf blowers/Vacuums	Air Compressors <50 hp	Plate Compactors
Rear Eng. Riding Mowers	Gas Compressors <50 hp	Concrete Pavers
Front Mowers	Welders <50 hp	Rollers
Chainsaws <6 hp	Pressure Washers <50 hp	Scrapers
Shredders <6 hp		Paving Equipment
Tillers <6 hp	**Mobile Industrial**	Surfacing Equipment
Lawn & Garden Tractors	Aerial Lifts	Signal Boards
Wood Splitters	Forklifts	Trenchers
Snowblowers	Terminal Tractors	Bore/Drill Rigs
Chippers/Stump Grinders	Sweepers/Scrubbers	Excavators
Commercial Turf Equip.	Other Mobile Indust. Equip.	Concrete/Industrial Saws
		Cement and Mortar Mixers
Airport & Rail Service	**Agriculture**	Cranes
Airport Support Equipment	2-Wheel Tractors	Graders
Railway Maintenance	Agricultural Tractors	Off-Highway Trucks
	Agricultural Mowers	Crushing/Processing Equip.
Recreational	Combines	Rough Terrain Forklifts
All Terrain Vehicles	Sprayers	Rubber Tired Loaders
Minibikes	Balers	Rubber Tired Dozers
Off-Road Motorcycles	Tillers >6 HP	Tractors/Loaders/Backhoes
Golf Carts	Swathers	Crawler Tractors
Snowmobiles	Hydro-Power Units	Skid Steer Loaders
Specialty Vehicle Carts	Other Agricultural Equip.	Off-Highway Tractors
		Dumpers/Tenders
Recreational Marine	**Logging**	Other Construction Equip.
Vessels w/Inboard Engines	Chainsaws >6 hp	
Vessels w/Outboard Eng.	Shredders >6 hp	
Vessels w/Sterndrive Eng.	Skidders	
Sailboat Aux. Inboard Eng.	Fellers/Bunchers	Other Miscellaneous Off-Road Vehicles & Equipment
Sailboat Aux. Outboard Eng.		
Personal Watercraft		

Figure 1: Common Off-Road Applications, by Category [1]

Due to the absence of registration requirements (often with Provincial Ministries of Transportation) for most off-road vehicles and equipment in Canada, an estimation of off-road population, and subsequently total fuel consumption, is difficult to obtain. In addition, fuel consumption data will be highly affected by the method in which vehicles and equipment are used, and therefore, it is difficult to determine the exact fuel consumption for any given off-road product. However, various estimates have been realized.

In 2004, EC estimated that the off-road sector contributed approximately 39.0 megatonnes (Mt) of GHG emissions in the year 2000, using a 'Canadianized' bottom-up[1] model from the United States (US) Environmental Protection Agency (EPA); in comparison, the top-down[2] approach estimated GHG emissions at 22.1 Mt.

Subsequently, in 2011, EC engaged a consultant team (Environ/PSR) to develop an electronic database of estimated population and activity data for off-road engine populations in Canada, for model year (MY) 1985 through 2010, for calendar year (CY) 1990 through 2016. This database, which is currently in final draft form, also provides fuel consumption rates for each off-road engine type. When finalized, these fuel consumption data could be used to estimate the total GHG emissions for the Canadian off-road engine population.

For the purpose of this study, the Environ/PSR fuel consumption and population data were used to identify the top fuel consuming off-road vehicles and equipment in order to determine the specific technologies and strategies that would be most effective in reducing and regulating GHG emissions from the off-road sector.

Many studies and test programs have identified effective measures to reduce GHG emissions from vehicles in the on-road sector (e.g. passenger cars, trucks, etc.). For instance, in 2008, the EPA released a report entitled *Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions*, which focuses on technologies for on-road passenger vehicles. In addition, a study published in 2010 by the US National Research Council, in conjunction with the US Department of Transportation's National Highway Traffic Safety Administration (NHTSA), entitled *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicle,* focuses on reduction technologies for traditional tractor-trailers.

In contrast, there has been limited analysis in the area of GHG reduction technologies for the off-road sector; this is partially due to the vast range of off-road applications, each with their own unique considerations (e.g. duty cycle, load, human factors, etc.). Some studies have briefly examined emissions reduction strategies for specific off-road categories or engine types. For example, a 2007 EPA report entitled *Cleaner Diesels: Low Cost Ways to Reduce Emissions from Construction Equipment,* explores reduction options for construction vehicles, and a 2011 British Columbia (B.C.) Government review entitled *Reducing Greenhouse Gas Emissions in the B.C. Road Building and Maintenance Industry*, examines solutions for application in the construction and industrial categories. However, these reports focus primarily on regulated emissions (e.g. nitrogen oxides, particulate matter, etc.), as well as passive fuel consumption strategies (e.g. improved scheduling, route optimization, etc.), as opposed to non-regulated GHG emissions reduction technologies and strategies. This report analyzes GHG emissions reduction technologies for the top fuel consuming vehicles and equipment in the off-road sector in Canada.

[1] Bottom-up approach: estimates emissions from each product, multiplied by product population

[2] Top-down approach: estimates emissions by the overall quantity of fuel consumed and applies various emissions factors

1.3 Scope

The analysis of GHG emissions reduction technologies for the off-road sector was performed with the following scope:

- Off-road applications, such as those listed in Figure 1 – does not include aviation, rail or commercial marine applications;
- New vehicles and equipment only – does not include retrofit technologies;
- Mobile off-road equipment only – does not include stationary off-road applications;
- Carbon dioxide (CO_2) emissions reductions, via a reduction in fuel consumption – does not include regulated emissions (see Section 2.1);
- Spark and compression ignition engines, powered primarily by gasoline or diesel fuels – does not include alternative fuels, such as biofuel or hydrogen;
- Technologies that are currently available, in development, or in the process of commercialization; and
- Implementation focused solely at the manufacturer level, for years 2015 through 2020.

1.4 Limitations

The Environ/PSR electronic database, which contains the fuel consumption data used as part of the study, was in draft form at the time of this review. Consequently, Section 4 and Section 6, which analyze the database to identify top fuel consumers and assess applicable technologies for these top consumers, should be deemed as preliminary until such time as the database information is finalized. Although preliminary, the results still provide adequate direction for regulators. Should the database be finalized, the fuel consumption analysis could be adjusted accordingly. The technologies and strategies presented in Section 5 are based on the findings in Section 4; some additional technologies may need to be explored in more detail if the focus of the database results change significantly.

The Section 5 review provides a very broad overview of technologies with GHG emissions reduction potential for the off-road sector. Specific technology brands/models/types and manufacturer's claims have not been included as part of this report, unless required to convey a unique, yet prominent idea or concept.

Section 6 assesses the applicability of technologies and strategies to specific vehicles and equipment. Given the wide range of GHG reduction technologies and strategies, and the broad scope of off-road engines (varied type, application, duty cycle, etc.), it is possible that not every conceivable technology or strategy-to-application match has been captured. In addition, combinations of technologies/strategies (i.e. applying more than one technology/strategy to one off-road product type) were not analyzed as part of this study.

The assessments in this report are intended to primarily capture the off-road vehicles and equipment that have the potential to be regulated easily and/or could yield considerable GHG emissions reductions; more comprehensive analyses are outside the scope of this study.

In addition, given the ever-changing, technology-driven off-road industry, new technologies are being developed and introduced at a rapid pace. The technologies in Section 5 and their respective fuel consumption reduction potentials in Section 6 are likely to see improvements beyond what is presented in this report; however, the estimates herein are considered valid and reasonable for the purpose and timeline of this report.

Furthermore, it is assumed that the vehicles/equipment analyzed in this study do not already make use of suggested fuel consumption reduction technologies/strategies. A review of the technical specifications of every piece of equipment on the market would be required to confirm, or deny, the existence of a technology; such an exercise is outside the scope of this project.

2 THEORY

The off-road technologies reviewed in this report have the potential to achieve GHG emissions reductions via a reduction in overall fuel consumption. Some of the fundamental concepts related to fuel consumption/GHG emissions reduction potential, as well as off-road powertrain systems are described in Section 2.1 and Section 2.2, below.

2.1 Fuel Consumption and Emissions

Fuel is consumed by an engine to produce useful work. In Canada, the typical fuels in widespread use are gasoline and diesel, both of which are hydrocarbon-based fuels.

When hydrocarbon fuels are burned in an internal combustion engine (ICE), they produce emissions which are released via the exhaust system. The primary tailpipe emission is CO_2 (carbon dioxide). CO_2 is produced as a result of complete combustion and has been linked to global warming and the 'greenhouse effect'. There are currently no regulations in place in Canada with regards to CO_2 tailpipe emissions for the off-road sector. Unlike some regulated emissions (e.g. HC, NOx, etc.), there are no emissions-specific devices to reduce CO_2; the only way to reduce CO_2 production is to use a fuel with a lower carbon content or to burn less.

A diesel engine will produce approximately 2.68 kilograms (kg) of CO_2 for every litre of fuel it burns. In comparison, a gasoline engine produces roughly 2.34 kg of CO_2 for every litre consumed[2]. However, diesel engines usually burn less fuel per unit of mechanical work as output than similarly sized gasoline engines, and therefore the more relevant measure for emissions (particularly in the on-road sector) is not the mass of CO_2 produced per litre (L) burned, but rather the mass of CO_2 produced per distance traveled, or per unit of work output by the engine.

In terms of fuel consumption, the ratings for on-road equipment are generally measured in litres of fuel per unit distance (e.g. L/100 km), which is very similar to what a consumer might see on a typical car dashboard. Off-road equipment, on the other hand, will often report fuel consumption in terms of fuel per unit time (e.g. L/hour), and usually at a particular load or duty cycle (e.g. 50 percent, 85 percent, etc.).

There is a direct relationship between GHG emissions and fuel consumption, as noted above; in the context of this report they could be used synonymously. However, given that fuel burn is the root of GHG emissions, and given that most technologies/strategies are best described in terms of fuel and not emissions, the remainder of the report is written from a fuel consumption perspective.

2.1.1 Fuel Consumption Factors

The factors that influence fuel consumption for off-road vehicles and equipment depend heavily on the specific application, duty cycle, and/or operating condition. The level of contribution of each factor varies significantly, as well. Compared to on-road applications, the factors that influence fuel consumption are much more varied and differentiated.

Table 1, below, provides a general summary of vehicle and equipment fuel consumption factors, their applicability to the off-road sector, their estimated relative reduction potentials, and the technologies and strategies that may be applicable to address each fuel consumption factor.

Table 1: Fuel Consumption Factors for Off-Road Equipment and Vehicles

Fuel Consumption Factor	Off-Road Applicability	Fuel Consumption Reduction Potential	Primary Applicable Reduction Technologies/Strategies[3]
Grade/Elevation Changes	High	High	- Hybrid/electrification with energy storage - Lightweighting - Human factors
Speed/Direction Changes	High	High	- Hybrid/electrification with energy storage - Lightweighting - Human factors
Human Factors	High	High	- Operator training/education
Powertrain Losses	Med	Med	- Powertrain (engine/transmission) technologies
Parasitic Losses	Med	Med	- Parasitic loss reduction technologies
Friction	Med	Low	- Friction reduction technologies
Aerodynamic Drag	Low	Low	- Aerodynamic aids
Rolling Resistance	Low	Low	- Low rolling resistance tires

Elevation/grade changes and speed/direction changes are related factors; for mobile off-road equipment they play a major role in the consumption of fuel. The greater the mass of the equipment, the more energy it needs to climb a grade or accelerate up to speed; for off-road vehicles this energy comes from the ICE. As well, although many types of off-road equipment may not move very fast, if at all, they are often large and heavy and move very large loads. For example a typical crawler-excavator does not move much faster than walking speed but can expend a great deal of energy to swing a loaded bucket when doing work.

The manner in which a human operates a piece of equipment is also a primary factor in fuel consumption. Just as aggressive driving in a passenger car on the highway leads to increased fuel consumption, so can aggressive operation of off-road equipment. High accelerations, large throttle settings when part-throttle will perform the function, and unnecessary idling times all negatively affect fuel use.

The powertrain is integral to the operation and function of the equipment – any improvements in powertrain efficiency will reduce fuel consumption. Powertrains for off-road equipment include the engine, transmission, and all of the powered accessories that are required by the equipment to perform the task that it is designed to do.

Internal friction and parasitic losses are inherent in any machine, whether ICE-powered or electric powered. Reductions in these losses are an on-going exercise for original equipment manufacturers (OEMs), for both on- and off-road equipment. However, for off-road applications, especially most heavy-duty equipment, there are additional parasitic losses that are not present in on-road vehicles. For example, most agricultural tractors are outfitted with hydraulically operated implements and tools, requiring a hydraulic system to be run by the ICE, and as a result, the internal friction of the hydraulic fluid system is a portion of the frictional losses. Unfortunately the contribution of friction on fuel consumption is difficult to quantify as it depends heavily on the usage patterns, implementation methods, and plumbing configurations. Quantifying the fluid friction loss becomes even more difficult as heavy-duty equipment can be ordered in a wide variety of optional configurations.

[3] These technologies and strategies are described in Section 2.2 and their applications are described in Section 5.

For on-road vehicles, aerodynamic drag and tire rolling resistance are significant fuel consumption factors. However, for off-road vehicles and equipment, these factors may not affect fuel consumption at all, notably for equipment that is often stationary, or for very slow moving equipment. However, improvements could be made to certain products using aerodynamic aids or low rolling resistance (LRR) tires.

As a result, care must be exercised when looking at fuel consumption reduction strategies as the applicability of various strategies is highly dependent on the application. Even within an application, the way equipment is used will strongly influence the expected fuel use reductions that the various technologies promise.

In the following sections, the theory related to the technologies and reduction strategies listed in Table 1 is summarized. The application of these technologies and strategies to off-road vehicles and equipment is presented in Section 5.

2.2 Powertrain Systems and Fuel Consumption

Off-road equipment and vehicles exist in a very broad range of types, with vastly different sizes and functions. The sizes can range from very large rigid haul trucks and specialized construction equipment, down to small consumer-marketed all terrain vehicles (ATVs) or small portable generators. Functions can range from small portable pumps, to crawler-excavators, and agricultural tractors. This range in size and function is unlike the on-road vehicle sector, in which there is a limited variation in size, weight, and engine power.

The range of sizes and functions results in a large variety of powertrain[4] systems installed in off-road equipment and vehicles. For example, ATVs have a similar powertrain to on-road vehicles, consisting of an ICE, a transmission, drive shafts, differentials, and drive wheels. The primary purpose of the ATV is to carry passengers and light cargo, therefore it is to be expected that some fuel consumption reduction technologies that are applicable to on-road applications may also apply to ATVs.

In contrast, a large crawler-excavator may have a powertrain consisting of a large diesel ICE, a hydraulic pump, high pressure hydraulic lines, hydraulic motors for propelling the crawler on tracks, and hydraulic cylinders (actuators) which power the excavator mechanism. The primary purpose of the excavator is not forward motion, but rather excavating earth, and as such, some of the fuel consumption reduction strategies used for on-road vehicles may not apply to the excavator. As well, there may be technologies and strategies which have far greater benefits in off-road applications compared to on-road vehicles.

The majority of technologies presented in Section 5 are targeted at the engine and transmission components of the powertrain. There are a wide variety of engine[5] technologies in use in off-road vehicle and equipment applications, however, this report is only concerned with the internal combustion reciprocating piston engine, more commonly referred to as an ICE as this is the most common type in Canada for off-road applications.

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[4] A powertrain is an interconnected series of components (engine, transmission, driveshaft, etc.) that generate and deliver power from a power source to one or more points of use (tires, hydraulic pumps, etc.). The powertrain may also convert, combine, or split the source power to a form of power more suitable for the point of use.

[5] An internal combustion engine, often simply referred to as an engine, consumes fuel to generate useful mechanical work. In contrast, a motor (electric, hydraulic, etc.) generates useful mechanical work without changing the composition of its energy source. For this document, the term ‘engine’ will refer to an internal combustion engine and is not interchangeable with the term ‘motor’ which will refer to an electric or hydraulic motor.

2.2.1 Engine

The engines in use in off-road equipment and vehicles in Canada have a vast range in power, from one horsepower to over 8000 horsepower. The population of engines also includes every major type of ICE configuration, with far more variety than is seen in on-road vehicles. The following sections broadly review the major areas of technology related to ICEs in off-road applications.

The Environ/PSR database, which contains the fuel consumption data used as part of the study, classified the ICEs used in off-road equipment and vehicles in Canada by:

- Fuel type: gasoline, liquid petroleum gas (LPG), natural gas (NG), or diesel fueled;
- Ignition type: spark ignition (SI) of compression ignition (CI); and
- Cycle[6]: two-stroke or four-stroke.

For most of the off-road equipment in Canada, the term ‘spark ignition’ refers to a gasoline fueled engine, and ‘compression ignition’ refers to a diesel fueled engine, however, there are many off-road applications with SI ICEs powered by LPG or NG.

Figure 2 outlines the major operating components of a typical IC engine. A general theory section regarding engine types and engine technologies is presented below.

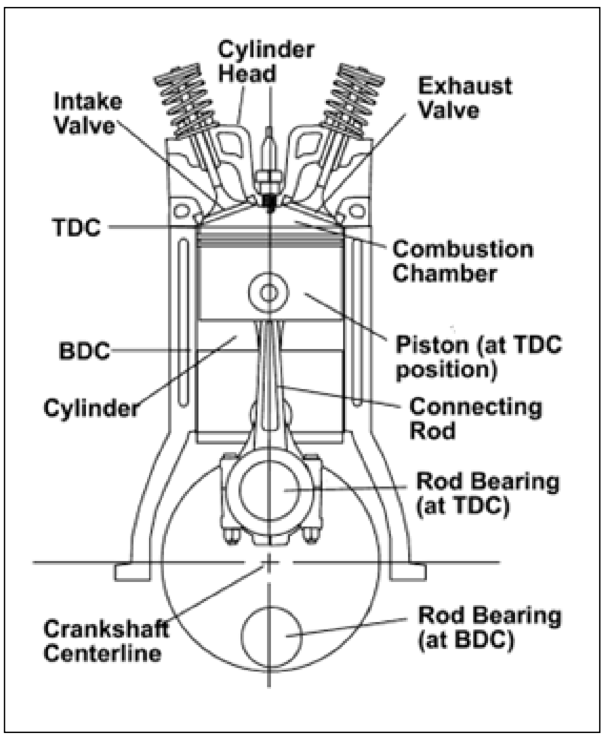

Figure 2: Major Operating Components of the Reciprocating-piston ICE (TDC: top dead centre; BDC: bottom dead centre) **[3]**

[6] It is also common to refer to these engine classifications as two-cycle or four-cycle, but for this report the term ‘stroke’ will be used.

2.2.1.1 Ignition Type: Spark Ignition and Compression Ignition

There are two major types of ICEs in use: spark ignition and compression ignition. As noted above, an SI engine is generally fueled by gasoline and a CI engine is generally fueled by diesel.

SI engines employ a spark plug to initiate the combustion event. Engine power output is controlled by throttling the intake air, while the air/fuel ratio (the ratio of the amount of fuel mixed with the air) is maintained within a narrow range under all operating conditions. SI engines typically have a useful operating speed range between 1500 to 6000 revolution per minute (RPM).

In a CI engine, the intake air is not throttled to control engine power; engine power output is controlled by varying the amount of fuel delivered, with a constant amount of air used for all power outputs, thus the air/fuel ratio of a CI engine is variable depending on the operating conditions. For ignition of the air-fuel mixture, the combustion air is heated during the compression stroke to a temperature high enough to cause the fuel to spontaneously ignite when injected. The ignition event is controlled strictly by the timing of the injection of the fuel. Compression ratios are higher than in SI engines, resulting in higher combustion chamber pressures, and higher piston loads than in a SI engine. To withstand the higher loads a CI engine is built with stronger components, the result being a heavier engine than a comparable SI engine. The useful engine speed range is typically between 1000 to 4000 RPM, which is lower than a comparable SI engine. However a CI engine typically produces more torque than a SI engine of equal displacement. [3][4][5]

2.2.1.2 Cycle: Two-Stroke and Four-Stroke

The SI and CI piston engine can also be designed to run in two-stroke or four-stroke operating cycles. The numbers two and four describe the number of piston movements required to complete one combustion cycle. A complete combustion cycle consists of the following events: induction, compression, ignition/expansion, and exhaust. A two-stroke engine completes all four events with two movements of the piston, whereas a four-stroke engine requires four piston movements for a complete cycle. Figure 3 shows the stages of operation for a four-stroke spark ignition engine. Figure 4 shows the stages of operation for a two-stroke compression ignition engine.

Two-stroke engines are generally found in applications which favour high power density, low weight, and/or high speed. Gasoline fueled two-stroke engines are most commonly found powering small consumer equipment such as chainsaws, snowmobiles, and motorcycles. Diesel fueled two-stroke engines are used to power some off-road equipment and vehicles, such as large rigid haul trucks and industrial pumps or generators.

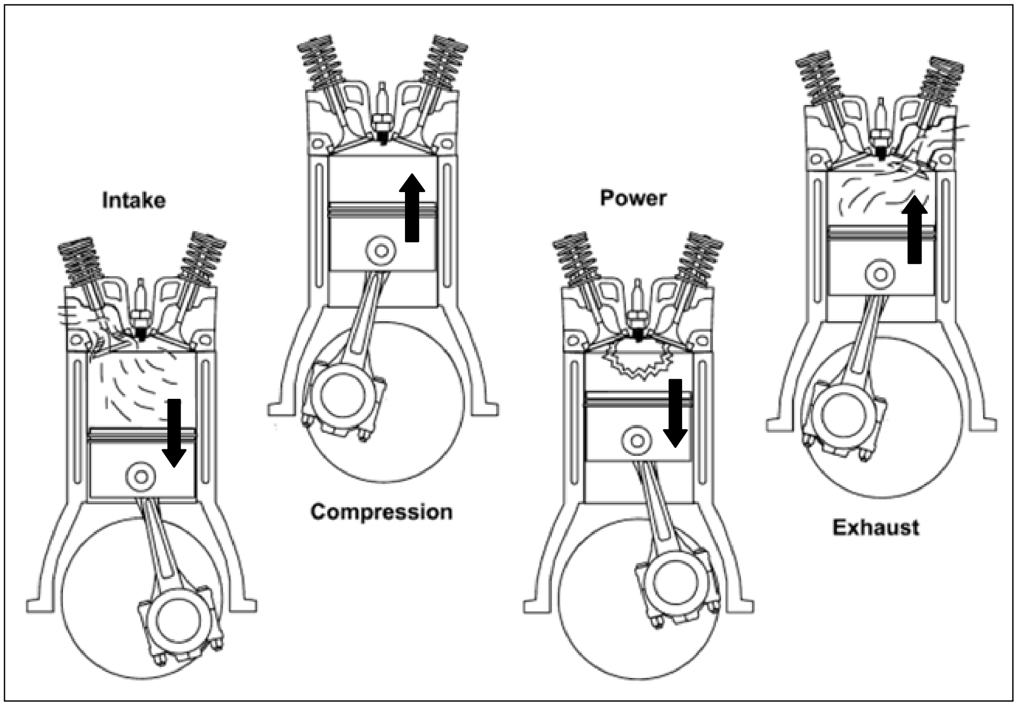

Figure 3: Four-stroke Operating Cycle, Shown for a Spark Ignition Engine (Arrow indicates direction of piston motion) **[3]**

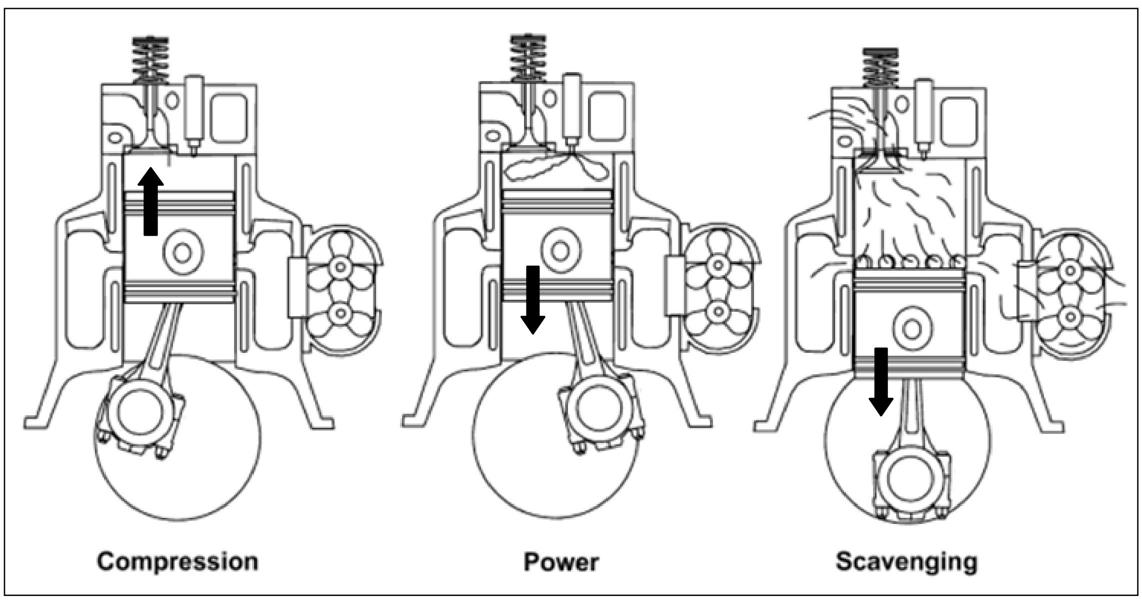

Figure 4: Two-stroke Operating Cycle, Shown for a Super-charged, Compression Ignition Engine (Arrow indicates direction of piston motion) **[3]**

For a given engine weight and displacement, a two-stroke engine can produce more power in either SI or CI applications. This often made two-stroke designs advantageous from a power-to-weight ratio standpoint in many hand-held applications. However, to meet stringent emissions requirements, many applications have switched from two-stroke to four-stroke designs, despite a weight increase. That said, advanced two-stroke designs, using direct injection fuel delivery, have improved the emissions output of two-stroke design such that they may continue to be used in some off-road applications [6].

As well, there is research by Ricardo PLC into producing an engine which can switch from two-stroke to four-stroke operation depending on engine load conditions and speed. The experimental system requires computer control of an electro-hydraulic valve-train to accomplish the two- to four-stroke transition. At low engine RPM the valve-train, fuel, and ignition systems operate the engine in two-stroke mode; as engine speed increases, the engine controller switches operating modes to a four-stroke cycle. This allows the engine to produce greater torque at lower speeds than it normally would. Fuel consumption gains are realized when the engine is downsized and turbocharged [7] .

2.2.1.3 Advanced Combustion Methods

Alternatives to the standard gasoline and diesel combustion processes have been investigated. For many fuel types, low-temperature combustion (LTC) processes, a general classification that includes premix charge compression ignition (PCCI) and homogeneous charge compression ignition (HCCI), have been under investigation by many researchers [8][9][10][11]. These combustion processes can be more efficient than standard combustion modes under some conditions. However, they may also require the application of several other technologies such as variable valve lift, direct injection, variable charge intake motion, and very advanced computer control systems to control the timing of the combustion process. The focus of the research on these alternative combustion cycles in on-road vehicles is mainly to achieve lower regulated emissions, which can lower the cost of exhaust aftertreatment equipment. As well, significant fuel savings may also be seen with these technologies if lean-burn conditions can be achieved at low engine speeds [8].

Of the above-mentioned technologies, HCCI has been the focus of considerable research to date [8][9][10][11]. HCCI can offer substantial emission reductions (including CO_2) and can be applied to engines using a variety of fuels, including gasoline and diesel. For conventional engines running on either diesel or gasoline, the ignition of the cylinder charge is triggered externally though fuel injection (diesel) or spark (gasoline). The combustion of the fuel then proceeds along a high temperature flame front, travelling outwards from the ignition source. The high temperatures in the flame front, and the speed the flame front travels, are factors in the production of unwanted emissions in SI and CI engines. In HCCI, spontaneous and homogeneous ignition of the air-fuel mixture can occur through precise control of the temperature and pressure in the combustion chamber. Figure 5 illustrates the differences in the ignition methods.

Since HCCI combustion occurs simultaneously throughout the combustion chamber at lower temperatures and without forming a flame front, engine-out particulate matter (PM) and NO_x emissions are very low. While significant effort is being directed to its development, some technical challenges remain before it becomes commercially applicable [8][9][10][11]. At present, while many OEMs have demonstrated HCCI operation in on-road applications with engineering test cases, HCCI operation is possible only in a portion of the engine's operating range. HCCI would not be possible without electronic controls for the timing of the combustion as the window for successful HCCI operation (i.e. spontaneous combustion without pre-ignition resulting in engine knocking) is very small. No commercially viable engine using HCCI operation is currently available or announced, though several OEMs have stated that they are committed to commercializing the technology as soon as possible.

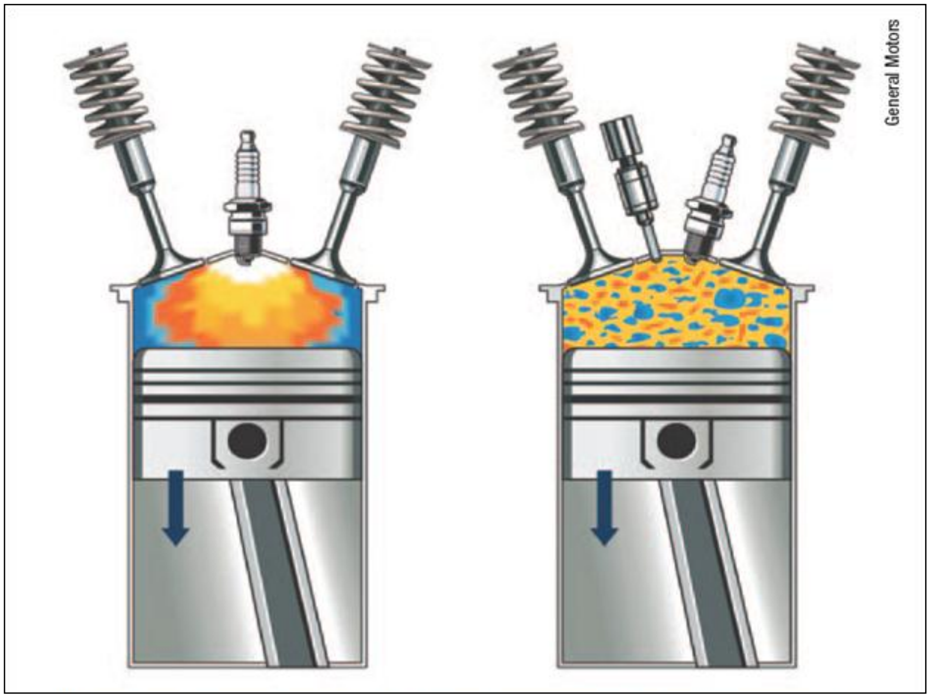

Figure 5: Illustrations of Normal Combustion (left) and Homogeneous Charge Compression Ignition (right) [10]

2.2.1.4 Engine Downsizing; Engine Displacement Control

Engines that power off-road vehicles and equipment must be sized to produce enough power for the expected peak power demands of the work environment. With a normally aspirated engine of a given design, the engine displacement is correlated with the peak power output: more power requires a larger displacement engine. However, when an 'over-sized' engine is not being used to produce peak power, it runs less efficiently than a smaller engine would in the same situation, mainly due to increased pumping losses and friction of the larger engine, in comparison to a smaller displacement engine.

There is a potential for fuel consumption reduction if an engine could be produced which was smaller ('downsized'), and therefore more efficient at low power output, but still capable of producing higher power when needed. There are two methods currently available to produce an engine which is high-powered only when needed: using forced induction and through cylinder deactivation.

Forced Induction

By using some form of forced induction, where the intake charge air is pressurized and forced into the cylinder during the intake stroke, an engine can be made with a smaller total cylinder displacement that produces the same power as a larger engine. Forced induction is achieved by using an engine-driven super-charger or an exhaust-gas-driven turbo-charger. The 'downsized' engine is more efficient than the larger displacement engine because of lower friction losses in the smaller engine, the increased thermodynamic efficiency gains due to turbo-charging, and lower pumping losses in the intake ducting at low throttle settings [5][9]. Engine 'downsizing' is most applicable in applications where peak power demand is not frequent, and a wide range of partial power settings is typical.

Forced induction also increases the intake air temperature due to compressive heating of the incoming air. This heating is undesirable as cooler intake air is denser and therefore has more oxygen for combustion. The intake air temperature can be reduced with the use of an intercooler. However, the addition of an intercooler can increase the overall packaging volume requirements for a given engine displacement.

Both SI and CI engines benefit from the increased thermodynamic efficiency of turbo-charging. However, diesel engines respond better to forced induction due to the air intake system not being throttled, and they generally have a lower exhaust temperature, which reduces stress on the turbo-machinery. Turbo-charging is the single most effective method by which to increase the power output of a diesel engine of any given displacement, and is virtually standard on most high powered engines.

For off-road applications that currently use turbo-chargers, adopting advanced turbo-charging technologies (e.g. variable geometry, dual-stage, etc.) and/or electronic controls (versus mechanical or vacuum controls) can provide additional gains in fuel consumption reduction, as well as improved engine responsiveness (i.e. reduced lag).

Turbo-compounding

There is also the possibility of recovering the heat energy in the exhaust gases of an ICE and using that energy to generate shaft power. The two methods discussed here attempt to recover exhaust gas heat through a turbine. Although both methods use an exhaust gas driven turbine as a method of recovering useful work from the exhaust gas heat, neither method uses this work to compress intake charge air.

Mechanical turbo-compounding uses a turbine in the exhaust stream, which is coupled to a transmission and a fluid coupling to reduce the turbine shaft speed to match the engine speed, and to transfer the generated torque to the crankshaft [9]. The system works best at full engine load, and is less effective at low loads. The primary benefit of mechanical turbo-compounding is that the additional recovered energy is added directly to the engine output shaft; for OEMs this means that there are no additional components that need to be added to their products. The primary drawback is the additional mechanical complexity of the engine as a whole. Several turbo-compounding systems are currently in production [12][13].

Electrical turbo-compounding is a similar system that uses a turbine in the exhaust stream, which is connected to an electrical generator. The electricity produced can be used to charge a battery system, or power other engine devices. The primary benefit of electric turbo-compounding is that the turbo-generator can be located with greater flexibility as it does not need to be coupled to the output driveshaft. Additionally, the electrical output of the turbo-generator can be directed to a point of use that is different than the engine output [14]. Electrical turbo-compounding would integrate very well with a hybrid engine system, where the electricity generated can be stored in the battery system.

Cylinder Deactivation

Cylinder deactivation technology retains the 'over-sized' engine displacement, but reduces fuel consumption at lower power settings by reducing the effective engine displacement by deactivating (turning off) a portion of the cylinders in an engine. In typical on-road passenger car applications, an eight cylinder engine will run with four cylinders deactivated during periods of low to moderate power demand. To achieve this, the engine has special valve, fuel, and ignition control technologies, such that at idle and moderate loads, the engine controller cuts off fuel and ignition to specific cylinders and the intake and exhaust valves are deactivated to reduce pumping losses. When full power is required, the controller reactivates the deactivated cylinders. [5]

A challenge for cylinder deactivation is maintaining an even firing order with deactivated cylinders. Uneven firing causes an increase in vibration that can cause damage if it is not managed properly. Even with an even firing order, there is still significant noise, vibration and harshness (NVH) issues as the excitation frequencies change as the cylinders are turned on and off [5]. This may require the use of more costly passive or active engine mounts to absorb unwanted vibrations and prevent them from being felt by the user. Despite this challenge, cylinder deactivation has been successfully implemented by several on-road vehicle manufacturers such as Honda, GM, and Chrysler.

2.2.1.5 Advanced ICE Design

The reciprocating piston engine is the standard design used for all off-road ICEs identified in the Environ/PSR database. However, there has always been a continued effort on the part of many to further improve the design in order to extract more work from the combustion process. These advanced designs, which are in experimental phases and do show promise for potential future applications, are the five- and six-stroke cycle engines and the opposed piston, opposed cylinder (OPOC) engine.

The five-stroke design, currently in prototype stage uses an extra cylinder to expand the hot exhaust gases produced by a pair of working cylinders operating on the same crankshaft in a standard four-stroke mode. The makers claim that the system operates with an expansion ratio approaching that of a diesel engine, with significant gains above current four-stroke technology. [15]

There are various versions of the six-stroke engine, some of them originating as far back as 1920 [16]: however, all of them use a standard reciprocating piston design but add an extra crank revolution to the cycle following the standard four-stroke cycle. The extra two strokes allow for an added power stroke to further expand and cool either the exhaust gases from the previous combustion cycle, or air heated by the hot exhaust, or water injected into the hot cylinder. [17][18]

Another area attracting renewed interest is the opposed piston opposed cylinder (OPOC) engine architecture. An engine of this design has a pair of pistons which move in opposition to each other, meeting at top-dead-centre of a shared cylinder. The design requires two crankshafts or a more complex connecting rod arrangement, but the engine has no cylinder head. The intake and exhaust is controlled by ports in the cylinder walls. The design should not be confused with the horizontally opposed cylinder arrangement (eg. Subaru, Porsche automobile engines), which uses a single common crankshaft and a pair of cylinder heads with valves.

An OPOC engine can be designed to run on diesel fuel or gasoline and operates as a four-stroke engine, but with the simplicity of a two-stroke. This design has the potential to have significantly decreased fuel consumption for an equivalent power output, as compared to a conventional four-stroke engine. Current generation OPOC engine technology is still experimental, but at least one OEM (Ecomotors) has announced their intention to produce a commercial OPOC engine in the near future [19][20]. Figure 6 is an illustration of the experimental OPOC engine being developed by Ecomotors [20] for use in industrial applications. The Ecomotors design can be assembled in a modular fashion and connected together via an electronically controlled clutch to form a variable displacement engine.

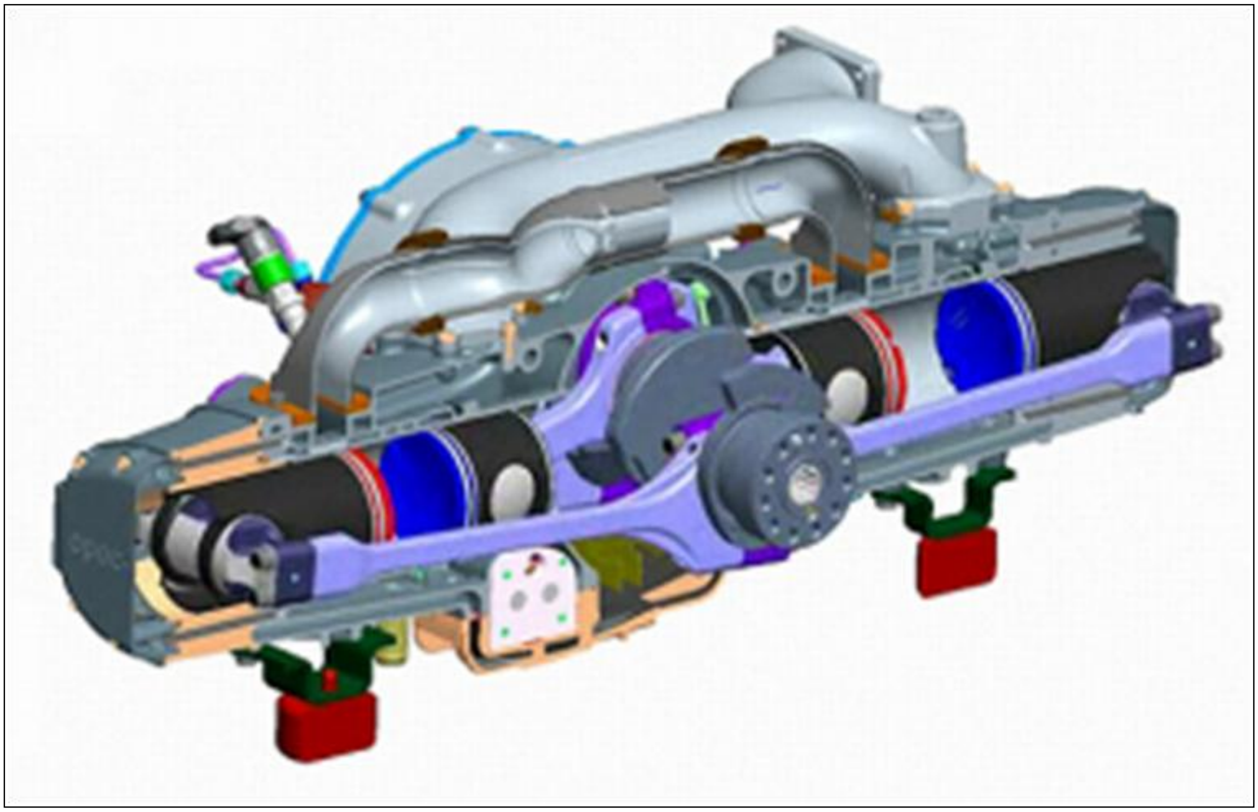

Figure 6: Illustration of the EcoMotors Opposed Piston Opposed Cylinder (OPOC) Engine [20]

2.2.1.6 Fuel Delivery Systems

Fuel delivery strategies have a strong potential to reduce fuel consumption by way of precision metering. By only delivering the required amount of fuel to the engine for the operating regime, the fuel consumption for a desired power setting can be minimized. For typical SI gasoline engines the fuel delivery system is designed to maintain a specific air-to-fuel ratio (AFR) for the selected throttle setting, engine speed, and load. There are three main methods of metering fuel to the quantity of intake air entering into the cylinders of a gasoline engine: a carburetor, port fuel injection, and direct injection (DI). For a diesel engine, direct injection of the fuel into the combustion chamber is inherent in the design.

For gasoline engines, especially small engines (e.g. lawn mowers), the traditional method of metering fuel is with a carburetor. In a carbureted engine, the tuning of the carburetor compromises some fuel savings to provide reliable starting and running throughout the operating envelope. As a result, the engine generally runs rich, using more fuel than necessary, to achieve low-temperature starting and to reduce the likelihood of overheating at high power output levels. Carburetors are typically still used on small two-stroke and four-stroke engines. Some small engine makers have incorporated advanced carburetor designs, with electronic controls, into their products.

A more precise fuel delivery control method is fuel injection. Modern electronic fuel injection (EFI) systems control the air-fuel mixture entering the engine with electronics that deliver only the required amount of fuel for the desired operating condition (e.g. cold start, high temperature, etc). Fuel injection systems spray the fuel into the intake air stream, metering the fuel based on the volume of air entering the engine. Fuel injection systems include single injector systems, multi-injector systems, and multi-port systems, with simpler systems injecting the fuel continuously, and other more advanced systems injecting on a timed basis.

EFI systems are currently well established in applications such as ATVs and snowmobiles. High-end and performance models that have the cost margins to support the additional equipment costs were the first models to adopt advanced fuel management systems such as EFI. As the cost of components is reduced through volume, and development costs are recovered, the penetration of EFI has steadily increased to mid-range models and, like most other engine technologies has propagated to lower cost models [21].

Unlike port fuel injection, gasoline direct injection (GDI) sprays the fuel directly into the combustion chamber in a manner very similar to that of a diesel engine. GDI can operate in two very different manners; stoichiometric[7] and lean burn combustion modes. Stoichiometric GDI is currently used in some on-road engines. The fuel savings in this mode come about from more careful fuel control compared with port injection, and from improved combustion charge cooling due to more complete fuel charge vaporization. This charge cooling effect allows for the engine to be designed with a higher compression ratio, increasing efficiency [5][9].

The other mode of operating a GDI engine is to design it for ‘lean-burn’ operation, such that at low throttle settings, less fuel is injected than needed for a stoichiometric mixture, and power is controlled with less throttling losses. The drawback to this method is that where emissions are regulated, the use of a three-way catalytic converter is not possible due to the nature of its operation, in which it requires combustion products from a near stoichiometric air-fuel mixture (i.e. low in free oxygen). As well, while lean operation can produce fuel consumption reductions, it may also increase NOx emissions due to the higher combustion temperatures [5][9].

For off-road applications, GDI technology for two-stroke SI engines has great potential for reducing GHG emissions. Two-stroke SI engines equipped with carburetors have typically exhibited high fuel consumption due to unburned fuel (and oil) entering the exhaust. This is inherent in the operation of a two-stroke SI gasoline engine, where scavenging[8] the cylinder of combustion gases with intake charge ensures reliable combustion. By using direct injection for two-stroke SI engines, scavenging can take place with intake air which has no fuel mixed in it,

[7] Stoichiometric air-to-fuel ratio (AFR) is the ratio of the mass of the air to the fuel to theoretically achieve complete combustion of the fuel. For gasoline this ratio is 14.7:1 on a mass basis. A non-stoichiometric AFR is lower or higher than the ideal ratios [9].

[8] Cylinder scavenging: the act of expelling the consumed fuel/air charge inside an engine cylinder and drawing a fresh fuel/air charge into the cylinder for the next combustion cycle. In a four-stroke engine, cylinder scavenging is carried out by a discrete exhaust stroke in which the spent gases are pumped out of the engine. In contrast, a two-stroke engine does not have a discrete exhaust stroke and so cylinder scavenging is normally achieved by using the incoming fresh fuel/air charge to displace the spent gases. For maximum power and response, some of the incoming fuel/air mixture is lost in the exhaust and exits the engine as unburned HC.

and the fuel is injected just prior to ignition, in a manner very similar to that of a two-stroke CI (i.e. diesel) engine. The result is that unburned hydrocarbon emissions are reduced significantly.

A new type of gasoline fuel injection, pulse count injection (PCI), is a variation of the port injection system commonly found in on-road cars. Where port injection systems regulate the amount of fuel delivered by varying the length of time the injector is on, the PCI system regulates the amount of fuel delivered by varying the number of times the injector is switched on, where each pulse of a PCI injector is extremely short and happens very rapidly.

PCI technology was specifically developed for small displacement gasoline engines under 19 kilowatts of power [22]. It allows small engines, such as those found in scooters, small motorcycles, lawn and garden equipment, and other such applications, to benefit from EFI technology without the cost and complexity.

Diesel engines, by design, use high pressure fuel injection. For small displacement diesel engines (e.g. garden tractors), the typical method of injection is achieved by way of a mechanically adjustable plunger-type fuel pump for each cylinder. This method is simple and robust although it compromises fuel use in exchange for reliable performance.

Almost all new diesel engines of mid- to large-displacement use some form of electronically controlled injection technology, whether common rail or unit injector/pump. Small displacement diesels are mixed in their adoption of advanced injection strategies, depending on their regulated emissions requirements. Current diesel injection development is focused on in-cylinder mixture control and exhaust after-treatment for regulated emissions (e.g. PM and NOx) and less about fuel consumption reduction.

Table 2 summarizes the fuel delivery systems in use in the majority of gasoline and diesel engines.

Table 2: Methods for Fuel Delivery for Internal Combustion Engines

Delivery Method		Advantages	Disadvantages
Gasoline	Carburetor	Simple, low cost, user maintainable	Poor fuel regulation at low speeds; pressure and temperature sensitive
	Electronic Fuel Injection	Greater precision and better charge mixing than carburetors	Increased complexity and cost (over carburetors); programming and additional parts required
	Gasoline Direct Injection (two-stroke)	More efficient cylinder scavenging; less unburned HC; lean operation possible	High fuel system pressure; control system complexity; higher cost
	Gasoline Direct Injection (four-stroke)	Lean operation possible	High fuel system pressure; control system complexity Increased cost
Diesel	Unitized pumps/ injectors	Increased control of injection event; multiple injections possible	Additional engine complexity
	Common rail	Increased control of injection event; multiple injections possible	High system pressure

2.2.1.7 Intake and Exhaust Systems

The intake of combustion air and the exhausting of combustion products in a four-stroke piston engine is controlled by valves. Two-stroke designs, diesel or gasoline, often use ports on the cylinder walls to control the intake and exhaust, but may use valves as well. The timing of the opening and closing of the valves is controlled by a camshaft. In standard piston engines, the opening and closing of these valves, both the timing and the lift, is designed to allow the engine to operate well at a selected engine speed. However, the lift and timing values that are ideal for one engine speed are often a compromise at lower and higher engine speeds.

Widening the range of speeds where an engine is most efficient requires that the timing of the valves and the amount of valve lift be adjusted throughout the operating speed of the engine. This can be achieved by specialized camshaft and lifter mechanisms that allow the valves to alter their opening and closing times with engine speed, known as variable valve timing (VVT), or with mechanisms that can alter the valve lift with engine speed, known as variable valve lift (VVL). A combination of these systems allows for improved control of the intake and exhaust processes throughout the speed range of the engine, reducing the compromising effects of fixed valve trains on engine operation [5].

VVT and VVL can be applied to both gasoline and diesel fueled engines, as well as naturally aspirated and forced induction engines. VVT and VVL technologies are especially beneficial to naturally aspirated engines. In all cases, variable valve trains improve engine efficiency through a combination of improved cylinder scavenging, improved intake charge filling, decreased pumping losses at low engine speeds, and increasing the effective compression ratio of the engine [5]. Use of these technologies in on-road vehicle applications has been increasing for over a decade, being implemented by manufacturers such as Honda, Nissan, Toyota, and BMW.

Another method to achieve VVT and VVL is to not use a camshaft to open and close the valves, but use high speed actuators to perform this function. Using hydraulic or electric actuators to open and close the valves frees the engine designers to tune the valve opening and closing times as well as the valve lift for the optimal settings for each engine speed and load condition. The benefit to the system comes from the ability of the engine to operate more efficiently at a wider range of speeds, reducing throttling losses at low speeds or idle but also under high power demand situations. To date this method is experimental and has not reached production in the off-road sector [5][9].

2.2.1.8 Advanced Ignition Technologies

Gasoline engines rely on an ignition source to begin the combustion process, which is typically provided by a high voltage ignition system using a spark plug. The ignition system generates a high voltage source which the spark plug uses to generate a spark within the combustion chamber to ignite the fuel-air mixture. Although reliable and robust, there is continued on-going research into alternative ignition systems. The goal of the advanced ignition technologies research is to increase the speed of the combustion process and to create high enough energy levels to be able to move to lean burn combustion.

A new development in combustion ignition replaces the spark plug with a similar looking device that “uses a high-energy, high frequency electrical field to produce repeatable, controlled ionization, creating multiple streams of ions to ignite the fuel mixture throughout the combustion chamber” [23]. This technology is being developed by Federal Mogul but is not yet commercialized.

Another experimental system with significant potential to improve fuel use is the Dual Coil Offset (DCO) ignition system developed by the Southwest Research Institute [24]. The system can deliver six to eight times the energy of a typical ignition system, in a controlled continuous fashion. The DCO device allows for up to a three-fold increase in the dilution limit (i.e. increased levels of exhaust gas recirculation (EGR) with a lean AFR) of an engine, enabling higher compression ratios and increased specific power levels while significantly increasing fuel economy [24].

Another system being investigated for improved combustion ignition is using lasers. Lasers have the potential to improve the initiation of the combustion process by igniting the mixture faster and with high energy levels, again for the purpose of igniting a lean mixture. The systems reported in the literature are experimental, with no set timeframe for commercialization [25].

2.2.2 **Transmission**

A transmission serves as an intermediary between the power source and the point of use, or the load. It can be designed to perform a variety of functions such as load decoupling (i.e. separating the engine from the load), speed regulation, power combining/division, torque multiplication, or any combination of these. Certain applications may not require a transmission, and in such cases, the load is directly coupled to the engine.

Mechanical transmissions transmit power through machine elements such as gears, chains, and belts. For this type, the load decoupling is usually achieved by way of a friction clutch or a torque converter. Engine speed regulation is performed through multiple gear ratios, selected manually by the operator or automatically by some type of control system. A typical passenger car transmission (automatic or manual) is an example of a mechanical transmission. Mechanical transmissions also include continuously variable transmissions (CVT), described below. Hybrid transmissions use electricity or hydraulic fluid to transmit power from the power source to the load. These transmissions types are discussed below.

Mechanical Transmissions

In terms of pure mechanical efficiency, the manual transmission is the most efficient. The high mechanical efficiency of the manual transmission in passenger car applications typically results in lower fuel consumption when compared to an automatic transmission equipped counterpart driven over the same test course. However, despite the efficiency advantages of a manual transmission, the selection of the proper gear ratio is highly dependent on the operator selecting the proper gear, which has a significant effect on fuel consumption.

A torque converter coupled automatic transmission does not need to consider operator skill as a factor in fuel consumption as it uses a control system (mechanical or computer) to select the proper ratio given the vehicle speed and engine load. The sole disadvantage is a reduction in overall mechanical efficiency, primarily as a result of the frictional fluid losses in the torque converter.

Advanced transmission technologies, such as the automated manual transmission (AMT), attempt to combine the efficiency of a manual transmission with automatic shifting capabilities, reducing the need for a skilled operator to achieve maximum fuel efficiency. In AMTs, a computer controls actuators which operate the clutch and the gear shifting. With optimized computer logic, the system is able to minimize fuel consumption [5].

Many modern transmissions are built with five to eight discrete ratios which allow the engine to operate closer to its optimum speed. Since the operator, or shifting algorithm, uses a transmission to attempt to match the engine speed to the load by selecting the most appropriate gear ratio, a greater number of discrete gear ratios results in a smaller change in engine speed between gears, allowing for a better match between the desired speed and the most efficient engine speed for the load [5]. The ideal transmission would be able to allow the engine speed to remain constant for a wide range of loading and vehicle speed conditions. This requirement can be met, with some limitations, by using a continuously variable transmission (CVT).

CVTs are mechanical transmissions that transfer power through friction, by using a metal or rubber belt, or rollers. By adjusting the size of pulleys, or moving a wheel on a cone, the transmission gear ratio can be continuously adjusted between the low and high limits of the design. This is in contrast to geared transmissions, which have a discrete number of gear ratios. The continuously variable gear ratio available between the lowest and highest ratios in a CVT allows the engine speed to remain nearly constant and independent of the speed of the load [5]. However, because surface friction rather than gear teeth is used to transmit torque, a CVT is limited to the amount of torque it can transmit without slipping of the friction surfaces. Development is actively underway to further increase these torque limits [26].

A CVT can also be used in the reverse manner, allowing the load to remain at a nearly constant optimum speed while the engine speed varies. The selection of implementation depends on the application. One example of this type of application is in the use with accessory drives, such as air conditioning (A/C) systems and power steering, among others. These accessories use the ability of a CVT to provide constant output speed while allowing the input speed to vary. The use of a CVT in these applications allows for the accessory components to be efficiently sized, by having reduced drag at high engine speed while providing the required output at a variety of engine speeds.

Hybrid Transmissions

In some heavy equipment applications, where vehicle mass is very large and/or grades are steep, a mechanical transmission with sufficient gearing would be very large and complex (i.e. heavy haul mine trucks and some agricultural equipment). In this environment a different type of transmission is required, using either an electric or hydraulic coupling. Both types can be broadly classified as a CVT as they also offer a continuously variable change in vehicle speed regardless of engine speed, however they do not use mechanical elements to transmit power. Instead, electricity or fluid flow is used to transmit power from the source to the load.

Electric coupling uses a generator that is attached to the ICE, which powers an electric motor that is attached to the drive wheels (or load). The most familiar example of an electric coupled vehicle is the diesel-electric locomotive. Electric coupling is also used in some very large rigid haul mine trucks [27][28] and wheel loaders [29][30].

Hydraulic coupling transmits power through a pressurized fluid, usually hydraulic oil, and is often known as a hydrostatic transmission. In a hydrostatic transmission, the ICE drives a variable displacement pump, the load is driven by a hydraulic motor, and the two are connected by high pressure hydraulic lines. Load decoupling is performed by setting the pump to zero flow and/or diverting the flow through a bypass valve or valves. Speed regulation is achieved by varying engine speed, pump displacement, or both. As a result a hydrostatic transmission has much higher power transmission capabilities than a mechanical CVT, which is limited by friction. However, hydrostatic systems do generate significant fluid heating, which requires substantial cooling capacity, which places a practical limit on the power capabilities. Hydrostatic transmissions are often used in agricultural equipment.

2.2.3 **Hybridization and Electrification**

2.2.3.1 Hybridization

In general, a hybrid powertrain refers to a system that combines two or more sources of propulsion energy (i.e. a gasoline powered ICE with a battery powered electric motor), and may include a means of energy storage [5]. There are numerous hybrid powertrain strategies, which may include one or more of the following configurations [9]:

- Series hybrid electric;
- Series hybrid hydraulic;
- Parallel hybrid electric;
    - Starter-alternator type,
    - Pre-transmission type, or
    - Post-transmission type,
- Parallel hydraulic hybrid;
- Power split hybrid electric;
- Power split hybrid hydraulic; or
- Plug-in hybrids.

The above list was compiled to capture the known on-road hybrid configurations, however the complexity and diversity of off-road equipment may result in hybrid configurations unique to the application that do not fall into one of the above system types. For example, the energy storage systems listed above include only electrical energy storage with batteries and mechanical energy storage with hydraulic fluid pressure; however, experimental hybrid systems have been developed which use high-speed flywheels, compressed gases, and ultra-capacitors to store energy.

As an overview of the concept, the two most common types of hybrid-electric vehicle powertrain, the series-hybrid and parallel-hybrid, are shown in Figure 7 and are described in the following paragraphs.

A series hybrid, as shown in the central flow chart in Figure 7, uses an ICE to exclusively power a generator to provide electrical power, and the load is driven exclusively by an electric motor. An energy storage system is included to recover braking energy or to store excess generating capacity, depending on the application. The ICE speed is completely independent of the vehicle speed, which allows the ICE to be smaller, and lighter, but also to operate efficiently over a narrow range of speeds. The Chevrolet Volt is an example of an on-road (plug-in) series hybrid-electric vehicle.

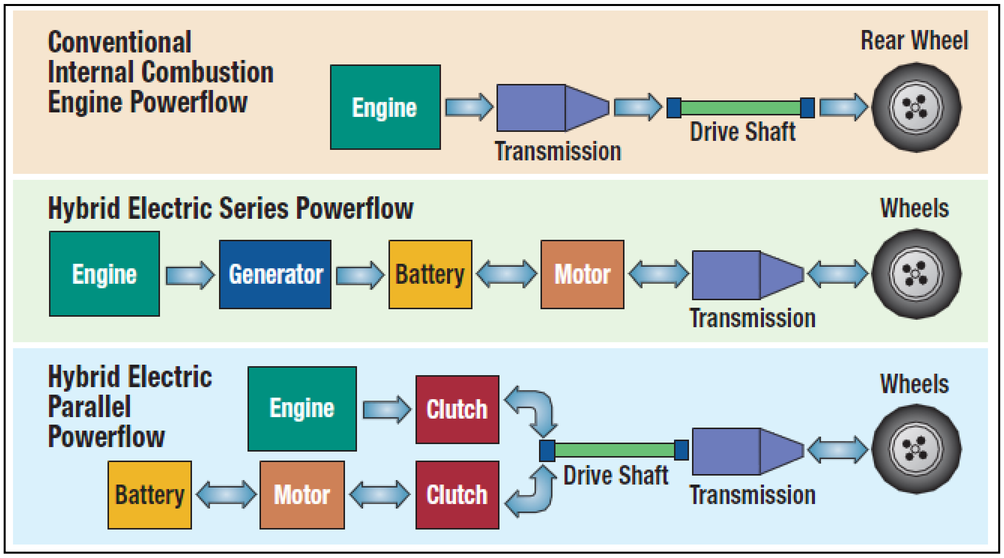

Figure 7: Conventional and Hybrid-Electric Vehicle Powertrain Configurations [31]

A parallel hybrid, as shown in the lower flow chart in Figure 7, uses an ICE to provide the majority of the required power and supplements any additional power requirements with an electric motor. More typically, the electric motor is in the form of a motor/generator that switches modes based on the power flow requirements. There is an energy storage system to recover braking energy and/or excess generation capacity for future use. In this system the ICE speed is dependant on the vehicle speed, but because of the supplemental power provided by the electric motor, the ICE can be sized smaller. Parallel hybrids use advanced transmission technologies to combine and divide power between the engine, the motor/generator, and the load. As well, through intelligent control systems, the power delivered to the wheels is divided between the ICE and the electric motor depending on the power demand of the operator. The Toyota Prius is an example of an on-road parallel hybrid system.

Regardless of the configuration or energy storage method, hybrid powertrains in general have the following advantages over ICE-only powertrains [5][9]:

- Allow for the recovery of input energy (e.g. regenerative braking)
- Higher system efficiency (series hybrid);
- Improved torque characteristics of the electric drive motor at low speeds;
- Reduced emissions, through elimination of idle and low speed ICE operation;
- ICE operates at best efficiency (series hybrid);
- ICE engine downsizing possible, reducing the weight of the ICE;
- Possibility for engine shutoff (anti-idle);
- Accessory electrification;
- Better reaction speeds, due to quicker operation of electric motors compared to ICEs;
- Robustness, in parallel systems where either power source can propel the vehicle; and
- Ability to plug-in for charging.

The disadvantages of a hybrid system include [9]:

- Increased complexity;
- Increase system mass;
- Increased system cost;

- Potential for lower overall reliability; and
- Potential to be improperly applied: i.e. best applied in wide power range duty cycle applications, but not in continuous full power demand applications.

Energy recovery is one of the main advantages of using a hybrid power train. Energy is required to accelerate a mass or to raise it up to a given height. To decelerate or lower a mass in a controlled manner, kinetic or potential energy must be dissipated; this usually occurs in the form of heat. Energy recovery (regeneration) seeks to capture the energy normally dissipated during deceleration or lowering in a form that can be used for future acceleration or raising. Once captured, the energy can then be released to provide energy for the next movement cycle. For example, a vehicle braking normally dissipates energy with brakes to slow the car down; by switching the electric drive motors to act as generators, they can provide a portion of the braking torque needed to decelerate a moving vehicle. Energy recovery for off-road applications is application- or motion-specific, but is still applicable, and for some off-road applications a considerable amount of energy can be recovered [32][33][34].

In the majority of on-road applications, energy storage is achieved with batteries. A drawback of batteries for energy storage in hybrid systems is that there is a limit to how fast a battery can accept and produce energy on demand (i.e. low power density), due to the fact that a battery stores energy as a chemical reaction. The reaction is also heavily influenced by temperature and battery age. Additionally, the energy density of the best commercial lithium-ion batteries is still only about one-tenth that of gasoline or diesel [9]. For some hybrid systems, especially those where large amounts of energy can be recovered and stored in a brief period of time, which may be typical of off-road equipment, a different form of energy storage is needed. For these systems, hydraulic pressure, flywheel systems, and capacitors[9] are more suitable as these methods can store energy at higher rates (i.e. at high power densities) than a battery system [9]. An example of hybrid off-road equipment, in this case using capacitor energy storage, is the excavator manufactured by Komatsu [33]. The powertrain system architecture for this product is shown in Figure 8.

[9] Ultracapacitors are being investigated as possible replacements for batteries; however, at current technology levels, they have lower energy densities that typical lithium-ion batteries but with higher power densities.

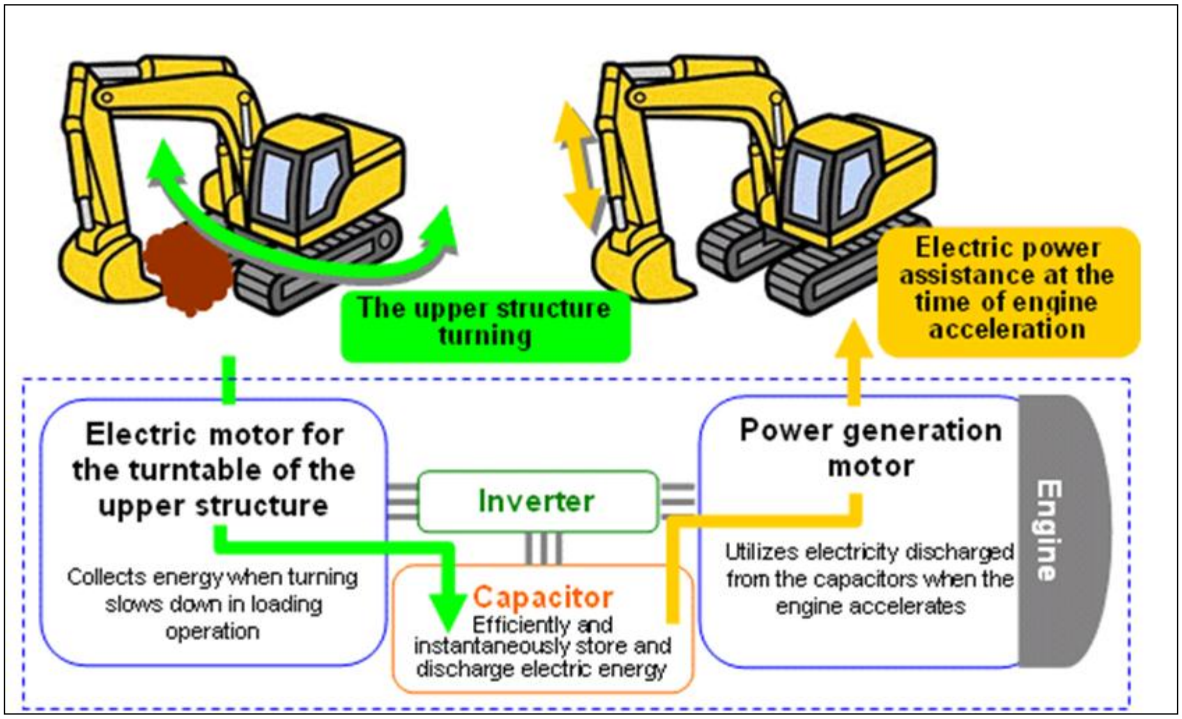

Figure 8: Example of Hybrid Power-System Applied to Commercially Available Off-Road Equipment, Komatsu Hybrid Excavator [33]

2.2.3.2 Electrification

In electrified vehicles or equipment, the ICE power source is replaced with an electric motor. A fully electric system can include one of the following powertrain strategies:

- Fully electric drive, with energy supplied by on-board batteries or fuel cells; or
- Fully electric drive with energy supplied through a connection to an external power source (grid power).

Electrification could see vehicles and equipment converted completely to operate on electric power only, where applicable. Certain types of ICE-driven off-road equipment may be easily converted to pure electric operation, either with batteries and plugged in for charging, or tethered directly to the electrical grid.

Grid powered equipment is the simplest type: electric motors are used for primary power and the power source is 120V or 240V AC source. The suitability of certain vehicles and equipment to pure electric operation is highly dependent on its expected usage profile and would need to be examined on a case-by-case basis. It is important to note that the energy from grid electricity must still come from a source which uses oil, coal, natural gas, hydroelectricity, wind, or nuclear sources of energy supply. Further study is warranted to examine the costs and CO_2 emissions associated with electrification of off-road equipment to the point of electricity generation.

Alternatively, electric fuel cell operation could also help reduce dependence on fuel. Hydrogen fuelled fuel cells would eliminate CO_2 emissions entirely if the hydrogen is sourced from renewable energy. However if the hydrogen fuel source is hydrocarbon based, then CO_2

emissions are removed from the vehicle location but are transferred to the hydrogen generating facility. As well, other types of fuel cells exist that are fuelled by alcohol, methane, or other hydrocarbon fuels; however these fuel cells produce CO_2 at the vehicle location.

Fuel cell powered equipment and vehicles have been demonstrated in specific off-road applications with success; for example, one agricultural tractor manufacturer (New Holland) has a second generation fuel cell tractor in current production [35]. The limitation with fuel cells is the availability, storage, and handling of hydrogen fuel. Hydrogen is very energy dense on a mass basis, but hydrogen itself has the lowest density of all fuels. This means that hydrogen must be stored under very high pressure or at low temperatures in order to allow for a useful amount of hydrogen to be carried. Additionally, since the ‘exhaust’ is water vapour, there is a concern of freezing when operating in cold weather.

2.2.4 **Friction Control**

Friction occurs at every connection, bearing, seal, and contact between components in an engine. It also occurs when fluid, such as lubrication oil, is pumped or flows through oil channels. Individually the frictional losses are small, but added up over the complete engine, the losses can be relatively significant.

Inside an engine, the single largest source of friction losses occurs between the piston and cylinder [36][37]. The primary sources of the friction are the piston rings, which seal the combustion gases inside the combustion chamber, and the piston skirt, which keeps the piston aligned with the cylinder bore. Lowering the ring tension and coating the piston skirt with solid lubricants can help reduce ring and piston friction. Other sources of friction inside an engine are related to crankshaft journal bearings, valve train cam followers, camshaft bearings, pump bearings, and oil seals. Special coatings to reduce surface contact friction losses are actively being researched [38].

In a complex piece of equipment, friction losses also occur with the transmission of power through transmissions, drive-shaft joints and bearings, rear axle differentials, and wheel bearings. These powertrain frictional losses can be significantly more than the losses within the engine. Powertrain losses due to friction can be minimized by using roller bearings rather than bushings, reducing the use of sliding contacts, using surface treatments, and through proper lubrication.

Lubricant selection can play an important role in reducing contact friction and fluid friction. High viscosity oils require more work to pump through an engine or transmission, adding to parasitic losses. They also produce higher drag forces in lubricated contacts or in hydrodynamic bearings. Low-viscosity lubricants are thinner, and require less effort to pump and create less frictional drag in bearings. Synthetic lubricants offer further reduction in friction loses by using additives to reduce contact friction, and by having near constant viscosity properties with temperature, which allows these lubricants to be effective in a wider range of operating conditions [5].

2.2.5 **Parasitic Loss**

Parasitic losses arise from accessory devices such as pumps, fans, compressors, and generators that are powered by the ICE, but can be removed and powered externally. These devices are typically driven by belts or gears and are mounted either externally from the engine, or internally. Although many of these accessory devices are required by the ICE for its operation, many of them are used intermittently, or work most efficiently at a specific speed, and most are driven at a wide range of speeds because they are engine-driven. [5]

One method to reduce parasitic losses is to use clutched accessory drives that operate the accessory only when required. Another method is to use a CVT-type drive to control the speed of the accessory independent of the engine speed, reducing the time the accessory spends operating at a less than ideal speed. Another option is to separate the accessories from the ICE drive completely and power them electrically.

Electrically driven accessories allows for the relocation of the ICE driven accessories, including engine oil pumps, power steering pumps, engine coolant pumps and A/C compressors. For many of these accessory devices, the required flow and pressure is generally fixed past a certain engine speed. By running these devices electrically with intelligent drives, the accessory drive speed can be regulated independently of engine speed, thus reducing wasted energy [9].

Electric accessory drives offer numerous advantages in terms of fuel consumption reductions, as well as increased design freedom since accessory devices no longer have to be mounted on, or even near, the engine. This allows the accessories to be placed in more advantageous locations for serviceability, environmental benefits, noise isolation, space claim, and other implementation factors. The primary downside of electric accessory drives is the additional load they place on the vehicle's electrical system. This increase in load will increase the parasitic drag on the alternator, which will cause the engine to work slightly harder; however, it is still less of a drag than what is required to power the accessories mechanically from the engine. This increased electrical load is best handled by a 42 V charging system, and the inclusion of a 42 V starter/generator in the engine system will allow the full benefits of electric accessories to be attained [5][9].

The increase in system operating voltage to 42 V reduces the current flows in the system for the same power demands, requiring smaller diameter wiring which weighs less. As well, the higher voltage system allows for more electrical loads to be added and for more efficient, lighter weight (high voltage) electric motors and generators to be used [5][9]. Several proposed designs use an integrated starter/generator (ISG) system to allow the starter motor to act as a low speed power source as well as the starter motor for the ICE [39].

For certain off-road applications that require an auxiliary shaft power, such as an agriculture tractor with power take off (PTO), the conversion to an electric PTO can be advantageous in that the PTO speed can be kept constant for maximum implement efficiency and can be independent of engine speed.

For heating, ventilation and air conditioning (HVAC) systems, another possible option to reduce parasitic loss is through absorption refrigeration, which provides cooling using only heat to drive the system. An absorption refrigeration system is very similar to a propane-powered fridge usually found in recreational vehicles (R/Vs) and campers. In the context of off-road applications, an absorption system would mean that the ICE driven air-conditioning compressor would be removed. The movement of the working fluids through the system is performed through the heating and expansion of a secondary fluid, without using moving parts such as pumps. The heat to drive the system would come from the heat in engine coolant or from a direct-fired heater when the engine is switched off; this strategy would still consume some fuel, but far less than the primary vehicle engine.

2.2.6 **Anti-Idle**

Idling engines consume fuel without performing any useful function. Typically for on-road applications, engine idling is used to maintain cabin temperature or warm-up the engine. The US EPA estimates that a typical idling diesel engine in an on-road tractor consumes 1.2 gallons of fuel per hour at high idle and 0.6 gallons per hour at low idle [40].

Very generally, there are two strategy types for reducing engine idle time: engine start-stop and engine-off. Engine start-stop systems control the engine idle with a timer, shutting it off and restarting depending on the control system settings. Engine-off solutions include direct-fired heaters, auxiliary power units (APUs), and shore power. In the absence of engine start-stop routines, idle time is often grouped into one of two categories: 'avoidable' idle and 'unavoidable' idle. Unavoidable idle typically occurs when a vehicle is stopped in traffic, say, at a red light. Avoidable idle typically occurs when the vehicle is parked and the operator has left the engine to idle for no particular reason or to power something that may not be necessary at that moment.

Engine start-stop technologies can be relatively simple solutions, where the engine is shut down entirely instead of letting it idle. At its simplest, a timer can be programmed into the engine controller that shuts off the engine after a set amount of idle time. Depending on the equipment and level of complexity, the engine controller can be programmed to restart the engine to maintain engine temperature, battery voltage, or any other combination of parameters. More advanced implementations use a high voltage (eg. 42V) integrated starter generator to restart the engine [5] [39].

Engine start-stop is easily applied to hybridized equipment. Hybrid equipment with suitable energy storage can use electric power for certain functions, such as low speed movement, or operator comfort features. Once the battery charge has dropped to a certain level, the engine would be restarted to provide primary power and recharge the storage unit. By allowing the engine to remain off for extended periods of time, greater reductions in fuel consumption may be possible.

For applications that only require engine idle for heat supply, such as engine and cab warming, a related technology known as a direct-fired heater can be beneficial. A direct-fired heater is similar in function to a standard electric engine block heater and is useful where there is no electric power conveniently available. These heaters use a small burner, fueled with the same fuel as the main engine, to heat the engine coolant directly. A small electric pump circulates the warmed coolant throughout the system. It can be an economical alternative to running the primary engine at idle for extended periods of time. This technology can be used for keeping equipment engine fluids warm and circulating during extended shutdown in cold climates and remote areas with thermostatically or timer-controlled heaters.

An auxiliary power unit (APU) is a small self-contained power source that can provide secondary power (i.e. electrical) to the attached vehicle or equipment. The APU consumes less fuel than the primary engine (which is shut down) and provides power to run accessories such as A/C, heating, and various other electrical loads. A study performed by NRC-CSTT [41] concluded that, on average, fuel and CO_2 reductions were in the order of 65 percent to 85 percent when highway tractors used APUs rather than idling the main engine. However, some APUs actually produced more regulated emissions (e.g. PM and NO_x) compared to the main diesel engine.

Shore power is the term applied to technologies that allow stopped equipment to be plugged into the standard electrical grid to maintain certain functions. For on-road applications, some long haul trucks use shore power to allow drivers to shut down the main engine and still enjoy comfort features such as A/C, and maintain electrical power for so called ‘hotel features’ such as reading lights and televisions, among others.

APUs and shore power are increasingly being used to reduce fuel consumption in on-road trucking applications to provide operator comfort during rest periods while allowing the primary engine to be shut off for extended periods of time. This strategy could also be applied to some off-road applications. Equipment that has been hybridized or has had the major engine accessories converted to electrical power will be better able to use shore power for operator comfort and engine warming. The use of all electric accessories such as HVAC fans, pumps, and compressors needed for cabin comfort and engine heating can be powered by shore power or battery storage.

2.2.7 **Intelligent Controls**

Intelligent controls are essentially on-board computers with sophisticated programming which enables highly accurate and precise control of various vehicle systems, such as engines, transmissions, or other peripherals. For the purpose of this document, intelligent controls also include the sensors, actuators, and cabling and connections (e.g. networks, communications protocols, etc.) required to form a complete system. Many of the technologies discussed in this report are not possible without intelligent controls.

One area where intelligent controls have the potential to make large scale changes to the use of off-road equipment is in the creation of autonomous and semi-autonomous machines. By removing the operator, or supplementing operator input with computer algorithm derived control strategies, equipment use could be further optimized. In some off-road applications, the removal of the operator would allow the equipment to be operated in harsh conditions without the parasitic losses due to providing operator comfort. As well, unnecessary idling for shift changes and aggressive operating techniques could also be eliminated. Semi-autonomous control is currently in use in many agricultural applications [42]. Fully autonomous control is being investigated for mining applications [43].

3 PROCEDURE

This review consisted of the following main tasks:

(1) Conduct an analysis of the Environ/PSR off-road database to identify off-road vehicles and equipment with relatively high fuel consumption;
(2) Perform a technology/strategy review to identify technologies and strategies with GHG emissions reductions potential in the off-road sector; and
(3) Perform an assessment of the applicability and effectiveness of the technologies and strategies identified in (2) to the high fuel-consuming vehicles and equipment found in (1).

The procedures for each of these tasks are summarized in Section 3.1 through Section 3.3.

3.1 Off-Road Database Analysis

EC provided NRC-CSTT with a draft electronic database of population and activity data for off-road engine populations in Canada for MYs 1985 and older through 2010, for CY 2010[10], compiled by a consultant team, Environ/PSR. NRC-CSTT reviewed the content of the database and provided feedback to EC, with regards to accuracy, source data, and completeness. After much discussion, it was agreed by all parties involved that the NRC-CSTT technology/strategy review would be performed with the database in its current draft state; however, the results would be deemed as preliminary (see Section 1.4 for further discussion).

NRC-CSTT performed an initial analysis of the comprehensive off-road database (with numerous queries, calculations, and filter applications), with a focus on the following key areas:

- CY 2010 Canadian off-road engine populations (at a national level);
- CY 2010 Canadian off-road engine fuel consumption (at a national level);
- Off-road vehicle and equipment classifications: by Segment (e.g. construction), by Application (e.g. off-highway trucks), and by Product (e.g. rigid haul trucks); and
- Fuel types (e.g. diesel), engine types (e.g. spark), engine stroke (e.g. two-stroke), and engine power ratings (unit horsepower).

Subsequent to this initial analysis, NRC-CSTT and EC agreed upon a narrowed scope, the details of which are presented in Section 4. Upon completion of the database analysis, NRC-CSTT performed a ranking of the top fuel-consuming off-road vehicles and equipment in Canada.

The results of the Environ/PSR database analysis and the list of top fuel consuming off-road applications can be found in Section 4.

[10] The Environ/PSR review covered CYs 1990 through 2016; however, only the CY 2010 data was presented to NRC-CSTT by EC for this review.

3.2 Technology/Strategy Review

To begin the technology/strategy review, NRC-CSTT consulted with NRC-CISTI (Canada Institute for Scientific and Technical Information) to develop a literature search approach and to identify the appropriate terminology for use in the review. NRC-CISTI carried out a thorough preliminary search, and provided the results to NRC-CSTT. NRC-CSTT reviewed the results, identified key areas of interest, and performed a final independent literature search.

The primary sources for the technology review were as follows:

- Online publication databases (e.g. SAE, ScienceDirect, etc.);
- Government/regulatory websites (e.g. EPA, CARB, etc.);
- General web-based sources; and
- NRC staff consultations.

The technology review revealed many potential GHG emissions reduction technologies and strategies; the results were grouped into appropriate categories (e.g. engine technologies, transmission technologies, etc.). Each category was examined under the following key headings:

(1) Overview (i.e. basic definition and examples);
(2) Applications (i.e. relevance to top fuel-consuming Applications); and
(3) Implementation Factors (i.e. factors to consider for each technology).

Various implementation factors were considered for each technology/strategy grouping; Table 3 lists these factors.

Table 3: Technology/Strategy Implementation Factors

Consideration	
1	Cost
2	Timeframe
3	Availability
4	Reliability, scalability, durability, and safety
5	Support and maintenance
6	Consumer uptake
7	Weight, volume, and power increases/decreases
8	Interaction with other emissions technologies
9	Co-benefits

The results of the technology/strategy review can be found in Section 5.

The literature search also revealed quantifiable reduction potentials, expressed in percent CO_2 reduction, or percent fuel consumption reduction, for many of the technologies and strategies which were reviewed. A summary of these fuel consumption reduction percentages are presented in Section 6.

3.3 Technology/Strategy-to-Application Assessment

With the results from both the off-road database analysis and the technology review, NRC-CSTT assessed the applicability of each technology/strategy grouping with each of the top fuel-consuming applications and developed a summary of the key findings. The findings were presented as follows:

(1) Qualitative Analysis Matrix: high-level ranked overview of potential matching of each technology/strategy grouping with each of the top fuel-consuming applications; and

(2) Quantitative Analysis Examples: specific examples of technology/strategy-to-application matching, with associated percent reduction and fuel savings (expressed in litres of diesel equivalent (DEQ) per year, based on Environ/PSR database information).

The results of the technology/strategy-to-application assessment can be found in Section 6.

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4 OFF-ROAD DATABASE ANALYSIS

The Environ/PSR database of Canadian population and activity data for off-road engines (as presented to NRC-CSTT by EC in draft form in October 2011) was analyzed following the procedure outlined in Section 3.

The ultimate goal of the database analysis was to identify the top fuel-consuming vehicles and equipment in the Canadian off-road sector. In order to identify the criteria and rationale associated with the final selection of top fuel-consumers, it was important to first understand the basic elements and content of the database (Section 4.1), and to examine some of the key findings with respect to fuel consumption in the off-road sector (Section 4.2).

4.1 Database Overview

The database categorizes off-road vehicles and equipment into six ‘Segments’: Industrial, Recreational, Construction, Agriculture, Lawn and Garden, and Marine Propulsion. These Segments are broken down into 74 specific ‘Applications’, and then further subdivided into 211 ‘Product’ types. In addition, each Product type can be broken down into a ‘Product Model’, based on MY (e.g. 2001), fuel type (e.g. gasoline), engine power ratings (units of horsepower), engine type (e.g. spark ignition), and engine stroke (e.g. two-stroke); each of these model specifications were elements in the database.

As sample breakdown of vehicle and equipment levels is as follows:

Recreational ***(Segment)*** → *Motorcycles and ATVs* ***(Application)*** →
Four-wheeled ATVs ***(Product)*** → *2007, Gasoline, 75 hp, Four-wheeled ATVs* ***(Product Model)***

As noted in Table 4, below, the database includes population and fuel consumption estimates for off-road vehicles for MYs 1985 and earlier through 2010; however, the scope of the NRC-CSTT analysis only includes MYs 2006 through 2010, for the following reasons:

(1) It was important for the technology/strategy-to-application assessment (Section 6) that the vehicles and equipment identified would be representative of the models of off-road vehicles and equipment that would be available in the 2015 to 2020 timeframe (the projected regulation implementation timeline). For example, there is a low likelihood that a MY 1995 vehicle, in any given Application group, would be directly comparable to equipment released 20 years later, particularly in terms of engine and/or material design. Newer MY vehicles provide a better indication of future trends and applicability of fuel consumption reduction technologies; and

(2) This five-year scope captures approximately 24 percent of the total Canadian off-road engine population. All vehicle and equipment types were fully captured at the Segment level (six of six) and the Application level (74 of 74). At the Product level, approximately 94 percent (199 of 211) were captured. Given that the scope of the technology/strategy analysis is ultimately focused at the Application level, it was determined that disregarding the 12 unrepresented units at the Product level would not significantly impact the validity of the results. It should be noted that, for the

purpose of this analysis, off-road engine population data for each product/application was second in importance to fuel consumption. The relationship between population and fuel consumption is discussed in more detail in Section 4.2.1 and Section 4.2.3.

Table 4 provides a comparison of the original database scope and the narrowed scope used by NRC-CSTT, as well as a summary of the off-road engine database elements which were used in the analysis.

Table 4: Summary of Analysis Scope and Database Elements

Database Element	Details	Original Database Scope	NRC-CSTT Analysis Scope	Level of Capture in Analysis
Model Year	Approximate year of product manufacture and/or sale	1985* - 2010	2006 - 2010	5 of 23
Segment	*e.g. Construction*	6	6	100%
Application	*e.g. Off-Highway Truck*	74	74	100%
Product	*e.g. Rigid Haul Truck*	211	199	94%
Product Models	*e.g. 2006, Diesel, 2000 hp Rigid Haul Truck*	~ 74,000	~ 25,000	~ 33%
Off-Road Engine Population	Number of engines in Canada in CY 2010	~ 37.0 million	~ 8.7 million	~ 24%
Off-Road Fuel Consumption	Total Fuel Consumption in Canada in CY 2010 (L DEQ / year)	~ 23.17 billion	~ 6.32 billion	~ 27%
Fuel Type	Gasoline, Diesel, LPG, Natural Gas, Dual-Fuel, Multi-Fuel	6	6	100%
Engine Type	Spark Ignition, Compression Ignition	2	2	100%
Engine Stroke	Two-stroke, Four-stroke	2	2	100%
Engine Power Rating	Horsepower (hp)	0.8 - 8467	~ 0.8 - 8467	~ 100%

*1985 and earlier

4.2 Fuel Consumption Findings

The Environ/PSR database provides a CY 2010 snapshot of the estimated fuel consumption data for each Product Model, measured in litres of diesel equivalent (DEQ) per year; using DEQ allows for a direct comparison between vehicles and equipment with varied fuel types.

As shown in Table 4, the total off-road sector fuel consumption in Canada in CY 2010, as presented in the original database (MYs 1985 and earlier through 2010), was estimated at 23.17 billion litres of DEQ per year; MYs 2006 to 2010 capture approximately 27 percent (or 6.32 billion litres of DEQ per year) of this total off-road fuel consumption.

4.2.1 *Segment Analysis*

Figure 9 illustrates the breakdown of total fuel consumption by off-road Segment for MYs 2006 through 2010. The two top fuel-consumers include the Industrial Segment (e.g. forklifts, generators, etc.), which accounts for almost half of the total fuel consumption at 46 percent, and the Recreational Segment (e.g. ATVs, snowmobiles, etc.) at 28 percent. In terms of litres of DEQ per year, these two Segments consumed approximately 4.68 billion litres of fuel in CY 2010; this fuel is consumed by roughly 9,200 out of 25,000 Product Models types (37 percent).

When combined, Construction (e.g. excavators, bulldozers, etc.) and Agriculture (e.g. tractors, combines, etc.) account for another quarter of fuel consumption, at 15 and eight percent, respectively. The lowest fuel consumption Segments are Lawn and Garden and Marine Propulsion at two and one percent, respectively.

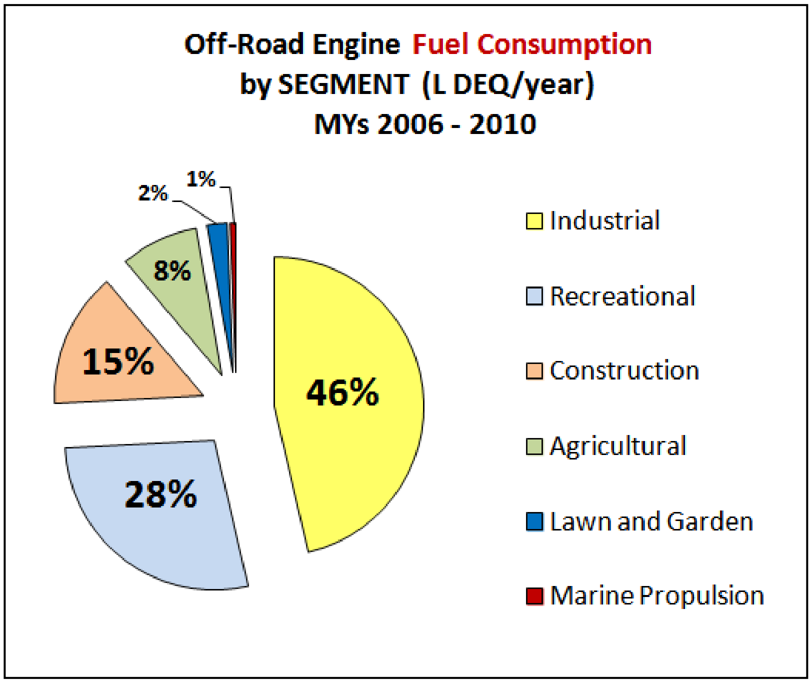

Figure 9: Off-Road Fuel Consumption by Segment for MYs 2006-2010

At the Segment, Application and Product levels, the off-road population data (i.e. number of units in use in Canada) is integral to the calculation of total fuel consumption. The fuel consumed by each individual Product Model is multiplied by the number of Product Model units to achieve Product Model fleet consumption; this fleet consumption can then be grouped and examined at the Product level (e.g. total rigid haul truck fuel consumption), Application level (e.g. total off-highway truck fuel consumption), or Segment level (e.g. total Construction fuel consumption, as in Figure 9). The majority of the analysis in this report is focused at the fleet level.

However, it is also possible to examine fuel consumption at the individual Product Model unit level (i.e. no consideration for number of units in the population); this helps to indentify vehicles and equipment with high unit (individual) fuel consumption. It also helps to examine fuel consumption in relation to other database elements, such as fuel type and engine horsepower.

4.2.2 *Fuel Type Analysis*

Table 5 presents off-road fuel consumption in terms of fuel type and engine horsepower, for MYs 2006 through 2010. As shown, approximately 98 percent of Products Models use either diesel fuel or gasoline, with diesel accounting for eight percent more than gasoline; the other fuel types (liquefied petroleum gas (LPG), natural gas, multi-fuel and dual-fuel) account for the remaining two percent.

Table 5: Fuel Consumption Analysis by Fuel Type and Horsepower, MYs 2006-2010

Fuel Type	Product Models (#)	Average Engine Power Rating (hp)	Total Fleet Fuel Consumption (L DEQ /yr)	Product Model Population (#)	Average Fuel Consumption per Unit (L DEQ /yr)
Diesel	13,395 **(53%)**	**193**	2,709,688,623 **(43%)**	445,218 **(5.1%)**	**8,993**
Gasoline	11,182 **(44%)**	**20**	3,101,138,175 **(49%)**	7,527,290 **(86.5%)**	**845**
Subtotal	24,577 **(97%)**	--	5,810,826,798 **(92%)**	7,972,508 **(91.6%)**	--
LPG	360 (1.4%)	72	197,536,697 (3%)	274,406 (3.2%)	3,957
Natural Gas	273 (1.0%)	323	283,108,030 (4.5%)	445,498 (5.1%)	4,444
Multi-Fuel	99 (~0.4%)	75	15,362,571 (0.3%)	5527 (~0.1%)	5,858
Dual-Fuel	1 (~0.004%)	8467	12,726,739 (0.2%)	43 (~0.0005%)	295,970
Total	25,310	--	6,319,560,838	8,697,982	--

In terms of total fleet fuel consumption, gasoline and diesel account for approximately 92 percent (or 5.8 billion litres of DEQ per year) of total fuel burn in the off-road sector, with gasoline burning six percent more than diesel.

However, in terms of Product Model unit population (e.g. number of *2007, Gasoline, 75 hp, four-wheeled ATVs in Canada in CY 2010),* the majority, 86.5 percent, are powered by gasoline; diesel and natural gas each account for approximately five percent, followed by LPG, multi-fuel and dual-fuel. This indicates that there are substantially more gasoline off-road engines in the Canadian population that are consuming less fuel compared to the low number of diesel units that are consuming high levels of fuel (both fuel types have relatively similar total fleet burn); this observation is directly linked to the relationship between average engine horsepower and the average fuel burn per Product Model unit.

The database analysis revealed that the average horsepower of diesel fuelled Product Model engines was nearly 10 times higher than that of gasoline engines (193 hp compared to 20 hp). Given that there is a strong correlation between engine power and fuel consumption, it is not surprising that the average fuel burn per unit is also roughly 10 times higher for diesel than gasoline (8,993 litres of DEQ per year compared to 845 litres of DEQ per year).

4.2.3 *High-Low 1% Analysis*

The high-low 1% analysis (outlined below) revealed similar findings as the fuel type analysis; however, the focus narrowed on specific Product Models, with a consideration for individual level fuel consumption. The results of this high-low analysis helped to assess key areas of consideration when identifying the top fuel-consuming Applications in the off-road sector.

Through a data sort at the individual fuel consumption level, the high-low 1% analysis first indentified the highest and the lowest individual Product Model consumers for MYs 2006 through 2010 (i.e. Product Models which burned the *most* amount of fuel per unit, and those which burned the *least* amount of fuel on a per unit basis). Subsequently, the fleet fuel consumption for each of the two groupings (high and low) were summed up from either the top down (for the high) or bottom up (for the low), until they reached a fleet fuel consumption total of one percent, relative to the total fleet fuel consumption; total fleet fuel consumption for the off-road sector for MYs 2006 through 2010 is estimated at 6.3 billion litres of DEQ per year, therefore, one percent is approximately 63 million litres of DEQ per year.

This exercise helped to isolate and analyze specific data elements that were unique for each of the two groupings (highest and least amount of fuel consumed per unit), given that the fuel consumption amount was held constant at one percent. These data elements included engine horsepower ranges, fuel type, Product Model/Product Model unit populations, and the corresponding Segment and Application.

The findings of this analysis are shown in Table 6.

Table 6: High-Low 1% Analysis Results, MYs 2006-2010

1%	Segment	Application	Product Models (#)	Product Model Population (#)	Fuel Type	Engine Power Rating (hp)
Highest Individual Fuel Consumption	Construction	Off-Highway Trucks	30	170	Diesel	2700 – 6115
	Industrial	Generator Sets	1	43	Dual-Fuel	8467
	2 (out of 6) **33%**	**2** (out of 74) **2.7%**	**31** (out of 25,310) **0.12%**	**213** (out of 8.7 million) **0.0025%**	**80% Diesel** 20% Dual-Fuel	Average: **3741 hp**
Lowest Individual Fuel Consumption	All	Various	**80.3%** Lawn and Garden	**98%** Lawn and Garden	3 of 6	Range: 0.8 – 14.5
	6 (out of 6) **100%**	53 (out of 74) **72%**	2,778 (out of 25,310) **11%**	2.8 million (out of 8.7 million) **32%**	**98% Gasoline** 1.6% Diesel 0.4% NG	Average: **3.7 hp**

The 1% top-down (high) analysis revealed that one percent of all off-road fuel consumption in Canada is consumed by a very small number of Product Models (31 out of 25,301, or 0.12 percent), which represents a very small portion of the entire Product Model population (213 out of 8,700,000, or 0.0025 percent). The majority of these Product Models were off-highway construction trucks; the remaining Products Models were large industrial generator sets.

Related directly to the findings of the fuel type analysis, these Product Models were fueled primarily by diesel, with a high average engine power rating of 3741 horsepower.

This small portion of Product Models accounts for a relatively large portion of total fuel consumption in Canada, and one would, upon first observation, target these Products Models as prime candidates for the implementation of fuel consumption reduction technologies and strategies. However, given the notably low populations and the likelihood of infrequent replacement (by the nature of their application), these unique Product Models would likely not be the best target for regulations related to fuel consumption technologies and strategies.

The 1% bottom-up (low) analysis revealed that one percent of total off-road fuel in Canada is consumed by a relatively large number of Product Models (2,778 out of 25,310, or 11 percent), which represents a relatively large portion of the entire Product Model population (2,800,000 out of 8,700,000, or 32 percent). Each of the six Segments is captured in this bottom-up population, and 53 out of 74 applications are represented; however, the majority (98 percent) are vehicles and equipment in the Lawn and Garden Segment (e.g. trimmers, lawn mowers, etc.). The average engine power rating for these Product Models is 3.7 horsepower, and in accordance with the fuel type analysis, a large portion (98 percent) is fueled by gasoline.

This analysis would suggest there are a relatively large number of low horsepower, low usage (seasonal) off-road engines, which, individually, consume relatively low amounts of fuel, but as a whole, consume one percent of the total off-road fuel in Canada. Similar to the 1% top-down analysis, it was concluded that targeting these low fuel consumers with regulated technologies and strategies may not be the most effective strategy.

4.2.4 *Application Analysis*

The key assessment method by which the top fuel consumers were identified was the Application analysis. Unlike the high-low analysis which focused on individual fuel consumption levels for specific Product Models, this method targets fleet fuel consumption at the Application level.

Given the ultimate goal of matching technologies with specific vehicles and equipment, it was determined that a Product Model level analysis (with approximately 25,000 models) was too narrow for the scope of this project. Similarly, if the fuel consumption was assessed at the Product level (with 199 products), the analysis would still be too narrow to match the scope. Hence, the final list of top fuel consumers was focused at the Application level (74 Applications); although, specific Products were subsequently identified within each of the top fuel-consuming Application categories for the purpose of the exercise in Section 6.

The 74 Applications in MYs 2006 through 2010 were sorted by fleet fuel consumption. Table 7 highlights the Top 10 fuel-consuming Applications (within a list of the top 25), and provides corresponding Product Model populations as well as minimum/maximum engine power ratings.

Table 7: Fuel Consumption Analysis by Application, MYs 2006-2010

	Segment	Application	CY 2010 Product Model Population (#)	Fleet Fuel Consumption (ML DEQ /year)	Min Power Rating (hp)	Max Power Rating (hp)
1	Recreational	Motorcycles and ATVs	518,864	**1,291**	1.0	140.0
2	Industrial	Generator Sets	743,312	**1,047**	5.4	8,467.2
3	Industrial	Pumps	3,121,047	**917**	1.3	599.4
4	Agricultural	Agriculture Tractors	77,638	**452**	11.8	800.0
5	Recreational	Snowmobiles	157,980	**331**	4.0	163.0
6	Industrial	Utility Vehicles	102,058	**265**	5.5	237.0
7	Construction	Off-Highway Trucks	2,774	**202**	130.0	6,115.0
8	Construction	Forestry Equipment	4,749	**150**	4.8	500.0
9	Construction	Excavators	17,310	**149**	4.8	2,500.0
10	Industrial	Forklifts	25,224	**133**	15.4	470.0
Subtotals: *(for MYs 2006-2010)*			**4,770,956** (of 8,697,982) **54%**	**4,937** (of 6,319) **77%**	Range: **1 – 8467 hp**	
11	*Recreational*	*Personal Watercraft*	*168,375*	***128***	*75.0*	*255.0*
12	*Construction*	*Wheel Loaders and Dozers*	*11,368*	***117***	*11.7*	*3,155.0*
13	*Industrial*	*Air Compressors*	*162,041*	***101***	*2.7*	*21.5*
14	*Construction*	*Graders*	*6,681*	***97***	*49.0*	*800.0*
15	*Industrial*	*Oil Field Equipment*	*1,816*	***89***	*20.1*	*2,250.2*
16	*Industrial*	*Irrigation Sets*	*14,956*	***88***	*5.4*	*199.8*
17	*Construction*	*Skid Steer Loaders*	*21,257*	***56***	*8.5*	*127.0*
18	*Agricultural*	*Other Ag Equipment*	*71,719*	***53***	*3.5*	*800.0*
19	*Construction*	*Tractor/Loader/Backhoes*	*7,877*	***49***	*8.5*	*275.0*
20	*Lawn and Garden*	*Lawn and Garden Tractors*	*155,494*	***48***	*9.0*	*100.0*
21	*Industrial*	*Welders*	*21,392*	***46***	*4.7*	*225.0*
22	*Industrial*	*Rough Terrain Forklifts*	*11,104*	***42***	*11.7*	*354.0*
23	*Construction*	*Crawler-Excavators*	*2,377*	***41***	*8.5*	*1,473.0*
24	*Industrial*	*Aerial Lifts*	*23,377*	***35***	*4.8*	*140.0*
25	*Marine Propulsion*	*Outboard Engines*	*70,915*	***25***	*2.0*	*755.0*
…	…	…	…	**…**	…	…
74	*Industrial*	*Other Equipment*	*6*	***0.004***	*4.7*	*60.0*

In selecting the top fuel-consuming Applications for the analysis, NRC-CSTT aimed to capture the following:

- A large portion of the total Product Model population and total off-road fuel consumption;
- Approximately 10 percent of all Applications (out of 74); and
- A wide range of engine sizes (low and high horsepower).

The Top 10 list of Applications presented in Table 7 satisfied this aim, capturing 54 percent of the total Product Model population, 77 percent of the fuel consumption, 13 percent of all Applications, and the full engine power range in the database.

For Applications 11 through 25, the fuel consumption values decrease at a faster rate; these 15 Applications represent 13 percent of the total fuel consumption, which is minimal compared to the Top 10 at 77 percent. In addition, the population-engine power relationship (as explained in Section 4.2.3) begins to be more apparent in Applications 11 through 25. The instances of higher populations matched with lower power ratings (e.g. Lawn and Garden), and those of higher horsepower engines corresponding to lower populations (e.g. Construction trucks) are more prevalent in Applications beyond the Top 10. As discussed in Section 4.2.3, these Application (and Product) types are not conducive to off-road engine regulations and, thus have not been included in the Section 6 analysis. Conversely, the Top 10 Applications provide a good balance of population, fuel consumption, and power rating, and are prime candidates for further analysis.

Table 8 provides a summary of the database elements that were captured in the Top 10 fuel-consuming Applications, in relation to the NRC-CSTT analysis scope (originally presented in Table 4).

Table 8: Level of Database Capture for Top 10 Fuel-Consuming Applications

Database Element	Original Database Scope	NRC-CSTT Analysis Scope	Level of Capture in Analysis	Level of Capture for Top Fuel Consumers (Top 10 Applications)		Details
Model Year	1985* - 2010	2006 - 2010	5 of 23	5 of 5	Full coverage	MY population coverage by Product Model (% of total): MY 2010 – 1361 (19.3%) MY 2009 – 1341 (18.9%) MY 2008 – 1450 (20.4%) MY 2007 – 1479 (20.8%) MY 2006 – 1465 (20.6%) Total – 7096 (100.0%)
Segment	6	6	100%	4	No Lawn and Garden No Marine Propulsion	Fuel consumption by Segment (Top 10 vs. Total[11], %): **Industrial – 48%** (vs. 46%) **Recreational – 33%** (vs. 28%) Construction – 10% (vs. 15%) Agricultural – 9% (vs. 8%)
Application	74	74	100%	10	**13%** of NRC-CSTT scope	Table 7
Product	211	199	94%	37[12]	**19%** of NRC-CSTT scope	Appendix A, Table A1
Product Models	~ 74,000	~ 25,000	~ 33%	7096	**28%** of NRC-CSTT scope	(In database)
Off-Road Engine Population	~ 37.0 million	~ 8.7 million	~ 24%	~ 4.7 million	**54%** of NRC-CSTT scope	Table 7
Off-Road Fuel Consumption (L DEQ/yr)	~ 23.17 billion	~ 6.32 billion	~ 27%	~ 4.9 billion	**77%** of NRC-CSTT scope	Table 7
Fuel Type	6	6	100%	6	Full coverage	Fuel Type for Products in Top 10 Applications (% of total): **Diesel – 28 (47%)** **Gasoline – 17 (28%)** LPG – 8 Natural Gas – 6 Multi-Fuel – 1 Total – 60[11]

[11] See Figure 9

[12] Sorting/grouping by database element: 37 products with full grouping; 60 products with fuel type sort; 72 products with fuel and engine type/stroke sort

Database Element	Original Database Scope	NRC-CSTT Analysis Scope	Level of Capture in Analysis	Level of Capture for Top Fuel Consumers (Top 10 Applications)		Details
Engine Type	2	2	100%	2	Full coverage	Engine Type for Products in Top 10 Applications (% of total): Spark – 40 (55%) Compression – 32 (45%) Total – 72[11]
Engine Stroke	2	2	100%	2	Full coverage	Engine Stroke for Products in Top 10 Applications (% of total): **Four-stroke – 61 (85%)** Two-stroke – 11 (15%) Total – 72[11]
Engine Power Rating	0.8 - 8467	~ 1 - 8467	~ 100%	1 - 8467	Full coverage	Engine Power Rating for Top 10 Applications: Average: **296 hp**

*1985 and earlier

The Top 10 Applications captured Product Models in all five model years, with approximately equal representation in each year. In terms of Segments, four out of six were captured; Lawn and Garden and Marine Propulsion, which together represent three percent of total fuel consumption, were not included. The relative contribution of fuel consumption by each Segment was fairly consistent between the NRC-CSTT scope (Figure 9) and the Top 10 analysis; the range of variance was between two and five percent. Therefore, it can be concluded that the level of capture in the Top 10 Applications in the NRC-CSTT review is a good approximation of the total fleet fuel consumption for MYs 2006 through 2010.

The various vehicle and equipment levels were relatively well-represented in the Top 10 Applications (in comparison to the NRC-CSTT scope); 13 percent of all Applications, 19 percent of all Products, and 28 percent of all Product Models were captured. These population representations may seem low at first glance; however, it is important to remember that the focus of this review is primarily on fuel consumption, and not all vehicle and equipment fleets consume the same amount of fuel. The Top 10 Applications capture over three-quarters of the total fleet fuel consumption and over 50 percent of the off-road engine population.

Within the NRC-CSTT analysis scope, all fuel types, engine types, engine stroke and power rating ranges were captured in the Top 10 fuel-consuming Applications. Three-quarters of the Product Models use gasoline or diesel fuel (47 percent and 28 percent, respectively), and the average engine power rating was roughly 300 horsepower. In terms of engine type, spark ignition and compression ignition are approximately equal in use (55 percent and 45 percent, respectively), and the majority (85 percent) are four-stroke engines.

As shown in Table 9, the Top 10 Applications can be subdivided into 37 Products. These Products, which vary in use, type and size, even within their respective Application levels, will be considered in the assessment of applicable technologies and strategies for reducing fuel consumption in the off-road sector, as presented in Section 6.

Table 9: Product Types within Top 10 Applications

Industrial **48%** Fuel Consumption 14 Products	**Recreational** **33%** Fuel Consumption 6 Products	**Construction** **10%** Fuel Consumption 13 Products	**Agricultural** **9%** Fuel Consumption 4 Products
Generator Sets Auxiliary Power Units Industrial Portable Residential Trailer Mounted Recreational Vehicle	**Motorcycle and ATV** Three-wheelers/Four-wheelers Four-wheel ATVs Off-Road Motorcycles Other Recreational Products Scooters/Mini-bikes/Mopeds	**Off-Highway Trucks** Articulated Rigid Haul	**Agriculture Tractor** Two-wheel Drive Four-wheel Drive Mechanical Front Wheel Drive Tracked Agriculture
Pumps Concrete Pumps Fire Pumps General Industrial Pumps Industrial Sprayers	**Snowmobiles** Snowmobiles	**Forestry Equipment** Feller Bunchers Forwarders Log Loaders Log Loaders (Trailer Mounted) Other Forestry Equipment (Stationary/Self-propelled) Skidders Tree Harvesters	
Utility Vehicles Commercial Turf Utility Industrial Utility Personnel Carriers		**Excavators** Crawler-Excavators Mini Excavators Wheeled Excavators	
Forklifts Forklifts			

5 TECHNOLOGY/STRATEGY ANALYSIS

The results of the technology literature review are presented in Section 5.1 through Section 5.9.

The intent of this project was to review and quantify the fuel consumption reduction potential of various technologies and strategies for the off-road sector. To that end, the way in which specific technologies/strategies could be matched to specific Applications/Products was examined; suitable pairings were identified and analysed, while technology/Application pairings that were deemed unsuitable were excluded from further analysis. However, this approach did not consider the net effects of combining two or more technologies onto one Application (further study is warranted for such an analysis).

Many of the technologies that are presented in this report could likely be combined together to provide even greater fuel consumption reductions; however, testing of each of these combinations would be required to determine the net effect of combining technologies. It is possible that some combinations could be complementary and result in an additive fuel consumption reduction, whereas other combinations could conflict with one another, thus resulting in an overall fuel consumption reduction that is less than the sum of the individual reductions. A detailed study of how operators use the equipment would be required to determine the best strategies and technologies to implement for a particular Application.

Many of the technologies cannot be implemented to their fullest capabilities without the use of other complimentary technologies. For example, VVT coupled with adaptive fuel delivery/ignition timing maps requires the use of intelligent electronic controls. Also, energy recovery and reuse with a hybrid-electrification design may require the combination of advanced transmission technologies and intelligent electronic controls. The combination of technologies will be application specific. As well, there are technologies which can be applied to other technologies, with overlapping benefits; for example, friction management can be applied to bring about improvements in engine and transmission systems, as well as reduce losses in parasitic accessories.

As well, this report does not summarize all the details relating to every aspect of the technologies used in the design, manufacturing, and operation of any complex machine, or sub-system, such as an engine or transmission. The key aspects of a technology group will be discussed and summarized, and the broad applications of these technologies will be the focus of the results.

All of the technologies outlined in Sections 5.1 through Section 5.8 must be designed, implemented, and installed by the OEMs rather than the end-user. However, the way in which the end-user operates a piece of equipment will affect the overall fuel consumption of the equipment. In other words, the effects of a fuel saving technology could be negated by an operator who does not use the product sensibly.

The Environ/PSR database contained many applications, products, and product models. A complete technology-to-inventory analysis for each off-road vehicle/equipment category level was not performed; however, the Top 10 Applications (Table 7), and/or 37 Product Types (Table 9/ Appendix A), were analyzed in this section, as well as in Section 6.

The future application of these technologies is not a certainty. The recommended pairings of the technologies to specific Applications/Products in this section was based on the broad technical knowledge of the authors regarding powertrain systems and mobility systems applications. In cases where a reference was found that indicated that a technology was/is being investigated for a particular application, this reference was included. In many cases, the use of a technology in on-road applications has been used as an indication of the potential use in an off-road application for a similar product. However, as the off-road class of equipment is very broad in scope, there are many off-road vehicles and equipment for which there is no comparable on-road vehicle. In these cases, the technical understanding of the systems and the applications was used to determine a match of Application/Product to technology.

Table 10: Summary of Technologies/Strategies for Fuel Consumption Reduction in the Off-Road Sector

Section	Technology/ Strategy	Overview
5.1	**Engine**	Engine systems and architecture to improve energy conversion efficiency
5.2	**Transmission**	Optimize engine operating speed, reduce losses
5.3	**Electrification/Hybridization**	Hybrid drivetrain, energy recovery, grid electric
5.4	**Friction Control**	Advanced bearings, materials, friction modifiers, synthetic lubricants,
5.5	**Parasitic Loss Reduction**	Reduce excess power loss due to accessories through the use of various strategies
5.6	**Anti-Idle**	Engine stop-start; engine-off technologies
5.7	**Intelligent Controls**	Sensors, on-board computers, actuators/electronic controls are used to optimize vehicle/equipment operation
5.8	**Lightweighting and Other**	Lightweighting; rolling resistance reduction; aerodynamic drag reduction; maintenance practices; solar technologies
5.9	**Human Factors**	Driver training; on-board devices and tracking

In assessing the various technologies and strategies which offer fuel consumption reduction potential for the off-road sector, it is important to consider related implementation factors. Table 11 provides a list of implementation factors (as presented earlier in Section 3, Table 2), as well as a brief description for each as they relate to this report. Using Table 11 as a guide, an implementation factor analysis was carried out for each of the various technology/strategy categories listed in Table 10, in each of their respective sections.

Table 11: Summary of Implementation Factors

Implementation Factor	Description
Cost	Estimate of development, capital, and operating costs
Timeframe	Estimate of time before technology is available for implementation: currently available; near-term; long term; research only
Availability	Location of market presence: Canada (OEM or dealer), worldwide, etc.
Reliability, scalability, durability, and safety	Does/can the technology: change reliability; be scaled for mass production; compromise durability; affect end-user safety
Support and maintenance	Does the technology: require specialized support; reduce or increase maintenance requirements
Barriers to consumer acceptance	Will the technology affect consumer purchases
Weight, volume increases; power requirements	Does the technology significantly increase, or decrease the weight or volume of the equipment; will the power requirement still be met
Effect on (other) emissions	Does the technology contribute to the production or reduction of other (regulated) emissions
Co-benefits	What other benefits may exist, not covered by the above factors

5.1 Engine

5.1.1 *Overview*

The off-road vehicles and equipment examined in this review had a vast engine power output range of 1 hp to 8467 hp. The expansiveness of this power range is especially apparent when compared to typical on-road passenger car engines, with a 100 hp to 500 hp range, or on-road heavy haul truck engines with a 300 hp to 600 hp range. As well, while the ICEs used in on-road applications are very similar in type and design for each class, with passenger cars typically using SI-ICEs, and trucks typically using CI-ICEs, off-road engines have vastly different power outputs, displacements, and uses depending on the application or industry. The result is a large variety of engine types and designs that are found in off-road applications. This represents a challenge in terms of broadly highlighting potential technologies/strategies that can be applied to off-road engine applications.

In general, to reduce fuel use, an engine technology/strategy must make the engine more efficient, or help the engine be operated in a more efficient manner, or both. Very broadly, engine technologies/strategies can be implemented in two ways:

(1) at the system level for existing engine designs; or
(2) through a change in engine type, design, or operation.

System level improvements can be made to specific areas of an engine. These improvements generally do not alter the fundamental construction or design of an engine, but improve the sub-system performance; when applied together, the overall engine fuel efficiency is improved.

These sub-systems are often interrelated, such that changes to one area may require design changes to another system.

A change to the fundamental design of an engine requires an OEM to make more drastic modifications to vehicles/ equipment in order to reduce fuel consumption. An example of such a change would be a switch from a SI engine to a CI engine, or from a two-stroke to a four-stroke design. An even more drastic change would be from a traditional piston engine design to a radically different design, such as opposed cylinder, or five- or six-stroke system.

Table 12 summarizes the classes of engine technologies/strategies identified by the literature which, if implemented in off-road applications to existing engine designs, may reduce fuel consumption. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 12: Engine Technologies/Strategies

Technology/Strategy	Options
Two-Stroke versus Four-Stroke	▪ Change from two- to four-stroke ▪ Advanced clean burn (direct injection) two-stroke ▪ Advanced two/four- stroke combination
Diesel versus Gasoline	▪ Change from gasoline to diesel
Advanced Combustion Methods	▪ Homogenous Charge Compression Ignition (HCCI) ▪ Variable Compression Ratio (VCR) ▪ Variable charge motion
Engine Downsizing; Engine Displacement Control	▪ Turbo-charging with intercooling ▪ Turbo-compounding (mechanical and electrical; exhaust energy recovery) ▪ Cylinder deactivation
Advanced ICE Design	▪ Opposed cylinder design ▪ Five-, six-stroke system
Fuel Delivery Systems; Injection Technologies	▪ Gasoline direct injection – stoichiometric ▪ Gasoline direct injection – lean burn stratified ▪ Advanced high speed diesel direct injection
Intake and Exhaust Systems	▪ Variable Valve Timing (VVT), cam phasing (e.g. intake, exhaust, dual, etc.) ▪ Variable Valve Lift (VVL) – discrete; continuous ▪ Camless valve train – electromagnetic; electrohydraulic
Advanced Ignition Technologies	▪ Advanced ignition control system ▪ Plasma; laser ignition (future)

In the following sections, each of these technologies will be briefly discussed, with a focus on the specific applications to off-road usage, their implementation in off-road applications, and the factors that may weigh-in on the decision to implement a particular technology/strategy.

5.1.2 ***Applications***

Two-Stroke versus Four-Stroke

Motorcycles, ATVs, snowmobiles, pumps and generators commonly use either two- or four-stroke engines. For example, in the Environ/PSR database, snowmobiles are split 58 percent two-stroke to 42 percent four-stroke for the CY 2010 data. Fuel savings may come about with the replacement of old-technology two-stroke designs with advanced clean burn (low emissions) direct injection two-stroke engines, or with four-stroke designs. An engine of this type could be implemented in applications such as snowmobiles, industrial pumps, and small generator sets. In addition, new experimental technologies are combining two- and four-stroke cycles to optimize fuel consumption at low and high engine speeds.

Diesel versus Gasoline

For off-road equipment the selection of an SI (gasoline) or a CI (diesel) engine is partly dependent on the operating conditions. The increased weight and cost of diesel engines favours installation in heavier, higher capital cost equipment. For example, diesel engines are currently in use in portable generators, pumps, agriculture tractors, and off-highway trucks. In contrast, gasoline engines are less complex and less expensive to build than a diesel engine, favouring low cost, low powered applications such as motorcycles, ATVs, pumps, and generators. Currently the majority of low powered engines identified in the Environ/PSR database are gasoline fuelled. Future fuel savings may result with the replacement of a significant number of these engines with advanced gasoline designs, or diesel engines.

Advanced Combustion Methods

Advanced combustion technologies can be applied to all ICEs, however, the majority of these technologies are still in the research stage. As emerging technologies, they will most likely find future applications in high capital cost, high fuel use applications, such as large off-highway trucks or agricultural equipment, where yearly fuel savings may be significant enough to justify the additional cost. Advanced combustion technologies include HCCI, variable compression ratio (VCR), and variable charge motion.

Engine Downsizing; Engine Displacement Control

Downsizing and engine displacement control are most relevant in applications where the engine duty cycle includes significant time at partial or low power use, such as forestry equipment, forklifts, ATVs, and motorcycles. Applications where full or near-full power is needed for a significant portion of the duty cycle, such as pumps, generators, or tractors, would not be good candidates for engine downsizing.

Advanced ICE Designs

Advanced ICE designs can be applied to most off-road engine applications; however, these technologies are still in the research stage. As emerging technologies, they will most likely find future applications in high capital cost, high fuel use applications, such as large off-highway trucks or agricultural equipment, where the yearly fuel savings may be significant enough to justify the additional cost.

Fuel Delivery Systems

Current low power gasoline engines, as used in motorcycles, small pumps, or generators often use carburetor technology for fuel delivery. Changing from carburetors to a fuel injection delivery system has a high potential to reduce fuel consumption. Fuel injection systems are already in use in large gasoline and diesel engines, such as those found in agricultural tractors, off-highway trucks, or excavators. To decrease fuel consumption for large engines, advanced fuel injection systems could be installed.

Intake and Exhaust System

Active valve systems, such as VVT or VVL, are most applicable where the engine speed range varies and where low engine speed is frequently used. Examples of applications that may benefit from these advanced intake systems are forestry equipment, forklifts, ATVs, and motorcycles.

Ignition Technology

Advanced ignition technologies can be applied to all ICEs; however, these technologies are still in the research stage. As emerging technologies, they will most likely find future applications coupled with advanced combustion technologies (i.e. lean burn, HCCI) in high capital cost, high fuel use applications, such as in large gasoline powered off-highway trucks or agricultural equipment, where the yearly fuel savings may be significant enough to justify the additional cost. When the technologies are mature, lower powered, lower cost gasoline engines may benefit, such as those used in snowmobiles, ATVs, pumps, and generators.

Energy Recovery

Exhaust energy recovery through turbo-compounding is also in active development; however, there is much less activity in terms of commercial product offerings. Several prototypes have been demonstrated [12][14] with substantial increases in power and/or fuel efficiency, and at least one engine OEM has a commercial product currently available [13].

5.1.3 *Implementation Factors*

In general, improved engine technologies/strategies will be implemented at the engine OEM level, and offered to the manufacturers of off-road vehicles and equipment as part of a complete engine package for installation in the final product. Some off-road equipment manufacturers design and build their own engines, and may be capable of incorporating sub-systems, such as fuel injection that are offered by sub-suppliers, into their engine designs.

The factors influencing the implementation of engine technologies/strategies can be grouped into two major categories:

- Engine sub-systems: technologies which can individually be applied to existing engine designs; and
- Whole engine systems: technologies which require a complete engine redesign.

In reference to Table 12, engine sub-system implementation includes the following technologies and strategies; fuel delivery system, intake and exhaust systems, and ignition technologies. These sub-system technologies can be implemented on current engine designs as incremental improvements to the existing systems. For example, VVT or VVL technologies can be implemented with changes to the cylinder head design, and tuned intake and exhaust systems can be implemented with no changes to the core engine structure and may be installed by the end user. As expected, when multiple systems are utilized and optimized to work together, the aggregate results may exceed the results seen individually.

In reference to Table 12, whole engine implementation includes the following technologies and strategies; two-stroke and four-stroke engines, diesel or gasoline engines, advanced combustion methods, engine downsizing, engine displacement control, and advanced ICE designs. The changes needed to implement these technologies/strategies all require a complete change in engine design.

As well, these technologies are inter-related; for example, it may be possible to reduce fuel consumption by replacing an existing large displacement, normally aspirated four-stroke gasoline engine with a two-stroke turbo-charged (downsized) diesel engine, which incorporates advanced combustion and fuel delivery technologies. These complex changes will require the engine supplier to invest considerable effort into research and development. For the off-road equipment OEM, implementing new engine designs as they become available will require a redesign of the product to fit the new engine.

Advanced ICE designs are technologies currently in their infancy, in the research stage, and would be offered by engine OEMs following significant market and economic feasibility analyses.

Table 13 provides a summary of various implementation factors with regards to engine technologies and strategies.

Table 13: Implementation Factors for Engine Technologies/Strategies

Implementation Factor	**Sub-systems Technologies** (fuel delivery system, intake and exhaust systems, ignition technologies)	**Whole Engine Technologies** (two- and four-stroke engines, diesel or gasoline engines, advanced combustion methods, engine downsizing, engine displacement control, advanced ICE designs)
Cost	Low to medium, application dependent	High, application dependent
Timeframe	Immediate to near-term; COTS, but customized to each application	Near-term; COTS, but customized to each application
Availability	Canada and worldwide	Canada and worldwide
Reliability, scalability, durability, and safety	All technologies are relatively mature in on-road applications	Some technologies reaching maturity in on-road applications
Support and maintenance	High level of support for mature technologies	High level of support for mature technologies
Barriers to consumer acceptance	Concerns about reliability with increased complexity	Concerns about reliability with increased complexity; Ease-of-maintenance concerns; Concerns with vibration, noise, and harshness

Implementation Factor	Sub-systems Technologies (fuel delivery system, intake and exhaust systems, ignition technologies)	Whole Engine Technologies (two- and four-stroke engines, diesel or gasoline engines, advanced combustion methods, engine downsizing, engine displacement control, advanced ICE designs)
Weight, volume increases; power requirements	Increased complexity; Packaging volume increase	Increased complexity; Switch to diesel may increase weight and volume Switch to four-stroke from two-stroke may increase weight and volume
Effect on (other) emissions	Potential decrease	Potential decrease Switch to diesel will alter emissions profile Switch to advanced two-stroke from four-stroke may increase emissions
Co-benefits	Increase in power	Decreased engine weight; Increase in power

COTS – Commercial-off-the-shelf

5.2 Transmission

5.2.1 *Overview*

Many of the off-road Applications indentified as significant fuel consumers are self-propelled, and will use a transmission of some type to transfer power from the engine to the drive wheels. As outlined in the Theory section above (Section 2), a transmission serves as an intermediary between the engine and the drive wheels, matching the desired vehicle speed with an appropriate engine speed.

Table 14 summarizes the transmission technologies and strategies identified by the literature review that, if implemented in off-road applications to existing equipment designs, may reduce fuel consumption. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 14: Transmission Technologies/Strategies

Technology/Strategy	Options
Advanced Transmission Systems	▪ Continuously Variable Transmission (CVT) ▪ Automated Manual Transmission (AMT) – single; dual-clutch ▪ Hybrid transmissions (ICE-electric and ICE-hydraulic)
Shift Strategies	▪ Automatic transmission – five- to eight-speed ▪ Shift logic ▪ Early torque lock-up

Advanced transmission systems have the potential to decrease fuel consumption in two ways:

(1) by allowing the engine to operate at, or near, the speed of maximum efficiency; and
(2) by minimizing the time required to change from one gear ratio into another, which preserves momentum and minimizes energy loss between shifts.

Computer-controlled shift strategies coupled with existing transmission designs or with advanced designs, would control the engine-transmission system in a manner that minimizes fuel use. The shift strategies will be highly dependent on the vehicle or equipment type, the loading, and the operating conditions.

5.2.2 *Applications*

Advanced Transmission Systems

Some recreational off-road applications, such as snowmobiles and some ATVs, currently use rubber belt type CVTs as their primary transmission type, often using purely mechanical control systems. The introduction of electronic controlled CVTs to these products may reduce fuel consumption. Motorcycles and ATVs typically use manual shift transmissions: a change to advanced dual-clutch manual transmissions (DCMT), or to AMTs may reduce fuel consumption in these products. Some ATV and motorcycle products may see fuel consumption improvements with a change to a CVT design.

Heavy vehicles, such as agricultural tractors or off-highway trucks, which currently use manual transmissions or automatic transmissions with torque converters may benefit from the change to an advanced transmission system, such as AMTs or DCMTs. Lower powered agricultural tractors may see improved fuel use with a change to CVTs, AMTs, or DCMTs. An example is the recently announced Dana HVT R3 hydraulic CVT, which was designed for front-end loaders, graders, forestry skidders, and other off-highway applications requiring up to 265 kW (360 hp). Tests on front-end loaders with the system demonstrate fuel savings in the drivetrain of more than 20% when compared with the same vehicle outfitted with a conventional torque converter transmission [44][45].

Large off-road equipment has also become available with ICE-electric transmission systems (see Section 2.2.2) in place of manual or automatic transmissions. Currently available using this technology are rigid haul trucks made by Komatsu [33], Liebherr [28], and Terex [27], large bucket loaders manufactured by LeTourneau [30] and bulldozers from Caterpillar [46]. The use of a hybrid ICE-electric drive system brings these manufacturers one step closer to offering a fully hybrid product with energy recovery and storage utilizing batteries, capacitors, or flywheels as part of the drive-train system.

Shift Strategies

All off-road vehicles with the capability for automatic shifting can benefit from some type of shift strategy optimization, if not already incorporated in the designs. As advanced transmission designs are implemented into more products, the opportunities for incorporating shift strategies to minimize fuel use will broaden. However, the decrease in fuel consumption obtained with using advanced transmission systems incorporating optimized shift strategies will be highly application specific. Applications where vehicle speeds vary from low to high frequently throughout the operation cycle will benefit the most. Examples of products which may benefit the most from optimized shift strategies are ATVs, motorcycles, off-highway trucks, and agricultural applications.

However, even the existing torque converter automatic transmissions can benefit from improved shift strategies. For example, for light to moderate loads (e.g. unloaded or light and level driving), shifting gears earlier and locking the torque converter at a lower engine speed can provide noticeable fuel consumption reductions. In applications currently using torque converter automatic transmissions, such as some agricultural tractors, this shift strategy may produce fuel consumption improvements.

5.2.3 *Implementation Factors*

In general, improved transmission technologies will be implemented at the transmission manufacturer level, and offered to the manufacturers of off-road vehicles and equipment as part of a complete transmission package to be installed in the final product. For applications currently employing torque converter automatic transmissions, optimized shift strategies may be implemented by the off-road equipment OEM through changes in the transmission shift control system.

Table 15 provides a summary of various implementation factors with regards to transmission technologies and strategies.

Table 15: Implementation Factors for Transmission Technologies/Strategies

Implementation Factor	Advanced Transmissions	Shift Strategies
Cost	Moderate to high	Low
Timeframe	Near-term	Immediate to near-term
Availability	Canada and worldwide	Canada and worldwide
Reliability, scalability, durability, and safety	Proven in on-road cars; Unknown in high torque applications	n/a
Support and maintenance	Mechanically complex; ICE-electric systems are less complex	n/a
Barriers to consumer acceptance	Reliability and increased cost concerns; Reduced user maintainability	Possible user concerns about shifting at lower than expected engine speeds
Weight, volume increases; power requirements	CVTs: Limitations on input power; All: changes in volume envelope requiring vehicle design changes	May require additional electronic sensors and controls
Effect on (other) emissions	Possible reductions	Possible reductions
Co-benefits	Improved operator comfort; Lower engine stress; Longer drivetrain life	Improved operator comfort; Lower engine stress; Longer drivetrain life

5.3 Electrification/Hybridization

5.3.1 *Overview*

Electrification and hybridization covers a vast range of possible vehicle and equipment configurations. Electrification refers to the replacement of the ICE with an electric motor, essentially moving the generation of emissions to the electrical source location. In general, hybridization can refer to the replacement of a fully mechanical power system, which does not recover energy, with a system that does (or has the potential to) in some manner. Off-road vehicles and equipment are well-suited to take advantage of these technologies due to the variety of tasks they perform. For example, off-road vehicles often transport heavy cargo loads, and self-propelled or mobile off-road equipment often perform energy intensive work functions when stationary. Due to the large variety of off-road equipment and vehicles, the possibilities for incorporating energy recovery technologies/strategies are also very broad.

Vehicles or equipment using hybrid or electric technologies have the possibility for energy recovery, storage, and reuse. Unlike on-road vehicles, many types of off-road equipment consume large amounts of fuel when performing working tasks while stationary. For example, the motion of an excavator when digging requires energy to lift and swing the load: the energy required to perform these motions could be recovered when the load is dropped or the swinging motion is stopped. Recovering a portion of the energy from performing these tasks has the potential to save considerable amounts of fuel.

In any of these systems, energy storage, if used, is typically achieved electrically with a battery or capacitor; however flywheels, fluid pressure, and gas compression can also be used to store energy.

Table 16 summarizes the electrification/hybridization technologies and strategies identified by the literature that, if implemented in off-road applications, may improve fuel usage. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 16: Electrification/Hybridization Technologies/Strategies

Technology/Strategy	Options
Electrification	▪ Shore power – catenary powered vehicles; plug-in mobile equipment ▪ Battery electric – vehicle (BEV); equipment ▪ Fuel cell electric – vehicle (FCEV); equipment
Hybridization	▪ Series hybrid electric ▪ Parallel hybrid electric ▪ Hydraulic/flywheel hybrid

5.3.2 *Applications*

Electrification

Converting to a fully electric power delivery system is highly dependent on the vehicle/equipment, and the electrical power source. Low power products may be able to convert to battery power; these include forklifts, smaller light-duty agricultural equipment, ATVs, snowmobiles, and scooters. For recreational vehicles, the Zero Motorcycle company manufactures battery electric off-road motorcycles [47]. Several other products such as ATVs and scooters are also in production or have been demonstrated as concepts. For the agriculture segment, New Holland has begun production of a hydrogen fuel cell powered agricultural tractor [35].

Tethered grid electric equipment is suitable for equipment that operates in a fixed location, or that only moves within a relatively small area. Shore/catenary power can apply to: rigid haul mining trucks, or where the vehicles travel over a fixed route; some excavating equipment; pumps; and industrial sprayers. Examples of existing tethered grid electric power applications include airport baggage/fixed gate support equipment, and gravel pit operations and equipment [48].

Hybridization

Almost any vehicle with a duty cycle that varies between low to maximum power is suitable for hybridization. For example, rigid haul trucks may benefit from a hybrid power train with energy storage as a result of the difference between the fully loaded vehicle weight and the empty vehicle weight; this scenario guarantees that in some applications, half of the duty cycle is at a lower power setting. In addition, applications where the vehicle repeatedly climbs and descends, such as in mining or forestry applications could make use of energy recovery techniques on the descending stages of the operations.

For high-cycle start/stop energy recovery, current development for off-road applications focuses on energy recovery for specific movements. Examples include excavator turntable slewing and boom lowering. There is currently active development in this area by a variety of equipment suppliers, and several OEMs have launched commercial products using energy recovery in some form in the past few years [32][49][50][51][53].

Where energy recovery would occur at a rate faster than battery technology can absorb, capacitors can be used. Komatsu is using capacitors for energy recovery for a hybrid crawler-excavator [32]. Capacitors are also being used in an electric-hybrid forklift for energy storage (Komatsu) [52] as well as in a prototype triple hybrid forklift (Proton) that uses a fuel cell, a battery, and super-capacitors [54][55]. OEM supplier Dana is also developing a parallel hybrid drive system specifically designed for off-highway vehicles [56]. Hybrid technology (ICE-electric with energy storage) is also currently available in forklifts manufactured by Toyota [57][58][59][60] and Mitsubishi Heavy Industries [61].

5.3.3 *Implementation Factors*

Table 17 provides a summary of various implementation factors with regards to electrification/hybridization technologies and strategies.

Table 17: Implementation Factors for Electrification/Hybridization Technologies/Strategies

Implementation Factor	Battery/Fuel Cell Electrification	Shore Power Electrification	Hybridization
Cost	Moderate to high	Low to moderate	Moderate to high
Timeframe	Near-term	Near-term	Near-term
Availability	Canada and worldwide	Canada and worldwide	Canada and worldwide
Reliability, scalability, durability, and safety	High durability; electrical safety concerns	High durability; electrical safety concerns	High durability; electrical safety concerns
Support and maintenance	Lower maintenance, but special training and tools required	Lower maintenance	Similar maintenance schedule, but special training and tools required
Barriers to consumer acceptance	Fear of battery run-down	Reliance on external power source	Complexity
Weight, volume increases; power requirements	Moderate weight; Volume increase	Lower weight; Lower volume	Moderate weight; Volume increase
Effect on (other) emissions	No, or lower emissions (fuel cell)	No on-site emissions	Lower emissions
Co-benefits	No on-site emissions (battery)	Lower mass; No on-site emissions	Easily adapted to shore power for anti-idle benefits

5.4 Friction Control

5.4.1 *Overview*

Friction reduction technologies and strategies have been separated into two main sections for this report:

(1) Lubrication; and
(2) Contact friction reduction.

Lubrication technologies/strategies are concerned with the use of new or advanced lubricants to reduce energy loss in a machine. Contact friction reduction technologies are concerned with reducing the friction levels that exist between two moving surfaces that are in contact, regardless of whether there is a lubricant present or not. Both of these technologies/strategies can be applied throughout any system of the off-road equipment.

Table 18 summarizes the friction technologies/strategies identified by the literature that, if implemented in off-road applications, may improve fuel usage. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 18: Friction Control Technologies/Strategies

Technology/Strategy	Details
Lubrication	▪ Low-viscosity ▪ Synthetics
Contact Friction Reduction	▪ Roller bearings ▪ Roller followers (camshafts) ▪ Lower spring tension (valve springs) ▪ Piston/cylinder coatings (engines, hydraulics) ▪ Surface treatments (surface control, coatings) ▪ Ring: profile, tension, and number (engines) ▪ Seals: materials, geometry, number, tension ▪ Component weight reduction

5.4.2 *Applications*

These technologies are, for the most part, widely applied in all sectors of the off-road industry. However, there are some specific examples where improvements in fuel use could be realized with the increased application of these technologies/strategies.

Lubrication

The industrial off-road environment is very demanding of lubrication performance as applied to the ICE, the powertrain, and throughout the vehicle or equipment as a whole. In hopes of achieving longer engine life, and reducing oil burning/blow-through, fleet managers often choose higher viscosity oils and thicker greases for their off-road equipment. A reduction in ICE engine friction can result from lower viscosity lubricants, but the engine design must be able to accept these reductions. Engine cooling systems must be able to maintain constant temperatures, and an oil cooling system may be necessary. The use of synthetic lubricants can result in some benefits, especially at start-up in cold climates, such as in Canada.

Contact Friction Reduction

Areas where improvements can be made in contact friction are mostly incremental in nature, changing from a simpler technology to a more complex one. Examples include: replacing oiled bronze bushings in some applications with roller bearings, or with low-friction polymer bushings; replacing a sliding contact with a rolling contact, such as at the camshaft-to-lifter interface within an ICE by using an advanced lifter design; or, using a low-friction coating on a piston skirt, to reduce the dry friction between the contacts and further reduce the lubricated friction levels.

Examples of recently introduced friction reducing technologies include coated pistons [62], coated bearing shells [63], low friction seals [64], and coated piston rings [65].

5.4.3 *Implementation Factors*

Lubrication

There is a compromise with the use of low-viscosity lubricants; these lubricants can cause reliability and wear issues as thinner lubricants can get squeezed out between highly loaded components, such as gear teeth and bearings (this is not an issue for higher viscosity lubricants). However, additives such as friction modifiers and viscosity improvers can help alleviate these concerns, while retaining their benefits.

Contact Friction Reduction

Some contact friction reduction strategies can involve a compromise; for example, reducing piston ring tension does in fact lower cylinder friction, but it also decreases combustion chamber sealing, which could result in greater combustion gas blow-by, dilution and contamination of engine oil, and increased HC and PM emissions. The balance to achieve the correct tension in this example is carefully studied by the engine designer and not often a concern of the end user.

However, other strategies or technologies do not involve an operational compromise, but will incur a higher cost, either in maintenance or purchase. For example, a roller bearing installed instead of a bushing will cost more during manufacturing, and will also cost more to replace should it fail. Surface coatings will cost more to install, but may increase the life of the components, paying back the initial cost.

The effects of these technologies/strategies on fuel consumption are difficult to quantify, as many of these strategies are incorporated alongside other technologies, making the individual contributions difficult to isolate.

Table 19 provides a summary of various implementation factors with regards to lubrication and friction control technologies and strategies.

Table 19: Implementation Factors for Friction Control Technologies/Strategies

Implementation Factor	Lubrication	Contact Friction Reduction
Cost	Low to moderate	Low to moderate
Timeframe	Immediate to near-term	Immediate to near-term
Availability	Proven in on- and off-road applications	Proven in on- and off-road applications
Reliability, scalability durability, and safety	Lighter weight lubrication oil enhanced with additives may increase reliability and durability	Reliability and durability are technology dependant;
Support and maintenance	Possibly increased maintenance schedules	Possibly increased maintenance schedules
Barriers to consumer acceptance	Cost	Cost; Complexity
Weight, volume increases; power requirements	n/a	Possible weight increases

Implementation Factor	Lubrication	Contact Friction Reduction
Effect on (other) emissions	Possible reductions due to improved fuel consumption, but possible increase in HC and PM from oil burning	Possible reductions due to improved fuel consumption, but possible increase in HC and PM from oil burning
Co-benefits	Longer component life; Lower noise	Longer component life; Lower noise

5.5 Parasitic Loss Reductions

5.5.1 *Overview*

Parasitic losses are those that arise from using the ICE to: power pumps, fans, compressors, and other equipment for the operation of the engine itself; increase operator comfort; or power auxiliary equipment. The reduction or removal of the parasitic losses allows the ICE to be lower powered, and thus use less fuel.

For example, the use of accessories, such as A/C and power steering, create parasitic losses. While the comfort of the operator is increased with these functions, the additional power needed to run the accessory load requires the engine to output more power, which in turn, requires more fuel. Engine oil pumps and coolant pumps are also considered accessories and a source of parasitic losses, despite the fact that their functions are necessary for engine operation. This is primarily due to the way they are configured; at low to moderate engine speed they provide the required flow and pressure, but at high engine speed they provide excess flow and pressure, and thus require more power (and fuel) than is needed.

Table 20 summarizes the common parasitic losses into two broad categories, and summarizes the technology/strategy options available to address the loss. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 20: Parasitic Loss Reduction Technologies/Strategies

Parasitic Loss	Technologies/Strategies
Fans, Pumps and Compressors	▪ Hydraulically-driven ▪ Electrically-driven ▪ Demand-based usage ▪ Variable pitch (fans) ▪ Variable displacement (pumps) ▪ Variable speed ▪ Electrically driven (coolant, oil, HVAC) ▪ Clutching
Electrical Accessories	▪ Lighting (e.g. LED) ▪ Charging system –12V; 42 V

LED – Light-emitting diode

5.5.2 *Applications*

Solutions to reduce parasitic loss are very specific to the source and type of parasitic loss. Some solutions, such as pumps with clutches, variable displacement pumps, or variable pitch fans, may be installed into existing designs, possibly retaining the typical belt-driven format. Vehicle applications, where throttle setting and speed vary throughout the operation, are most suited to the application of parasitic loss reduction technologies; equipment which runs at a constant speed would benefit less from parasitic loss technologies/strategies.

That said, the application of electrically driven engine accessories for fans, or for fuel, oil, coolant and other fluid pumps, is universally applicable to all ICEs, removing the need for an accessory drive belt. The full benefits are realized if the ICE electrical system can take advantage of what the electrified accessories provide: lower pumping losses at high engine speeds, and the ability to control when accessories are powered. A fully electrified engine accessory system is also easily integrated with anti-idle technologies using shore power.

5.5.3 *Implementation Factors*

Table 21 provides a summary of various implementation factors with regards to parasitic loss reduction technologies and strategies.

Table 21: Implementation Factors for Parasitic Loss Reduction Technologies/ Strategies

Implementation Factor	Fans, Pumps and Compressors	Electrical
Cost	Moderate to high	Low to moderate
Availability timeframe	Immediate to near-term	Immediate to near-term
Reliability, scalability, durability, and safety	Proven in on-road applications	Proven in on-road applications
Support and maintenance	Potentially lower repair costs	New service procedures
Barriers to consumer acceptance	Confidence in new technologies	Potential changes in operation and maintenance
Weight, volume increases; power requirements	Increased electrical system demands	Increased electrical system demands
Effect on (other) emissions	n/a	n/a
Co-benefits	Design freedom; Easier implementation of anti-idle technologies	Design freedom

For a standard 12 V electrical system, considerable current is required to achieve adequate power, which often leads to heavy gauge wiring and requires suitable power electronics to control them. Increased system voltage (e.g. 24 V, 36 V, or 42 V) can significantly reduce current requirements; however, components suitable for higher voltage may not be as readily available. With a higher voltage system a 12 V supply would still be provided to maintain compatibility with existing 12 V automotive accessories (e.g. cell phone chargers, satellite radios, etc.).

5.6 Anti-Idle

5.6.1 *Overview*

In off-road applications, engine idling occurs most often when changing equipment operators, waiting to load/unload, refueling, warming up an engine before use, or running an engine to keep it warm in very cold conditions. Some equipment, such as generators, idle in stand-by mode when attached loads are in a low power state. In the case of off-road equipment such as forestry, mining, agricultural, or construction, engines may be left idling for a variety of reasons related to operator comfort or habits.

Very generally, the technological approaches to reducing engine idle time can be grouped into two types:

(1) engine start-stop; and
(2) engine-off technologies.

These approaches will be discussed below with respect to off-road equipment and vehicle applicability and their implementation.

Table 23 summarizes the anti-idle technologies/strategies identified by the literature that, if implemented in off-road applications, may improve fuel usage. Quantitative fuel consumption reduction potentials for each of these technologies/strategies, expressed in percentage reduction of CO_2, are presented in Section 6.

Table 22: Anti-Idle Technologies/Strategies

Method	Example
Engine Start-Stop	Idle-stop system
Engine-Off	Direct-fired heater
	APU/Battery-powered system
	Shore power

5.6.2 *Applications*

Idle-stop has shown promise in on-road applications to provide meaningful gains with moderate modification to existing designs, making it attractive as a near-term solution. For certain off-road applications, idle-stop technologies could also be applied successfully [39]. However, current lead-acid starting batteries do not have the life for the high charge/discharge cycles associated with idle-stop and would result in a greater replacement and disposal burden. Advanced battery technologies may be required in some applications.

Some form of operator warning or interlock would be necessary to inform the operator that the equipment is still energized and capable of starting without warning at any time. Operators not accustomed to idle-stop may wrongly assume that equipment is malfunctioning or turned off when it is in a stand-by state. OEMs would need to account for operator and co-worker interactions with equipment which may stop and start without notice.

Additionally, vehicle systems such as HVAC, steering, and brakes would have to be redesigned to operate without engine power for extended periods of time. Idle-stop would likely have to be combined with other technologies/strategies, such as electrification of engine accessories, resulting in a cost increase. Any cost increases would have to be justified through the expected savings due to fuel consumption reduction.

Large diesel engines, such as those found in mining haul trucks, require considerable power to start and are usually started with compressed air instead of the usual electric starter found on passenger cars. Converting these engines to an electric starter motor capable of turning over an engine of that size would be an added expense, and the additional weight of the starter motor and batteries would reduce the revenue payload capacity of such a vehicle. Additionally, such equipment is often operated continuously and seldom shut down, even during shift changes. In the case of equipment such as this, the application of idle-stop technologies may not be appropriate.

5.6.3 *Implementation Factors*

Anti-idle technologies/strategies are best suited for applications where engine idling is considered a necessity by the operators, for either comfort or operational reasons, and where operator training alone cannot reduce the idling time of the equipment. Anti-idle technologies would allow the operators to maintain the required functions of the equipment while reducing engine idling time.

Table 23 provides a summary of various implementation factors with regards to anti-idle technologies and strategies.

Table 23: Implementation Factors for Ant-Idle Technologies/Strategies

Implementation Factor	Engine Start-Stop	Engine-Off
Cost	Low to moderate	Moderate
Timeframe	Immediate to near-term	Immediate to near-term
Availability	Canada and worldwide	Canada and worldwide
Reliability, scalability, durability, and safety	Easily implemented	Currently aftermarket products
Support and maintenance	Depends on implementation	Aftermarket support
Barriers to consumer acceptance	Operator interference; Throttle lag; Operator training	Additional service item(s) and fear of return on investment
Weight, volume increases; power requirements	Minimal where engine starter and battery systems are in place	Additional weight and volume required
Effect on (other) emissions	May reduce NOx, PM, CO, HC, dependant on start-stop cycle and engine warm up	May reduce or increase NOx, PM, etc.
Co-benefits	Longer engine life	Faster cabin heat; Reduced cabin noise; Longer engine life

5.7 Intelligent Controls

5.7.1 *Overview*

Intelligent controls, as defined in Section 2, are not considered a direct solution to reducing fuel consumption; however, intelligent controls support and enable many of the other reduction strategies, such as engine downsizing, transmission technologies, electrification, anti-idle, autonomous running, or operator assistance. Intelligent controls consist of a powerful embedded computer working with input from sensors to control numerous equipment functions. Complex systems, such as those found on mobile equipment, may also include networks and communications protocols, which enable information sharing between systems.

Along with improved engine and equipment functions, intelligent control systems also enable enhanced diagnostics, equipment life prognostics, demand-based preventative maintenance, and equipment usage monitoring. These functions help reduce overall costs and fuel consumption by helping operators maintain equipment in good operating condition (see Section 5.8.4 and Section 5.9 for more on this).

5.7.2 *Applications*

Intelligent controls have been applied to almost all on-road vehicle systems: engine management, HVAC, transmission control, and chassis and suspension functions. For off-road equipment, intelligent controls can be applied to the same systems, but may also find applications with the more specialized tasks that off-road vehicles and equipment perform, such as controlling loader or bucket motions of a back-hoe, or optimizing the operation of agricultural equipment.

An area where off-road equipment currently leads on-road counterparts is in autonomous vehicle control, which is currently common practice in agriculture equipment. Global positioning system (GPS)-assisted control of chemical sprayers, tractors, combine harvesters and other equipment has lead to considerable fuel savings, but also savings in seed and chemical products used [42][66]. The use of GPS-assisted operator control is currently in use in mining operations [43] using Komatsu [67] and Caterpillar [68] equipment and is being investigated for forestry applications [69].

5.7.3 *Implementation Factors*

The increased processing power of intelligent controllers allows designers to incorporate more sophisticated control algorithms into the equipment, which allows for improved optimization of systems.

The implementation of intelligent controllers requires the installation of electronic devices, and any associated communications to the equipment (e.g. sensors, power circuits, solenoids, and electrically controlled engine or equipment devices). Consideration must also be given to the electrical infrastructure to ensure it is compatible with the controllers. Additional implementation factors include possible changes to the operator interface; for example, removing direct control from the user over items such as engine speed or fuel-to-air ratio, or adding actuators to the steering mechanism to incorporate autonomous controls.

Table 24 provides a summary of various implementation factors with regards to intelligent control technologies and strategies.

Table 24: Implementation Factors for Intelligent Controls

Implementation Factor	Details
Cost	High cost of development and validation
Timeframe	Immediate (COTS) to near-term (custom), depends on application
Availability	Canada and worldwide
Reliability, scalability durability, and safety	Electronics are generally very reliable; Good scalability through networks; Electronic failure state unknown
Support and maintenance	OEM and dealer level service required; Replace not repair; Limited user serviceable components
Barriers to consumer acceptance	Increased system complexity; Limited to no user serviceability
Weight, volume increases; power requirements	Small weight and volume increase for system components
Effect on (other) emissions	Reduced emissions with improved system efficiency gains
Co-benefits	Increased features; OEM flexibility for options; Styling freedom; User aesthetics (LCD/LED display systems); Equipment self-diagnostics possible

5.8 Lightweighting and Other

Sections 5.1 through 5.7 have focused on powertrain technologies and strategies which offer relatively significant fuel consumption reduction potential in the off-road sector. The following section reviews technologies and strategies that, although highly applicable to the on-road sector, offer limited reduction potential in the off-road sector, but may apply to very specific applications. They include: lightweighting, rolling resistance reduction, aerodynamic drag reduction, maintenance practices, and solar technologies.

5.8.1 *Lightweighting*

For on-road applications, a reduction in vehicle size and weight can significantly reduce fuel consumption. A study performed by Ricardo [70] estimated fuel consumption reductions of between 2.7 percent and 4.1 percent for every 10 percent of weight savings, for light trucks and passenger vehicles. The relationship between weight and fuel savings in the on-road sector is closely linked to the rate at which the equipment accelerates from zero to a given speed, and the number of times it is required to accelerate to that speed. It is more difficult to quantify these savings for the entire off-road sector given that some types of off-road equipment (e.g. pumps) will rarely, if ever, accelerate up to speed, whereas other equipment (e.g. ATVs) may do so with the same frequency as vehicles in the on-road sector. Therefore, the relationship between weight savings and potential fuel consumption reductions must be considered on an application-to-application basis for the off-road sector.

Quantitative fuel consumption reduction potentials for lightweighting, expressed in percentage reduction of CO_2, are presented in Section 6.

In some cases, certain types of off-road equipment require high mass to maintain acceptable operating performances; drawbar pull force, traction in mud and snow, bucket breakout force, and ripper pry-out force are all examples of performance metrics that are related to equipment mass. However, increased mass means that more energy must be expended to move a piece of equipment or change its direction of movement (e.g. an excavator's superstructure swing, see Section 0), therefore more fuel is consumed.

Other types of off-road equipment can benefit from a reduction in mass, but more as a method of increasing payload capacity. Equipment such as haul trucks are rated by their payload or haulage capacity, therefore a reduction of the equipment's mass would mean an increase in the payload potential, while maintaining the same gross weight. The fuel usage remains the same for each haul, however, the increased payload capacity may reduce the total number of hauls required, thus reducing fuel consumption.

At the opposite end of the spectrum, off-road equipment such as snowmobiles and ATVs can benefit from lightweight materials. However, in these applications, the operator forms the single largest portion of the equipment's total mass, therefore the gains in terms of fuel consumption may be limited. As well, the consumer product aspect of ATV and motorcycle sales has already lead to lightweighting as being a significant aspect of current designs, as manufacturers use low mass as a performance measure and compete to bring low weight products to market.

Aluminum has been used successfully in on-road applications for vehicle components such as engine blocks, transmission and gearbox housings, and suspensions elements, among others. In off-road applications, lightweight materials have been used for similar components in smaller products such as lawn and garden equipment, snowmobiles, and ATVs; however, magnesium is being increasingly used as a lighter-weight replacement for aluminum, where applications allow, bringing about further reductions in mass.

For applications such as agriculture tractors and rigid haul trucks, the materials of choice remain steel and ductile (cast) iron for strength and durability reasons. Engineered aluminum housings are beginning to make inroads into areas traditionally dominated by steel and iron, where applications allow.

As engine-specific output (power per displacement) increases, compacted graphite iron (CGI) is beginning to see wider adoption in applications such as diesel engine blocks. Traditionally, diesel engine blocks were cast from gray iron for its superior vibration damping properties. As CGI offers increased strength over gray iron, design optimization is resulting in lighter engine blocks, while retaining most of the vibration damping properties of gray iron.

Engineering thermoplastics can also be used for off-road equipment in the form of cover panels and service access hatches. In these types of applications, the styling freedom and ability to incorporate multiple components, such as hinges and latches, into a monolithic part is often a driving factor to their uptake. For similar reasons, cabin interior applications could make extensive use of engineering thermoplastics.

The implementation of lightweight materials can have many different approaches, depending on the application. Typically it involves moving from a heavier material to a more lightweight solution (e.g. replacing steel with aluminum, or aluminum with magnesium, etc.), with an associated re-design of the component to account for the changes in material properties. In some instances, keeping the material unchanged, but re-designing for less material use, will bring about a weight savings; for example even a material such as cast iron can be considered a lightweight material when designed for lightweight use. However, there are significant costs associated with material upgrades and it is important to note that lightweight materials are not a drop–in (easy) replacement, especially if optimal results are to be achieved.

The choice of material is highly dependent on the specific vehicle or equipment application; the expected loads, operating duty cycle, service temperature, wear resistance, and service life all need to be considered when making the switch to lightweight materials.

Certain materials can bring significant weight savings; however some of these materials lack the damage tolerance and/or reparability of the heavier, traditional materials. This is a major consideration as some off-road vehicles and equipment are expected to operate in remote and hostile environments where expedient field repairs will be needed to keep equipment operating.

Material cost is a major consideration when determining the suitability of alternative materials in the off-road sector. Aluminum has lower weight, but the material cost is significantly higher when compared to steel. Additionally, the processing parameters for aluminum are different than steel, which means new manufacturing processes will be required.

Depending on the volume and value of a particular component, the rolled-up costs of switching materials can be prohibitive. Like many of the other technologies considered in this report, cost, particularly in the manufacturing chain, is a significant consideration. Even if the cost of switching to improved lightweight materials is neutral compared to keeping the status quo, it is possible that a manufacturer may opt to stay the course rather than risk a design change, as changing processes can lead to unexpected production and quality issues. There needs to be a demonstrated cost savings in manufacturing in order to justify the move to lightweight materials.

Table 26 provides a summary of various implementation factors with regards to lightweighting technologies and strategies.

Table 25: Implementation Factors for Lightweighting

Implementation Factor	Details
Cost	Low to high, major consideration
Timeframe	Immediate to near-term
Availability	Canada and worldwide
Reliability, scalability, durability, and safety	Mature
Support and maintenance	Material dependant
Barriers to consumer acceptance	Perceived lack of performance (i.e. consumer sensitivity to the use of ‘cheap’ materials)
Weight, volume increases; power requirements	Reduced weight; may reduce volume
Effect on (other) emissions	Reductions with decreased fuel use
Co-benefits	Possible performance improvements

5.8.2 *Rolling Resistance*

Rolling resistance is the force that is required to maintain the forward motion of a loaded tire as it rolls along the ground. It is influenced primarily by tire tread, tire size, tire structure, and inflation pressure. As the rolling resistance increases, the engine must work harder to propel the vehicle forward, and will therefore consume more fuel in the process. Rolling resistance in on-road applications, which involve standard pneumatic rubber tires travelling on concrete or asphalt surfaces, can often be reduced by the use of LRR tires. These special tire designs often have low-resistance properties such as special tread patterns/features, different rubber compounds, and unique construction.

However, for off-road applications, the ground conditions are highly variable (e.g. mud, snow, sand, etc.). Different off-road sectors have different performance requirements for a tire, such as damage tolerance or service life; thus rolling resistance of a tire is often not considered at all. As well, some specialized mobile equipment may be equipped with multiple balloon tires with very low inflation pressures in order to minimize ground pressure to allow the vehicle to travel over soft ground surfaces with minimal sinking. Other equipment may require superior damage resistance due to hazards such as sharp rocks. In both these examples, applying low rolling resistance tire technologies in these cases could compromise their primary performance metric, making them less attractive to buyers. However, in these instances tire pressure monitoring systems or automatic tire inflation systems could be beneficial to maintain the optimal inflation pressure for the task being performed, thereby increasing performance and productivity.

5.8.3 *Aerodynamic Drag*

Aerodynamic factors are important at high sustained speeds, such as highway operation. As a vehicle moves along the ground, it must push the air in front of it out of the way. The effort required to displace the air increases dramatically as speed rises, and this extra effort results in increased consumption of fuel. For off-road applications, aerodynamics is not a major factor as speed is often considerably lower than on-road vehicles. Certain off-road applications do operate at high speed; these include snowmobiles, motorcycles, and ATVs, among others. However, the open nature of these vehicles means that the human operator is exposed to the elements, typically sitting upright on an exposed seat, and forms a substantial portion of the aerodynamic drag of the system. Therefore, unless operators wore aerodynamic aids, or altered their ride position, the expected returns for addressing aerodynamics for off-road vehicles are not expected to be as significant as the gains made in on-road applications.

5.8.4 *Maintenance Practices*

Proper vehicle and equipment maintenance is a key strategy for the reduction of fuel consumption. Although not primarily implementable at the OEM level, preventative maintenance has been shown to significantly improve fuel consumption reduction by retaining engines and other components at their original level of performance. Examples of maintenance practices include: replacing spark plugs, cleaning and/or replacing filters, sharpening blades (for cutting equipment), fixing leaks, monitoring tire pressure, and ensuring proper lubrication for all necessary components.

As discussed in Section 5.7.1, intelligent controls can be used to support preventative maintenance by enabling enhanced diagnostics. Diagnostics tools, which are commercially available and could be implemented at the OEM level, would detect when the vehicle/equipment is not performing favourably, and could suggest solutions to help maintain optimal fuel usage.

5.8.5 *Solar Technologies*

Solar technologies are limited in their use for vehicles and equipment in the off-road sector, primarily due to their low power output and the relatively high costs. However, there has been demonstrated success in the road construction industry to power mobile, changeable message signs. This technology, which makes use of battery maintainers, is slowly replacing the traditional sign models, which are powered with diesel or gasoline-fuelled generators. Solar-powered message signs, which often employ power-saving LED lights, help to reduce (or eliminate) fuel consumption by lowering (or eliminating) the dependence on gasoline or diesel generators.

Another potential area of use for solar technologies is the use of solar cells for the slow-recharging of battery-powered off-road equipment. Smaller, lower-powered equipment may be charged by these devices, but the dependence on clear sunny conditions would make them limited in appeal and very likely require a portable generator as a supplementary backup power source.

5.9 Human Factors

The previous technology sections dealt primarily with the design, fabrication, and use of the off-road equipment itself. Reducing fuel consumption via equipment changes can be effective, yet improvements in the driving techniques of vehicle and equipment operators and the use of on-board fuel consumption devices have been shown to be the single most effective measure for reducing operating costs, fuel use, and emissions (see Table 27 for reduction potential).

The human operator can, in many cases, affect the amount of fuel that is used by the equipment. This influence can be minimal (for example, if an operator shifts gears at an engine speed that is 50 revolutions RPM higher than that stipulated by the OEM), or significant (for example, when an operator allows a very large engine to idle unnecessarily for many hours at a time). Regardless of the technology implemented, most machines will require some form of human intervention in order to operate optimally.

As well, human intervention can occur before the vehicle/equipment is even put to use for the first time. Equipment purchasers play a critical role in determining how much fuel will be burned on a yearly basis as they decide what size of equipment, and therefore what size of engine, is correct for the intended application. Due to the wide range of operating requirements in which any given unit of off-road equipment may need to perform, operators have traditionally selected equipment to have enough ‘reserve’ power to be prepared for any potential operating condition. Under-sized equipment seriously hampers productivity, negatively affecting schedules, reputation, and the financial returns. Equipment and engines that are each optimized for their intended duties would be ideal; however, there are costs associated with maintaining a fleet of differently sized equipment, as well as costs associated with underestimating performance needs. Over-sized equipment may consume more fuel than necessary, but some operators may view the additional fuel cost as insurance for the knowledge that any job can be completed on time, regardless of any unexpected conditions that may be encountered.

5.9.1 Operator Training

There are a number of opportunities for contractors and their employees to improve vehicle and equipment operation. Contractors can consider implementing training programs to refresh driver or equipment operator skills and help teach the effects of operating strategies for fuel consumption reduction. Potential areas of improvement to the human-machine interface include:

- On-road truck speed has the single largest operator impact on fuel consumption. As speed increases over 80 km/h, more and more horsepower is required to overcome aerodynamic drag. For a highway truck, each two-km/h increase in speed above 90 km/h decreases fuel economy by approximately two percent [41]. At higher speeds, the efficiency losses are typically greater for haul trucks, as compared to highway trucks, because of the lack of aerodynamic aids and irregular loads. Many contractors and trucking companies have set policies for their drivers to reduce cruising speeds, or to use electronic speed limiters (engine governors) to mechanically manage speeds;

- Maximize the use of cruise control on flat terrain (but not on hills), and choose a driving lane that avoids having to turn the cruise control off and on repeatedly;
- Avoid rapid acceleration and shift gears progressively on a manual transmission;
- Cut down on sudden braking and coast, in gear, as far as possible to slow down;
- Operate in the highest gear unless otherwise required for off-road applications (i.e. keep the engine below 1,500 RPM and downshift around 1,100 RPM);
- Avoid idling and minimize engine warm-up (e.g. five minutes) and cool-down times;
- Minimize accessory and parasitic loads on the engine A/C, fans, etc. Anti-idling techniques are described in more detail in Section 5.6; and
- Avoid over-filling the fuel tank. On many newer gasoline engines, overfilling the fuel tank causes fuel to be directed to a breather vent tube into an evaporative charcoal trap system. The liquid and vapour fuel are then stored in the trap until the next time the vehicle is started when a purge valve opens and draws the stored fuel vapour from the trap into the engine, to be burned. Although some small amount of fuel may remain in the trap, the system ensures that nearly all overflow fuel eventually reaches the engine. However, some older vehicles, particularly diesels, tend to use tank mounted breather hoses that simply vent the vapours or excess liquid to the surrounding area, never to be recovered or burned in the engine. Although the fuel is never actually burned in the engine, the effective fuel consumption is raised.
- Publications from the construction industry suggest that operator training programs can significantly reduce fuel consumption (see Table 27). Although not intended for the off-road market, training programs such as ‘SmartDriver’ [71] for transit buses, have been proven to be extremely effective at reducing fuel consumption, simply by training drivers how to drive their vehicles in a more fuel efficient manner. Typically, drivers are asked to drive instrumented vehicles to log performance and fuel consumption data. Then, drivers receive classroom and practical lessons on operating vehicles more efficiently. The drivers are then asked to repeat their driving route with the same instrumented vehicles, using the techniques learned while in training. The differences in fuel consumption before and after the training are recorded and compared. As a result of the training, many drivers have reduced the fuel consumption in their buses by as much as 10 percent, without a single change to the vehicles. Although this example pertains to on-road drivers, similar training packages could be developed for off-road vehicles and equipment to allow operators to better understand their equipment and the impact of their operation techniques on fuel consumption.

Furthermore, in the construction segment, contractors could plan their operations to more efficiently mobilize vehicles and equipment in order to reduce fuel consumption. For example, wherever feasible, they could shift more fuel-efficient vehicles and machinery into higher duty cycles, while less efficient equipment could be reserved for lower duty tasks. The number of required trucks on hand could be kept to a minimum (typically 10 percent extra) and backhauls could be used as much as possible. Better communications between the jobsite, plant, and haul units is also vital. Weights can also be minimized by removing any unnecessary equipment or loads, and by removing items like roof racks on higher speed units when not in use.

5.9.2 **On-Board Devices and Tracking**

Another method of fuel consumption reduction involves providing operators with the ability to view the fuel consumption of their equipment (either instantaneously, or over a period of time), while the device is operating. Fuel consumption can be somewhat abstract to an operator who simply performs their duty without any knowledge of how much fuel is being consumed, or more importantly, the relationship between duty cycle and fuel consumption. If an operator can relate duty cycle to fuel consumption, in real-time, they become more aware of the relationship between engine parameters (speed, engine idling, acceleration, braking, etc.) and fuel consumption. This information may allow the operator to alter their driving habits, or the settings on the machinery to optimize fuel consumption, while still performing a useful task. The key consideration for on-board devices is that any type of cuing system needs to be easy to see and comprehensible at a glance, while not interfering with the equipment operator's primary task (e.g. digging a ditch).

Similarly, contractors and owners can develop tracking systems to record fuel consumption by vehicle and equipment item, to help identify any changes in the fuel consumption of a particular piece of equipment, be it as a result of a fuel leak, a mechanical deficiency, or a change to the duty cycle. Subsequently, corrective action may be taken to restore the fuel consumption to acceptable levels. Or, as operating and equipment improvements are made, the impact on fuel consumption and emissions can be assessed and used to inform those in charge of future vehicle acquisitions.

Currently, almost all of the major heavy equipment manufacturers offer some form of usage tracking system, either as standard equipment or as an add-on option to their products. The challenge faced is the adoption of these technologies by the end user. As new equipment replaces older equipment, the uptake of monitoring systems can be expected to increase. However, in some industries, the larger concern is the availability of revenue-generating work for unused machines, rather than minute-by-minute fuel consumption data. Additionally, as some equipment is expected to operate in remote areas, the availability of suitably reliable communications links to monitoring centres is the key to ensuring accurate and up-to-date reporting of usage data.

Route management is another key factor in fuel efficiency. GPS technology, as mentioned in Section 5.7, can be used to optimize, for example, haul routes between the plant and jobsite. In addition, haul roads can be improved and traffic congestion managed to enable faster travelling times.

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6 TECHNOLOGY/STRATEGY-TO-APPLICATION ASSESSMENT

The following section presents estimated percent fuel consumption reduction potentials for the technologies/strategies presented in Section 5, and assesses the applicability of these reduction potentials to the Top 10 Applications identified from the Environ/PSR CY 2010 database.

In Section 6.1, the estimated fuel consumption reduction potentials for each technology/strategy are presented in tabular form, expressed in percent CO_2 reduction, or percent fuel consumption reduction.

In matrix format, Section 6.2 matches the technologies and strategies analyzed in Section 5 to the Top 10 Applications. This *qualitative* matching exercise assessed the potential applicability of a technology/strategy to a specific Application.

In Section 6.3, a sample *quantitative* analysis is presented, which illustrates specific examples of fuel consumption reduction potential for the Top 10 Applications and associated Products.

6.1 Percent Fuel Consumption (CO_2) Reduction Potential

The fuel consumption reduction values presented in tabular form in this section were compiled from the literature search, as outlined in Section 3.2. This data was collected from numerous sources, from both the on- and off-road sector, from small cars to heavy-trucks; these values were the best estimates at the time of the literature review.

The compiled set of reduction percentages is presented in Table 26. These results were compiled from approximately 24 sources in total. In cases where data from different sources spanned a similar range, or overlapped, the range presented is the span from the lowest to the highest percentage value found in the data sources.

Table 26 is separated into three result columns for percent fuel consumption reduction, based on the source material: Column 1 – passenger (car to light truck) for on-road applications only, Column 2 – medium- to heavy-duty truck for both on- and off-road applications, and Column 3 – advanced/application-specific technology results. Table 26 is also sorted by technology/strategy options, which match the technologies/strategies presented in Section 5. The results spans are broad in some cases, but they show the high and low range of fuel consumption reduction potential.

As the percent reduction figures for on-road vehicles are based on a very specific usage pattern, the extrapolation of these results to off-road uses will introduce uncertainties in the estimates. For example, given that off-road applications are of a very mixed nature, the way equipment is used will strongly influence the expected fuel use reductions that the various technologies promise. For this reason, the percentage ranges presented must be acknowledged as *estimates* of what may be achievable with the technologies. The actual fuel consumption reductions that result from the application of the technologies and strategies will vary with Application, Product, and use.

It is important to note that the percent values in Table 27 are also varied in the method by which they were collected (for example, modeling/simulation, in-service testing, laboratory testing, etc.) as well as the baseline comparison (i.e. different vehicles, scenarios, criteria, etc.). Also, some of the results are unique and have not been duplicated by other researches or verified over a range of duty cycles. In order to obtain accurate percent reduction potential, specific off-road vehicle and equipment testing and/or modelling would be required.

The percent fuel consumption reduction numbers are shown for individual technologies only, and do not reflect the results of combining technologies. Combining appropriate technologies may be the best course for some applications, however, for the reasons discussed in Section 1.4, the results of combining are not presented in Table 27. In some cases the technology options (and related percent reductions) are not additive, and determining which technologies could be combined would require further evaluation, in subsequent studies.

It must also noted that many of the technologies/strategies listed in Table 27 are in the early stages of development, or are currently applied in limited, highly-specialized situations. As noted in [9]:

> *"There is a tendency among researchers to evaluate technologies under conditions that are best suited to that specific technology. This can be a serious issue in situations where performance is strongly dependent on duty cycle, as is the case for many of the technologies evaluated in this report. One result is that the reported performance of a specific technology may be better than what would be achieved by the overall vehicle fleet in actual operation."*

Given that not all technologies/strategies can be applied to any given piece of equipment, it was necessary to determine which technologies/strategies could have a measurable effect on fuel consumption for any given piece of equipment. However, this method assumes that the piece of equipment does not already have a given technology/strategy applied. Therefore, some of the suggested technologies/strategies may not yield any fuel consumption reductions since the technology/strategy may already be installed on that piece of equipment.

The fuel consumption reduction potentials for the technologies/strategies described in Section 5 are listed in Table 27, below.

Table 26: Fuel Consumption (CO_2) Reduction Potential for Various Technologies/Strategies

Category	Technology/ Strategy	Option	Fuel Consumption (CO_2) Reduction Potential (%): Passenger Car/Truck Sources[13]	Medium to Heavy-Duty Vehicle Sources[14]	Advanced or Application-Specific Technologies	
			[5], [40], [72], [73]	[9], [10], [11], [74], [75], [48], [76], [77]	[Various Sources]	
Engine	Advanced Combustion Methods	Homogenous Charge Compression Ignition (HCCI)	5 - 12	10 - 15		
		Variable Compression Ratio (VCR)	5 - 7	n/a		
		Variable charge motion	4	n/a		
	Engine Downsizing; Engine Displacement Control	Turbo-charging with intercooling	2 - 6	2 - 5		
		Turbo-compounding – mechanical	3 -12	2.5 - 5		
		Turbo-compounding – electrical (exhaust energy recovery)	6	3 - 10		
		Cylinder deactivation	2 - 14	2 - 3		
	Advanced ICE Design	Opposed cylinder design	n/a		15 - 50	[19], [78], [79], [80]
		Five-, six-stroke system	n/a		10 - 40	[15], [17]
	Fuel Delivery Systems; Injection Technologies	Gasoline direct injection – stoichiometric	1 - 3	2 - 3		
		Gasoline direct injection – lean burn stratified	8 - 14	10 - 14		
		Advanced high speed diesel direct injection	23	n/a		
	Intake and Exhaust Systems	Variable Valve Timing (VVT), cam phasing	1 - 7	1 - 3.5		
		Variable Valve Lift (VVL) – discrete; continuous	3 - 6			
		Camless valve train – electromagnetic; electrohydraulic	5 - 15	n/a		
	Advanced Ignition Technologies	Advanced ignition control system	n/a		10 - 30	[23], [24]
		Plasma ignition; laser ignition	n/a		n/a	[25]
	Two-Stroke versus Four-Stroke	Change from two- to four-stroke	n/a		10 - 15	[81]
		Advanced clean burn direct injection two-stroke	n/a		10	[82]
		Advanced two/four stroke combination	n/a		30	[7]
	Diesel versus Gasoline	(Application dependent)	n/a	19 - 24		
Transmission	Advanced Transmission Systems	Continuously Variable Transmission (CVT)	3 - 7	n/a		
		Automated Manual Transmission (AMT) – single; dual-clutch	5 - 14.5	2 - 8		
	Shift Strategies	Automatic transmission – five- to eight-speed	1 - 6.5	7		
		Shift logic	1 - 2			
		Early torque lock-up	0.5	n/a		
Electrification/ Hybridization	Electrification	Shore power – catenary powered vehicles; plug-in mobile equipment	100	n/a		
		Battery electric – vehicle (BEV); equipment	100	n/a		
		Fuel cell electric – vehicle (FCEV); equipment	100	n/a		
	Hybridization	Hybrid electric – series; parallel	5 - 54	5.5 - 70		
		Hydraulic hybrid	12 - 68	20 - 70		

[13] On-road vehicles only
[14] On- and off-road applications

Category	Technology/ Strategy	Option	Fuel Consumption (CO_2) Reduction Potential (%): Passenger Car/Truck Sources[13]	Medium to Heavy-Duty Vehicle Sources[14]	Advanced or Application-Specific Technologies
			[5], [40], [72], [73]	[9], [10], [11], [74], [75], [48], [76], [77]	[Various Sources]
Friction	Lubrication	Low-viscosity; synthetics	0.5 - 4	1.5	
	Contact Friction Reduction	Various options[15]	0.5 - 5	1 - 2	
Parasitic	Fans, Pumps, and Compressors	Various options[16]	0.3 - 4	2 - 5	
	Electrical Accessories	Lighting (e.g. LED)	2.5		
		Charging system – 12V;42V	1 - 5		
Anti-Idle	Engine Stop-Start	Idle-stop system	2 - 8	3	
	Engine-Off	Direct-fired heater	n/a	1 - 3	
		Auxiliary Power Unit (APU) / Battery-powered system	n/a	1 - 9	
		Shore power	n/a	5 - 9	
Human	Driver Training	Various programs (e.g. speed, idling, shifting, accessory loads, etc.)	1.5 - 4.5	4.5 - 20	
	On-Board Devices and Tracking	Instantaneous fuel consumption monitors; fuel tracking;			
Other	Lightweighting	Advanced materials; Component downsizing	0.9 - 6.3	0.4 - 2.4 (per 1000 lbs)	
	Rolling Resistance	Low rolling resistance tires	0.2 - 3	4.5 - 9	
		Tire pressure monitoring; Automatic tire inflation systems	2.5	2 - 4	
	Aerodynamic Drag	Aerodynamic aids	0.2 - 1.5	3 - 15	
	Maintenance	General maintenance (e.g. filters, belts, fluids, etc.)	4 - 10	2 - 4	
	Solar Technology	Battery maintainers	n/a	n/a	(Limited Resources)

'n/a' – Either not applicable or no available CO_2 reduction percentages provided

15 Roller bearings, roller followers (camshafts), lower spring tension (valve springs), piston/cylinder coatings (engines, hydraulics), surface treatments (surface control, coatings), ring; profile, tension, and number (engines) seals: materials, geometry, number, tension, component weight reduction

16 Hydraulically driven, electrically driven, demand-based usage, variable pitch (fans), variable displacement (pumps), variable speed, electrically driven (coolant, oil, HVAC), clutching

6.2 Qualitative Analysis Matrix

This qualitative analysis selected example Applications and/or Products, and matched a limited number of appropriate technologies to them. A full analysis of matching all Applications and Products to all the potential technologies was not performed; however, it is felt that the example analysis provides a good indication of the type of future analysis that could be performed, either through further review or testing/modelling.

In Section 5, the qualitative applicability of technologies/strategies to off-road products was briefly discussed in each of the respective sections. This section summarizes this review in terms of Applications, rather than technology/strategy; the Top 10 Applications with the highest overall fleet fuel consumption were reviewed.

The fuel consumption reduction potentials, as summarized in Table 26, were not considered for this exercise; only the type of technology/strategy and the Application were considered. A qualitative grading method was used in the review: the applicability of a technology to an off-road Application was assigned a value of ‘1’ through ‘4’. The description of the grading system is presented as follows:

- Rank 1: indicates that the technology has a low applicability to the entire fleet;
- Rank 2: indicates that the technology is applicable to some products in the fleet;
- Rank 3: indicates that the technology is applicable to most products in the fleet; and
- Rank 4: indicates that the technology is very applicable to all products in the fleet.

For example, the application of electrification/hybridization as applied to generator sets was assigned a rank of ‘1’, with the following logic: The majority of generator sets will run intermittently, and when running, they will operate at a fixed speed setting to generate electricity as demanded by the load. As there is no large vehicle or mass being put into motion repeatedly, energy recovery strategies are minimal. Given these expected operating conditions, the benefits of a hybrid system were seen as not applicable and the match was given a rank of ‘1’.

As another example, the matching of engine-off technologies to forestry equipment was given a rank of ‘4’, with the following logic: Forestry equipment is often operated in all weather conditions, possibly year-round. The equipment most likely has an enclosed cabin, for operator comfort, but also for safety. Keeping the cabin warm in winter and cool in summer is most likely preferred by the operators, and keeping equipment running even when not in use to maintain these comfortable conditions is expected to occur. Given these factors, a rank of ‘4’ was assigned to this technology-Application match.

This exercise, based on the general understanding of the technologies/strategies as presented in Section 2 and Section 5, as well as the expected operating conditions of the Applications, was repeated for all the technology-application pairings. The results are shown in Table 28.

It must be noted that this qualitative overview is very broad in nature: the Application categories selected can be further subdivided into Products, which may each have a different ranking if the exercise were to be extended; only the Application level ranking was performed for the Table 27 analysis. As well, the expected use of the equipment was based solely on the description of the products as provided by the Environ/PSR database, and lacking any in-depth analysis and/or survey of the equipment usage patterns, the experience of the authors was used to determine the applicability ranking.

The purpose of Table 27, below, is to highlight which technologies/strategies would be most applicable to any given Application *regardless of fleet size or expected percent reductions in fuel consumption*. Given this fact, the rankings are not intended to be used as a guide or indication of which technologies/strategies would result in the highest fuel consumption reduction for each Application. For example, some application-technology matches with a ranking of '4' may not result in the highest overall nationwide fleet fuel consumption reductions due to the Application having a small fleet-size. As well, a technology/strategy may be highly applicable and easily implemented, such as friction reduction technologies, but because of the low estimated percentage gains in fuel consumption that can be achieved by the technology or strategy, it may not provide the highest amount of fuel savings, even if uniformly applied to a large fleet.

Table 27: Qualitative Technology/Strategy-to-Application Matrix (Currently Available Technologies Only)

		Top 10 Fuel-Consuming Off-Road Applications									
		Industrial				Recreational		Construction			Agriculture
Application		Generator Sets	Pumps	Utility Vehicle	Forklifts	Motorcycles/ ATVs	Snowmobiles	Off-Highway Trucks	Forestry Equipment	Excavators	Agriculture Tractor
Fleet Fuel Consumption (ML DEQ/year)		1,047	917	265	133	1,291	331	202	150	149	149
Technology/Strategy[17]	Engine Technologies	• Turbocharging (3) • Turbo-compounding (2) • GDI (2)	• Turbocharging (3) • Turbo-compounding (2) • GDI (2)	• Cylinder deactivation (2) • VVT/VVL (3) • GDI (2)	• Cylinder deactivation (3) • VVT/VVL (3) • GDI (2)	• Advanced two-stroke (3) • 4-stroke (4) • GDI (3)	• Advanced two-stroke (4) • 4-stroke (4) • GDI (3)	• Turbocharging (4) • Turbo-compounding (4) • GDI (2)	• Turbocharging (4) • Cylinder deactivation (3) • VVT/VVL (3) • GDI (2)	• Turbocharging (4) • VVT/VVL (3) • GDI (2)	• Turbocharging(4) • Cylinder deactivation (3) • VVT/VVL (3) • GDI (2)
	Transmission Technologies	(1)	(1)	• CVT (2) • AMT (2)	• CVT (2) • AMT (2)	• CVT (2) • AMT (3)	• CVT (4) • AMT (3)	• AMT (3) • Shift strategies (3)	• CVT (3) • AMT(3) • Shift strategies (3)	• Shift strategies (2)	• CVT (3) • AMT (3) • Shift strategies (3)
	Electrification /Hybridization	(1)	• Shore power (2) • Battery electric (1)	• Battery electric (2) • Hybrid-electric (2)	• Battery electric (2) • Hybrid-electric (3)	(1)	(1)	• Shore power (2) • Hybrid-electric (3) • Hydraulic hybrid (3)	• Battery electric (2) • Hybrid-electric (3) • Hydraulic hybrid (3)	• Shore power (2) • Hybrid-electric (4) • Hydraulic hybrid (3)	• Shore power (2) • Battery electric (2) • Hybrid-electric (2)
	Friction	• Contact friction reduction (3) • Low viscosity lubricants (3)	• Contact friction reduction (3) • Low viscosity lubricants (3)	• Contact friction reduction (3) • Low viscosity lubricants (3)	• Contact friction reduction (3) • Low viscosity lubricants (3)	• Contact friction reduction (4) • Low viscosity lubricants (4)	• Contact friction reduction (4) • Low viscosity lubricants (4)	• Contact friction reduction (4) • Low viscosity lubricants (4)	• Contact friction reduction (4) • Low viscosity lubricants (4)	• Contact friction reduction (4) • Low viscosity lubricants (4)	• Contact friction reduction (4) • Low viscosity lubricants (4)
	Parasitic Losses	(1)	(1)	• Electrified accessories (2) • LED lighting (2)	• Electrified accessories (2) • LED lighting (2)	• Electrified accessories (3) • LED lighting (3)	• Electrified accessories (3) • LED lighting (3)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3)
	Anti-Idle	(1)	(1)	• Start-stop (2) • Engine-off (2)	(1)	• Start-stop (3)	• Start-stop (3)	• Start-stop (3) • Engine-off (3)	• Start-stop (3) • Engine-off (4)	• Start-stop (3) • Engine-off (4)	• Start-stop (3) • Engine-off (4)
	Intelligent Controls	*	*	*	*	*	*	* • Semi-autonomous control (2)	* • Semi-autonomous control (2)	* • Semi-autonomous control (2)	* • Semi-autonomous control (2)
	Lightweighting and Other	(1)**	(1)**	• Maintenance (2) • Lightweighting (2)	• Maintenance (2) • Lightweighting (2)	• Maintenance (2)	• Maintenance (2)	• Maintenance (2) • Lightweighting (2) • Tire pressure monitoring (2)	• Maintenance (2) • Lightweighting (2) • Tire pressure monitoring (2)	• Maintenance (2) • Lightweighting (2) • Tire pressure monitoring (2)	• Maintenance (2) • Lightweighting (2) • Tire pressure monitoring (2)
	Human Factors	• Operator training (2) • On-board fuel tracking (2)	• Operator training (2) • On-board fuel tracking (2)	• Driver training (3) • On-board fuel tracking (3)	• Driver training (4) • On-board fuel tracking (4)	• Driver training (4) • On-board fuel tracking (4)	• Driver training(4) • On-board fuel tracking (4)	• Driver training (4) • On-board fuel tracking (4)	• Driver training (4) • On-board fuel tracking (4)	• Driver training (4) • On-board fuel tracking (4)	• Driver training (4) • On-board fuel tracking (4)

(1): Low applicability to entire fleet (examples not provided), **(2)**: Applicable in some products in the fleet, **(3)**: Applicable in most products in the fleet, **(4)**: Very applicable to all products in the fleet

* Included as part of most technologies listed – not a standalone technology

** Lightweighting for these Applications may reduce fuel consumption for the prime mover

[17] Combinations of some technologies/strategies may be required to be viable

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6.3 Quantitative Analysis Examples

Section 6.1 presented current fuel consumption reduction potentials of numerous off-road-applicable technologies/strategies (Table 26). In Section 6.2, a matrix exercise was completed, where specific technologies/strategies were matched with the Top 10 Applications, with an applicability ranking from ‘1’ to ‘4’. The intention of this section is to provide quantitative examples which will help answer the following question: how much of an improvement in fuel consumption will result from the application of a technology/strategy to a specific Application or Product? The answer to this question is not straightforward.

Two approaches were taken in this quantitative analysis. In the first approach, the major technology/strategy groupings were matched with two appropriate off-road Applications. The estimated percent reductions from Table 27 were used, along with the fleet fuel burn (in ML DEQ per year) as provided by the Environ/PSR database. For example, it is estimated that motorcycles and ATVs consume 1,291 millions of litres of DEQ per year. If all of these units were fitted with GDI engines, it is estimated that between 13 and 39 million litres of fuel would be saved every year. Similar calculations are presented for the other technologies/strategies, with fuel consumption reductions ranging from 1 to 70 percent. The results of this first approach are presented in Table 29.

For the second approach, the estimate of fuel consumption reduction was achieved by examining the off-road vehicles and equipment at the Product level (one step down from Application, as described in Section 4). For this example analysis, the Products from the Top 10 Applications (Table 10) with the 10 highest fleet fuel consumption totals (extracted from Appendix A) were matched with an appropriate technology/strategy. The technology/strategy matches were all ranked as either ‘3’ or ‘4’ in Table 28. The estimated percent reduction figures from Table 26 were used in this second approach, along with the fleet fuel burn data as provided by the Environ/PSR database. The results of this second approach are presented in Table 29.

The results from both approaches, presented in Table 28 and Table 29, are not intended to be conclusive/final recommendations of technologies/strategies to applications; rather, they are examples of the type of analysis that could be completed with the data provided in this report and with the Environ/PSR CY 2010 database. In addition, the results do not represent the most effective percent reduction strategies, nor do they intend on presenting the highest fuel savings achievable.

This quantitative analysis looked at only the Top 10 fuel consuming Applications (and related Products) from the Environ/PSR database, and did not explore all vehicle and equipment types. The determination of the highest fleet fuel savings for the entire Environ/PSR database require the following process to occur:

For each Product entry in the database, appropriate technologies/strategies would need to be assigned;

- For each technology/strategy-to-Product match, an estimated percent fuel consumption reduction figure would be assigned; and
- The total fleet fuel savings would be calculated based on fleet fuel burn and the percent reduction figure, and the results could be ranked from highest to lowest.

With over 25,000 Products (74 Applications) in the CY 2010/MY 2006 to 2010 Environ/PSR database, an exercise to match all of the appropriate technologies/strategies to all of the vehicles and equipment at the Product level is a considerable task, but may warrant future analysis. As well, a more realistic estimate of fuel consumption reduction would account for the combination of technologies, which could also warrant additional analysis.

Table 28: Application Level Examples of Technology/Strategy-to-Application Fuel Consumption Savings

Segment	Application	Fuel Type	Technology/ Strategy	Fleet Fuel Consumption (ML DEQ /year)	Fuel Consumption (CO_2) Reduction Potential (%)	Fuel Saved (ML DEQ/ year)	Notes
Recreational	Motorcycles/ ATVs	G	Engines: GDI	1,291	1 – 3	13 – 39	GDI is being applied to two- and four- stroke engines
Construction	Off-Highway Trucks	D	Engines: Mechanical turbo- compounding	202	2.5 – 5	5 –10	Mechanical turbo-compounding is commercially available for large diesel engines
Construction	Off-Highway Trucks	D	Transmission: AMT	202	2 – 8	4 –16	Where torque converter automatics are currently used, AMT offers improvements
Construction	Forestry Equipment	G/D	Transmission: CVT	150	3 – 7	4.5 – 11	Where torque converter automatics are currently used, CVT offers improvements
Construction	Forestry Equipment	G/D	Hybridization with energy storage	150	5.5 – 70	8.25 – 105	Assumption that repetitive lifting/climbing operations offer energy recovery benefits
Construction	Excavators	G/D	Hybridization with energy storage	149	5.5 – 70	8.2 – 104	Some equipment currently commercially available
Industrial	Pumps	G/D	Friction control	917	1.5	14	Pumps and generators have few technology options that are applicable
Industrial	Generator Sets	G/D	Friction control	1,047	1.5	16	
Construction	Forestry Equipment	G/D	Parasitic loss reduction	150	2 – 5	3 – 7.5	Assumption that medium- to heavy-duty vehicle gains can be matched in these applications
Construction	Off-Highway Trucks	D	Parasitic loss reduction	202	2 – 5	4 – 10	
Construction	Forestry Equipment	G/D	Anti-idle	150	1 – 3	1.4 – 4.5	Assumption that medium- to heavy-duty vehicle gains can be matched in these applications, where cabin comfort is the driving factor
Agriculture	Agriculture Tractor	D	Anti-idle	149	1 – 3	1.4 – 4.5	
Recreational	Motorcycles/ ATVs	G	Human factors	1,291	1.5 – 4.5	19.4 – 58	Assumption that passenger car/truck gains can be achieved through driver training and education
Construction	Off-Highway Trucks	D	Human factors	202	4.5 – 20	9.1 – 40.4	Assumption that medium to heavy-duty vehicle gains can be matched in these applications

Table 29: Product Level Examples of Technology/Strategy-to-Application Fuel Consumption Savings (Top 10)

Segment	Application	Product	Fuel Type	Technology/ Strategy	Fleet Fuel Consumption (ML DEQ /year)	Fuel Consumption (CO_2) Reduction Potential (%)	Fuel Saved (ML DEQ/ year)	Notes
Recreational	Motorcycles/ ATVs	Four-wheeled ATVs	G	Engines: GDI	703	1 – 3	7 - 21	GDI is being applied to two- and four- stroke engines
Industrial	Generator Sets	Trailer-mounted	D	Engines: Mechanical turbo-compounding	667	2.5 – 5	17 - 34	Assumes turbo-diesel already standard
Industrial	Pumps	General industrial pumps	G	Engines: Turbo-charging	613	2 – 5	12 - 31	Assumes normally aspirated gas engines currently standard
Agriculture	Agriculture Tractor	Mechanical FWD	D	Parasitic loss reduction	235	2 – 5	4.6 – 12	Assumes conversion of engine accessories to electrical drive
Industrial	Utility	Commercial turf utility vehicles	G	Driver training	227	4.5 – 20	10.2 - 45	Other technologies may also apply
Recreational	Snowmobiles	Snowmobiles	G	Engines: GDI	223	2 – 3	4.4 – 6.6	Assumes EFI currently standard
Recreational	Motorcycles/ ATVs	Scooters/Mini-bikes/Mopeds	G	Engines: GDI	198	2 – 3	4 – 6	Low-power (2 – 12.2 hp) class most likely currently carbureted as standard
Industrial	Generator Sets	Trailer-mounted	NG	Friction control	159	1 – 2	1.6 – 3.2	Top range assumes numerous technologies applied
Construction	Off-Highway Trucks	Rigid haul trucks	D	Hybrid-electric	140	5.5 – 70	7.7 – 119	Application specific
Industrial	Pumps	Fire pumps	D	Friction control	139	1 – 2	1.4 – 2.8	Top range assumes numerous technologies applied

7 CONCLUSION

Within the transportation sector, off-road vehicles and equipment are the second-largest source of greenhouse gas emissions in Canada, behind on-road vehicles, but ahead of air, rail and commercial marine sources.

NRC-CSTT was contracted to review technologies and strategies which offer potential greenhouse gas emissions reductions for vehicles and equipment in the off-road sector, and to assess the applicability and effectiveness of these technologies and strategies to the highest fuel consuming off-road vehicles and equipment in Canada.

The highest fuel consuming off-road vehicles and equipment were identified in a review of an off-road engine population database, provided to NRC-CSTT by Environment Canada. The database provided powertrain specifications (fuel type, engine type, engine stroke, power rating, etc.), as well as estimated fuel consumption data, for each model of off-road vehicle and equipment in Canada. A primary analysis of the database revealed approximately 74,000 individual Product Models (or 37 million Product Model units, from 74 Applications) from MYs 1985 and earlier through to MY 2010 in CY 2010, with a total fuel consumption of approximately 23.17 billion litres of fuel (diesel equivalent) per year.

Estimating the population and related fuel consumption of on-road vehicles in Canada is less difficult than estimating the population and related fuel consumption for off-road vehicles and engines given that all on-road vehicles must be registered with a Provincial Ministry of Transportation. However, off-road vehicles and equipment, for the most part, do not require licensing with a Provincial body. Therefore, accurate off-road vehicle and equipment population data (and related fuel consumption estimates) are much more challenging to obtain. In addition, it is not always evident how any given unit of equipment is used; for example, a piece of heavy forestry equipment may sit idle for months at a time or it may run 24 hours per day, all year long. For these reasons, it was a challenge to approximate legitimate fuel consumption values for any given Product Model, even with the available off-road database information.

A study of all 74,000 Product Models in the database was not within the scope of this project. Therefore, a limited model year range was selected (MYs 2006 through 2010) and a fleet-wide fuel consumption approach was taken, with a focus on specific Applications (Product Model groupings, e.g. tractors, generators, etc.), to identify potential off-road fuel savings. For example, there are millions of weed trimmers in use in Canada, but each unit burns a relatively small amount of fuel. Conversely, there are heavy-duty construction equipment units that burn thousands of litres of fuel every day; however, their population numbers are very low. In the analysis, when fuel consumption rates were combined with fleet populations for each Application, it became quite evident which Applications should be targeted as candidates for fuel consumption reductions technologies/strategies, as these technologies/strategies would have the greatest overall resultant fuel consumption reduction at the national level.

Based on this focused approach, the following Top 10 off-road Applications (corresponding to 72 Products and 7096 Product Models) were identified as the highest fleet-level, fuel consumers in Canada: motorcycles and ATVs, generator sets, pumps, agriculture tractors, snowmobiles, utility vehicles, off-highway trucks, forestry equipment, excavators, and forklifts.

A literature search was performed to gain insight into fuel consumption reduction technologies/strategies with potential application in the off-road sector. Any technology or strategy that could be legitimately applied to the Top 10 Applications was included in the study; a total of nine technology/strategy groupings were identified. To support the results of the final analysis, a summary of the theory of operation of all technologies/strategies was presented.

One of the primary results of this project was a tabular compilation of estimated percent fuel consumption (CO_2) reduction values resulting from the implementation of the technologies/strategies identified in the literature search. The percent fuel consumption reduction estimates for the identified technologies/strategies can be broadly summarized as follows: engine/transmission (1% to 15%); hybridization (5% to 70%); frictional/parasitic loss (0.3% to 5%); anti-idle (1% to 9%); human factors (1.5% to 20%).

These percent reduction estimates, when combined with the off-road population and fuel consumption data in the Environ/PSR database, could be used to calculate reduction potentials for all technology/strategy-to-Application pairings. The pairing and analysis of technologies/strategies for the Top 10 Applications was completed.

The analysis included a qualitative matching exercise of the Top 10 Applications to each of the identified technologies/strategies; an applicability rank from ‘1’ to ‘4’ was given to each match, and the result was a complete nine-by-ten technology/strategy-to-Application matrix. Some of the broad conclusions resulting from the qualitative matching exercise are as follows:

- Engine technologies/strategies can be universally applied, but their specific application will determine the level of effectiveness. In addition, some engine technologies are very costly to implement;
- Transmission technologies/strategies are limited in applicability to Applications that must accelerate repeatedly;
- Electrification/hybridization technologies/strategies are most applicable to vehicles or equipment with wide duty cycle ranges, where repetitive work functions create opportunities for energy recovery and storage;
- Friction control technologies/strategies can be applied universally, but the percent reduction potentials are low;
- Parasitic loss reduction technologies/strategies can be applied to all ICEs with some form of accessory device being driven by the engine, and the full benefits may only be realized when combined with other complimentary technologies/strategies;
- Anti-idle technologies/strategies are very application specific. Fully electrified engine and HVAC accessories will remove barriers to the implementation of anti-idle technologies/strategies;
- Intelligent controls are required for nearly all the technologies/strategies discussed in this report. Use in implementation of autonomous and semi-autonomous equipment will be important in some applications;
- Lightweighting can be universally applied in varying degrees, but the benefits seen in on-road applications may not be as great for off-road applications where equipment is often required to have high mass for operational reasons or for equipment that rarely moves; and
- Human factor technologies/strategies can be universally applied, but the application, as well as operator compliance and acceptance, will determine the effectiveness.

A second analysis was performed which examined the technology/strategy-to-Application matches from a quantitative perspective. This quantitative analysis, which provided example matches with percent reduction potentials and related fuel savings in litres of DEQ per year, aimed to answer the following question: how much of an improvement in fuel consumption will result from the matching of a technology/strategy to a specific Application or Product?

In total, 24 quantitative combinations of technologies/strategies-to-Applications (or Products) were identified, and a range of potential fuel consumption reductions were presented for each combination. These combinations were not ranked from highest to lowest potential fuel savings due to the large variation in estimated consumption reduction values and due to the fact that the example combinations represented an incomplete selection of Applications and Products from the database.

Many implementation factors must be considered when matching technologies/strategies with specific Applications. Due to the limited high-level analysis in the qualitative and quantitative analyses, the implementation factors identified in the report were not each accounted for explicitly. For example, the quantitative fuel reduction calculations did not consider cost or ease of implementation, and as such, the results of this exercise may be altered if time-to-implementation and cost-of-implementation were factors in a ranking system.

Both the qualitative matrix analysis and the example quantitative analysis aimed to demonstrate the applicability and effectiveness of matching specific fuel consumption reduction technologies/strategies with select Applications. A few observations resulted from these analyses:

(1) A small percentage reduction in fuel consumption applied to a fleet with a very large total fuel burn can equal or exceed the reductions resulting from more effective technologies applied to smaller fleets;
(2) Several technologies/strategies are not applicable to all Applications. Of the 90 technology/strategy-to-Application pairings in the nine-by-ten matrix, 27 were ranked a ‘4’, and thus seen as potentially applicable to all products in the fleet; and
(3) Several technologies/strategies have a very wide range of percent reductions: if the upper end of these estimates could be achieved, then even small fleets could realize significant fuel savings.

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8 RECOMMENDATIONS AND NEXT STEPS

Attempting to reduce fuel consumption across the entire spectrum of off-road vehicles/equipment would be a daunting task given the broad range of engine types, power ratings, duty cycles, applications, and methods of operator input. Many of the benefits of individual fuel consumption reduction technologies/strategies are well-documented, especially in the on-road sector, and most have been tested by OEMs or third-party independent firms to confirm the reduction of fuel consumption, often by modest amounts. However, the effects of implementing numerous technologies/strategies on off-road products are less well-known.

NRC-CSTT recommends that a more extensive application of the results of this report, particularly in relation to the Environ/PSR database, be performed. The results of this report were produced from a focused list of vehicles/equipment (Top 10 Applications), which were selected for analysis based on fleet fuel consumption. Specific technologies/strategies were then mapped to these vehicles/equipment and a reasonable estimate of fuel savings was made. However, it is conceivable that even greater fuel consumption reductions could be achieved by applying technologies/strategies to vehicles/equipment that were not included in the Top 10 Application analysis. In other words, it is possible that some Products excluded from this study, due to low to moderate fuel consumption, would be more compatible with some of the suggested reduction technologies/strategies than those captured in the Top 10 Application analysis.

For this reason, further study would be required to determine the effect of applying the identified technologies/strategies to all of the Products in the database, regardless of fuel consumption, to determine which combinations would provide the most fuel savings from the least amount of input to each individual Product: i.e. the tabulated percent reduction figures for technologies/strategies would be applied to all Products in the database, the estimated fuel savings would be calculated, and the results would be ranked by fuel savings. This analysis would identify the technology/strategy-to-Product matches that produce the greatest overall fleet fuel use reductions, and would also result in a Canada-wide fuel consumption inventory. When finalized, this fuel consumption inventory could be used to estimate total GHG emissions reductions for the CY 2010 Canadian off-road engine population. This, however, would be a very time-consuming undertaking, given the number of Products in the database, yet the results could be distributed to all of the segments, regardless of population.

Additionally, in this study, no consideration was given to comparing fuel consumption reductions to development and capital acquisition costs. NRC-CSTT recommends that costs be estimated for the identified technologies/strategies, and that these estimated costs be part of future analysis. For example, it is conceivable that two technologies could yield the same fuel consumption reduction potential, but one technology may cost orders of magnitude more than the other technology. Some consideration may need to be given to ranking potential results with consideration for cost and ease of implementation.

Following the extended database analysis, NRC-CSTT recommends selecting one Application, or one segment, for further study to determine which technologies/strategies could be implemented to yield the greatest fuel consumption reduction across that entire Application or segment.

It is clear that many of the fuel consumption reduction technologies/strategies require significant effort on the part of equipment OEMs (e.g. engine and transmission manufacturers). Although it is the end user who must ultimately purchase and use the equipment, the fuel savings technologies/strategies must be developed and tested by the OEMs, rather than simply added on by the end user. Computer modeling of powertrain systems could help OEMs identify the most suitable technologies/strategies to investigate for further research and possible prototype testing. As well, computer modeling of the off-road vehicle/equipment systems could also help OEMs to develop operating strategies and procedures that would reduce fuel consumption. NRC-CSTT recommends that computer models of the powertrain systems be created, which will allow for the simulation of the vehicles/equipment with different technology scenarios and operating conditions. The simulation of the vehicles/equipment would allow for combinations of technologies and strategies to be investigated, and the results of the simulations would aid in identifying technologies and strategies to be further studied with prototype testing and limited field testing.

Ultimately, testing would be required to quantify the individual or additive effects of implementing specific technologies to existing vehicles/equipment and operated in real-world conditions. Testing could be performed under controlled conditions in a laboratory, or in-situ (e.g. for large mining equipment) with conditions controlled as best as possible. During testing, different scenarios could be attempted to optimize fuel reduction possibilities for specific types of vehicles/equipment; the first technology would be tested and then complementary technologies would be added to determine if the effects were in fact additive, or to determine if the fuel consumption reduction capabilities of some technologies would be offset by those of another technology.

It is possible that human factor strategies for fuel consumption reduction could yield higher reductions, with less effort, and much sooner, than many of the technology-based methods. Operator training and on-board fuel consumption devices have all been shown, primarily in on-road applications, to reduce fuel consumption by a considerable amount. However, strategies to reduce fuel consumption via operator awareness and training may be better suited to applications that are industrial and commercial in nature, rather than for personal use. For example, snowmobile riders may be reluctant to save fuel via a reduction in speed since the very nature of the sport encourages high speeds. In contrast, training drivers of mining equipment to drive with the aim of fuel consumption reduction, often linked to part of an overall company energy savings program, could significantly reduce fuel consumption for a large fleet of vehicles, without the need to alter the equipment itself. This would allow fuel savings to occur in the near-term while fleet planners purchase more fuel efficient units of equipment for future use.

Given the above, NRC-CSTT recommends that studies be performed for specific segments to determine if the methods in which vehicles/equipment are being sourced and operated could be improved. The results of such a study could be a suggestion that acquisition and operator training be mandated to better educate fleet owners and users about fuel efficient practices. As well, instantaneous fuel consumption displays and fuel savings programs (similar to the ‘SmartDriver’ transit program) could be implemented for Applications, such as mining and forestry, to teach drivers to operate vehicles or machinery in a more fuel efficient manner. Ultimately, these near-term operator awareness programs could be combined with long-term equipment technology improvements, producing a compounding effect that could maximize fuel consumption reductions.

Finally, in the absence of regulations, such as the on-road corporate average fuel economy (CAFE), the manufacturers of off-road equipment may have little incentive to voluntarily initiate or engage in the recommended fuel reduction strategies described in this report. Incentive programs may need to be developed that would financially compensate the OEMs for electing to install technologies and apply strategies that lower fuel consumption for their products, or to the end users who elect to purchase a product with technologies which reduce fuel consumption.

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9 PROJECT TEAM

The project could not have succeeded without contributions by the following individuals:

- Jean Kneale (NRC-CISTI) - provided assistance with the literature review; and
- Jonathan Martin (NRC-CSTT) - managed the project.

The efforts of these people, and those not mentioned here, are appreciated by the authors.

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LIST OF ACRONYMS/ABBREVIATIONS

A/C	Air Conditioning
AMT	Automated Manual Transmission
APU	Auxiliary Power Unit
ATV	All Terrain Vehicle
CARB	California Air Resources Board
CGI	Compacted Graphite Iron
CI	Compression Ignition
CISTI	Canada Institute for Scientific and Technical Information
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COTS	Commercial-off-the-shelf
CSTT	Centre for Surface Transportation Technology
CVT	Continuously Variable Transmission
DEQ	Diesel Equivalent
DI	Direct Injection
EC	Environment Canada
EFI	Electronic Fuel Injection
EPA	Environmental Protection Agency
Gal	Gallon
GDI	Gasoline Direct Injection
GHG	Greenhouse Gas
GPS	Global Positioning System
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
hp	Horsepower
hr or h	Hour
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
kg	Kilogram
km	Kilometre
L	Litres
lb	Pound
LED	Light-Emitting Diode
LPG	Liquefied Petroleum Gas
LRR	Low Rolling Resistance
LTC	Low Temperature Combustion
Mt	Megatonne
MY	Model Year
NHTSA	National Highway Traffic Safety Administration (USA)
NO_x	Mono-nitrogen Oxides
NRC	National Research Council
NVH	Noise, Vibration, and Harshness
OEM	Original Equipment Manufacturer
OPOC	Opposed Piston, Opposed Cylinder
PCCI	Premix Charge Compression Ignition
PCI	Pulse Count Injection
PM	Particulate Matter
PTO	Power Take-off
RPM	Revolutions Per Minute

SAE	Society of Automotive Engineers
SI	Spark Ignition
US	United States
V	Volt
VVL	Variable Valve Lift
VVT	Variable Valve Timing

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Appendix A
Product Model Listing for Top 10 Applications

Table A1: Product Model Listing for Top 10 Applications in CY 2010 for MYs 2006-2010

	Segment	Application	Product	CY 2010 Canadian Product Model Population (#)	Fleet Fuel Consumption (ML DEQ/year)	Min Power Rating (hp)	Max Power Rating (hp)	Engine Fuel	Engine Cycle	Engine Type
1	Agricultural	Ag Tractors	2-Wheel Drive Tractors	25641	123.109	11.8	82.4	Diesel	4	Compression
2	Agricultural	Ag Tractors	Four-wheel Drive Articulated Ag Tractors	5022	82.729	170.0	408.3	Diesel	4	Compression
3	Agricultural	Ag Tractors	Mechanical Front Wheel Drive	46155	234.970	19.5	108.6	Diesel	4	Compression
4	Agricultural	Ag Tractors	Tracked Agriculture Tractors	820	11.427	48.0	226.8	Diesel	4	Compression
5	Construction	Excavators	Crawler-Excavators	8396	117.860	40.3	310.5	Diesel	4	Compression
6	Construction	Excavators	Mini Excavators	7609	18.065	6.0	41.2	Diesel	4	Compression
7	Construction	Excavators	Mini Excavators	29	0.005	4.8	4.8	Gasoline	4	Spark
8	Construction	Excavators	Wheeled Excavators	1276	13.585	59.0	177.0	Diesel	4	Compression
9	Construction	Forestry Equipment	Feller Bunchers	1497	55.425	200.0	275.2	Diesel	4	Compression
10	Construction	Forestry Equipment	Forwarders	116	3.192	125.0	213.3	Diesel	4	Compression
11	Construction	Forestry Equipment	Log Loaders Self Propelled	228	8.295	150.0	276.5	Diesel	4	Compression
12	Construction	Forestry Equipment	Log Loaders Trailer Mounted	1486	41.600	110.0	237.2	Diesel	4	Compression
13	Construction	Forestry Equipment	Other Forestry Equipment Self Propelled	38	1.119	94.0	202.3	Diesel	4	Compression
14	Construction	Forestry Equipment	Other Forestry Equipment Self Propelled	205	0.044	4.8	4.8	Gasoline	4	Spark
15	Construction	Forestry Equipment	Other Forestry Equipment Stationary	2	0.004	13.5	14.5	Diesel	4	Compression
16	Construction	Forestry Equipment	Other Forestry Equipment Stationary	1	0.001	20.5	20.5	Gasoline	4	Spark
17	Construction	Forestry Equipment	Skidders	807	26.391	177.0	227.5	Diesel	4	Compression
18	Construction	Forestry Equipment	Tree Harvesters	369	14.573	109.0	250.4	Diesel	4	Compression
19	Construction	Off-Highway Trucks	Articulated Trucks	1689	62.183	135.0	369.4	Diesel	4	Compression
20	Construction	Off-Highway Trucks	Rigid Haul Trucks	3	0.177	675.0	675.0	Diesel	2	Compression
21	Construction	Off-Highway Trucks	Rigid Haul Trucks	1082	139.933	130.0	1463.5	Diesel	4	Compression

	Segment	Application	Product	CY 2010 Canadian Product Model Population (#)	Fleet Fuel Consumption (ML DEQ/year)	Min Power Rating (hp)	Max Power Rating (hp)	Engine Fuel	Engine Cycle	Engine Type
22	Industrial	Forklifts	Forklifts	24	0.172	150.0	150.0	Diesel	2	Compression
23	Industrial	Forklifts	Forklifts	7050	27.307	15.4	118.2	Diesel	4	Compression
24	Industrial	Forklifts	Forklifts	1350	11.019	42.0	87.1	Gasoline	4	Spark
25	Industrial	Forklifts	Forklifts	15475	87.245	36.5	85.6	LPG	4	Spark
26	Industrial	Forklifts	Forklifts	1325	7.383	52.0	80.8	Multi-Fuel	4	Spark
27	Industrial	Generator Sets	Auxiliary Power Unit	19116	6.818	29.5	29.5	LPG	4	Spark
28	Industrial	Generator Sets	Auxiliary Power Unit	26026	9.894	5.4	16.6	Natural Gas	4	Spark
29	Industrial	Generator Sets	Industrial	54054	17.197	9.4	17.9	LPG	4	Spark
30	Industrial	Generator Sets	Industrial	123719	40.854	5.4	15.4	Natural Gas	4	Spark
31	Industrial	Generator Sets	Portable	265	1.356	124.7	149.4	Diesel	4	Compression
32	Industrial	Generator Sets	Portable	36034	10.153	9.4	18.8	LPG	4	Spark
33	Industrial	Generator Sets	Portable	84696	24.560	5.4	17.6	Natural Gas	4	Spark
34	Industrial	Generator Sets	Residential	17786	5.634	9.4	18.0	LPG	4	Spark
35	Industrial	Generator Sets	Residential	49753	19.298	5.4	16.5	Natural Gas	4	Spark
36	Industrial	Generator Sets	Recreational Vehicle	8962	3.531	13.4	23.6	LPG	4	Spark
37	Industrial	Generator Sets	Recreational Vehicle	21815	6.758	5.4	15.6	Natural Gas	4	Spark
38	Industrial	Generator Sets	Trailer Mounted	2	0.280	4000.3	4000.3	Diesel	2	Compression
39	Industrial	Generator Sets	Trailer Mounted	41866	666.920	124.7	535.4	Diesel	4	Compression
40	Industrial	Generator Sets	Trailer Mounted	43	12.727	8467.2	8467.2	Dual Fuel	4	Compression
41	Industrial	Generator Sets	Trailer Mounted	121873	62.888	9.4	130.9	LPG	4	Spark
42	Industrial	Generator Sets	Trailer Mounted	137302	159.040	9.4	520.3	Natural Gas	4	Spark
43	Industrial	Pumps	Concrete Pumps	3103	7.742	21.5	54.3	Diesel	4	Compression
44	Industrial	Pumps	Concrete Pumps	2048	1.960	6.7	31.6	Gasoline	4	Spark

	Segment	Application	Product	CY 2010 Canadian Product Model Population (#)	Fleet Fuel Consumption (ML DEQ/year)	Min Power Rating (hp)	Max Power Rating (hp)	Engine Fuel	Engine Cycle	Engine Type
45	Industrial	Pumps	Fire Pumps	15232	139.093	9.4	228.2	Diesel	4	Compression
46	Industrial	Pumps	Fire Pumps	394	0.594	53.6	53.6	Gasoline	2	Spark
47	Industrial	Pumps	Fire Pumps	164682	87.324	4.0	32.1	Gasoline	4	Spark
48	Industrial	Pumps	General Industrial Pumps	12526	5.132	4.0	11.8	Diesel	4	Compression
49	Industrial	Pumps	General Industrial Pumps	109967	50.369	1.3	6.5	Gasoline	2	Spark
50	Industrial	Pumps	General Industrial Pumps	2779098	612.778	1.3	8.9	Gasoline	4	Spark
51	Industrial	Pumps	Industrial Sprayers	1733	7.471	13.4	223.1	Diesel	4	Compression
52	Industrial	Pumps	Industrial Sprayers	32264	4.593	2.7	7.7	Gasoline	4	Spark
53	Industrial	Utility Vehicles	Commercial Turf Utility Vehicles	16825	11.946	16.0	41.5	Diesel	4	Compression
54	Industrial	Utility Vehicles	Commercial Turf Utility Vehicles	75652	227.067	5.5	25.2	Gasoline	4	Spark
55	Industrial	Utility Vehicles	Industrial Utility Vehicles	851	1.314	8.0	100.3	Diesel	4	Compression
56	Industrial	Utility Vehicles	Industrial Utility Vehicles	7180	22.203	9.0	26.9	Gasoline	4	Spark
57	Industrial	Utility Vehicles	Industrial Utility Vehicles	8	0.024	20.0	20.0	LPG	4	Spark
58	Industrial	Utility Vehicles	Personnel Carriers	1542	2.622	9.0	11.4	Gasoline	4	Spark
59	Recreational Products	Motorcycles and ATVs	3-Wheelers/4-wheelers	10	0.001	9.5	9.5	Diesel	4	Compression
60	Recreational Products	Motorcycles and ATVs	3-Wheelers/4-wheelers	390	0.319	3.5	7.1	Gasoline	2	Spark
61	Recreational Products	Motorcycles and ATVs	3-Wheelers/4-wheelers	10964	131.967	7.0	25.3	Gasoline	4	Spark
62	Recreational Products	Motorcycles and ATVs	4-Wheeled ATVs	86	0.014	16.0	16.0	Diesel	4	Compression
63	Recreational Products	Motorcycles and ATVs	4-Wheeled ATVs	7229	72.958	3.0	17.1	Gasoline	2	Spark
64	Recreational Products	Motorcycles and ATVs	4-Wheeled ATVs	185588	702.815	2.7	25.8	Gasoline	4	Spark
65	Recreational Products	Motorcycles and ATVs	Off-Road Motorcycles	16687	43.324	3.5	20.6	Gasoline	2	Spark
66	Recreational Products	Motorcycles and ATVs	Off-Road Motorcycles	43815	96.154	2.7	24.3	Gasoline	4	Spark
67	Recreational Products	Motorcycles and ATVs	Other Recreational Products	174	0.072	2.9	3.8	Gasoline	2	Spark

	Segment	Application	Product	CY 2010 Canadian Product Model Population (#)	Fleet Fuel Consumption (ML DEQ/year)	Min Power Rating (hp)	Max Power Rating (hp)	Engine Fuel	Engine Cycle	Engine Type
68	Recreational Products	Motorcycles and ATVs	Other Recreational Products	27	0.017	4.8	6.7	Gasoline	4	Spark
69	Recreational Products	Motorcycles and ATVs	Scooters/Minibikes/Mopeds	54878	45.742	1.0	8.3	Gasoline	2	Spark
70	Recreational Products	Motorcycles and ATVs	Scooters/Minibikes/Mopeds	199016	197.852	2.0	12.2	Gasoline	4	Spark
71	Recreational Products	Snowmobiles	Snowmobiles	92287	222.858	16.0	75.7	Gasoline	2	Spark
72	Recreational Products	Snowmobiles	Snowmobiles	65693	108.176	4.0	88.7	Gasoline	4	Spark