National Research Council Canada

Conseil National de Recherches Canada

Automotive and Surface Transportation

Automobile et transports de surface

NRC·CNRC

Environmental Study of Off-Road Engine Technologies – Phase II

Prepared for:

Mr. Andrew Giallonardo
Environment Canada
351 St. Joseph Blvd.
Gatineau, Québec
Canada, K1A 0H3

Prepared by:

B. Gaudet, P.Eng

T. McWha, P.Eng

Project A1-003916

ST-GV-TR-0016

July 3, 2014

UNLIMITED
UNCLASSIFIED

Canada

ENVIRONMENTAL STUDY OF OFF-ROAD ENGINE TECHNOLOGIES – PHASE II

Photo courtesy of www.bigstockphoto.com

Prepared for:

Mr. Andrew Giallonardo
Environment Canada
351 St. Joseph Blvd.
Gatineau, Québec
Canada, K1A 0H3

National Research Council Canada
Automotive and Surface Transportation
2320 Lester Rd.
Ottawa, Ontario K1V 1S2
Canada

Technical Report

ST-GV-TR-0016

CHANGE CONTROL

Version	Date	Description	Authors
1.0	March 27, 2014	Initial release	B. Gaudet T. McWha
2.0	July 3, 2014	Final release	T. McWha

ABSTRACT

Environment Canada (EC) has retained the National Research Council Canada (NRC), as represented by the Automotive and Surface Transportation (AST) portfolio to evaluate the fuel savings potential of various off-road engine technologies and fuel saving strategies. Each evaluated technology or fuel saving strategy was ranked based upon four separate criteria. Estimates as to the total quantity of fuel which could be saved through their implementation per piece of off-road equipment was estimated. Additionally, details on which of the evaluated technologies and strategies could be applied to specific equipment within the mining, construction and agricultural sectors was provided. Finally, where comparable equipment or machinery existed, a financial analysis was performed to determine the payback period associated with the use of a specific fuel saving technology or strategy. The research performed for this particular study primarily focused on fuel saving technologies or strategies that could be implemented on self-propelled vehicles in the mining, construction and agricultural off-road sectors operating within Canada. No consideration was given to increased operational efficiencies resulting in fuel consumption reductions due to improved operator effectiveness (i.e. driver training).

This page intentionally left blank

EXECUTIVE SUMMARY

Environment Canada (EC) has retained the National Research Council Canada (NRC), as represented by the Automotive and Surface Transportation portfolio, hereafter known as NRC-AST, to continue the investigation of key recommendations arising from NRC-AST research conducted in 2012 which evaluated the fuel savings potential of various off-road engine technologies and fuel saving strategies.

The purpose of this study was to evaluate previously and newly identified fuel saving technologies or strategies which are applicable to the off-road sector. The resulting evaluation was used to provide details on which of the evaluated technologies and strategies could be applied to specific equipment within the mining, construction and agricultural sectors. Finally, where comparable equipment or machinery existed, a financial analysis was performed to determine the payback period associated with the use of a specific fuel saving technology or strategy.

The research performed for this particular study primarily focused on fuel saving technologies or strategies that could be implemented on self-propelled vehicles in the mining, construction and agricultural off-road sectors operating within Canada. No consideration was given to increased operational efficiencies resulting in fuel consumption reductions due to improved operator effectiveness.

There were two main tasks associated with the research detailed within this report. The first task involved a literature review to identify any recently developed or improved fuel saving technologies or strategies that could be implemented on any form of off-road equipment, independent of the sector in which the equipment was operated. The second task involved the matching of fuel saving technologies and strategies with specific equipment operating within the mining, construction and agricultural sectors followed by a quantification of the fuel savings to be expected due to the implementation of the technologies and strategies.

An extensive literature review was undertaken in an attempt to identify any fuel saving technologies or strategies for off-road equipment that have been developed or improved upon since the generation of the previous NRC report. The literature review focused on research performed between January 2012 and present day, but did not necessarily exclude research performed outside of that timeframe. The fuel saving technologies and strategies identified within the literature review were displacement controlled hydraulic actuation, microstructured hydraulic pump surfaces, equipment operating modes, low temperature combustion, ultra low particulate combustion, hydrogen fuel cells and autonomous control systems.

The fuel saving technologies and strategies identified within the literature review were combined with those identified in the 2012 NRC-AST research to form a complete and updated list of such technologies and strategies. Each technology on the updated list was ranked based upon four separate criteria: reduction in fuel consumption, readiness of the technology for immediate use, the prevalence of the technology or strategy within commercially available equipment, and the ease of implementation of the technology or strategy. Each of these criteria were assigned a value from 1 to 5 and a weighted average was used to formulate the final ranking. The weighted average gave reduction in fuel consumption a 40% weighting and the remaining criteria 20% weightings.

The ranking revealed that the top five fuel consumption reduction technologies and strategies were low temperature combustion, hybridization, displacement controlled actuation, fuel cells and electrification (presented in order from greatest to lowest potential). It should be noted that the rankings were based upon the potential to reduce fuel consumption, and not the fuel savings

that are already being realized from the implementation of the fuel consumption reduction technologies and strategies. The rankings may be thought of as a long-term potential to realize fuel savings based upon technology or strategy implementation considered only from this point forward.

It was important to develop a means by which the magnitudes of possible fuel savings for each of the identified technologies and strategies may be calculated. A fuel consumption reduction factor was calculated for each of the identified fuel consumption reduction technologies and strategies. This fuel consumption reduction factor can be used, along with reliable census data, to calculate the total amount of fuel that could be saved by a certain piece of equipment by implementing the fuel consumption reduction technology and strategy under consideration.

In addition to identifying, ranking and quantifying the available fuel savings, each fuel consumption reduction technology and strategy was evaluated to determine what types of off-road equipment to which it may be applicable. In order to generate a list of applicable equipment, North American industry reports were consulted to determine which major OEMs were operating within the mining, construction and agricultural industries. It was determined that Caterpillar, Deere & Company and Case New Holland were the three largest providers of North American mining, construction and agricultural equipment. A survey of the product offerings of these three companies was performed and a list of the available equipment was compiled for each of the three sectors under consideration (mining, construction and agricultural). The complete list of available equipment was then compared to the evaluated fuel consumption reduction technologies and strategies to determine which piece of equipment could be paired with which technology and strategy.

It was found that all of the identified engine technologies were applicable to all types of identified equipment except for gasoline direct injection. Gasoline direct injection was not applicable due to the widespread use of diesel fuel within the three sectors under consideration.

In terms of transmission based technologies, it was found that continuously variable transmission technologies could be applied to all types of identified equipment whereas shifting strategies were most favourably employed in vehicles that operate from low to high speeds repeatedly during operational use.

The types of equipment to which electrification, hybridization and fuel cell technologies were applicable was also evaluated. Due to the nature of the environments in which they operate, off-road vehicles in the mining, construction and agricultural sectors do not lend themselves well to electrification. The equipment in these sectors is required to operate for long hours in locations that may or may not have access to electricity for recharging purposes. The considerable costs associated with the implementation of hydrogen fuel cells are currently precluding their widespread use. However, if the cost of hydrogen fuel cells were to decrease, they would become a viable alternative for many compression ignition and spark ignition engines. Hybridization is becoming more common in the mining and construction sectors, being implemented in vehicles which have components that are repeatedly accelerated and decelerated. However, the majority of the equipment in use in the agriculture sector operates at a relatively constant speed with little acceleration or deceleration, negating any usefulness of replacing a conventional driveline with a hybridization technology.

The use of low-viscosity synthetics will apply to any piece of equipment which uses an engine and are therefore applicable to all types of equipment in the mining, construction and agricultural sectors.

The technologies under consideration to reduce parasitic losses were LED lighting, 42V charging systems, displacement controlled hydraulic actuation and microstructured hydraulic pump surfaces. The expected fuel savings associated with the use of LED lighting and 42V charging systems may be applied to all equipment under consideration in the mining, construction and agricultural sectors. The use of displacement controlled hydraulics and microstructured hydraulic pump surfaces is limited to those pieces of equipment which employ the use of hydraulics.

The use of anti-idle engine stop/start system was found to be the most effective in off-road equipment that may be left to idle at regular intervals. However, the cost associated with implementing such a system may not be mitigated by the cost savings associated with the reduction in fuel consumption, especially with the increasing complexity of such systems as equipment size increases.

The use of operating modes to reduce fuel consumption was found to be applicable to any piece of off-road equipment that has a set of relatively well known operating conditions. This is typically the case for the more versatile equipment (e.g. excavator); equipment that serve a variety of purposes.

The light-weighting of off-road equipment as a strategy to reduce fuel consumption would in theory be applicable to all pieces of equipment under consideration. However, it is likely that the removal of weight from a vehicle operating in the mining, construction and agricultural sectors would result in increased payloads being applied to the light-weighted vehicle, maintaining the same gross vehicle weight, but simply lowering the fraction of the gross vehicle weight consumed by the base vehicle. Additionally, many pieces of equipment rely on weight over the driven axle(s) in order to maximize traction in loose soil. Therefore, the light-weighting of some pieces of equipment could have a detrimental effect on traction, and hence productivity.

To further examine the costs associated with implementing the fuel consumption reduction strategies described within this report and assess the payback period based on the achievable fuel savings, four case studies were undertaken. The case studies were limited to equipment which was available for purchase both with and without the technology of interest. For the purpose of calculating fuel savings and payback periods, an average price of coloured diesel of $1.31/litre was assumed. The results of the case studies may be found in Table ES1.

Table ES1: Results of case studies

Equipment	Technology	Load Factor	Savings		Payback Period (Years)
			Litres/Year	$/Year	
John Deere 644K Wheel Loader	hybrid-electric drive	Low	6,065	$7,944.51	6.7
		High	11,171	$14,634.63	3.6
Caterpillar D7E Bulldozer	diesel-electric drive	Low	5,020	$6,576.04	15.2
		High	9,247	$12,113.75	8.3
Caterpillar 336 E Excavator	hybrid swing drive (using hydraulic accumulators)	Low	7,852	$10,286.54	3.4
		High	14,465	$18,948.89	1.9
Caterpillar 966K Wheel Loader	continuously-variable transmission	Low	6,976	$9,138.49	2.6
		High	12,850	$16,834.06	1.4

Based upon the results of the study, it was concluded that there were no readily available technologies or strategies that could be easily implemented in isolation for the mining, construction and agricultural sectors to achieve significant fuel consumption reduction. Recent engine development to meet strict emissions regulations naturally resulted in more fuel-efficient engines incorporating proven engine technologies. Without regulations to drive further engine development to reduce fuel consumption, there is little incentive for OEMs to invest in the necessary research and development.

It was found that the most significant short-term reduction in fuel consumption would likely result from the replacement of older, less fuel efficient engines and equipment with modern ones incorporating the latest technologies. With suitable regulations in place, it is possible that OEMs could achieve a 20% reduction in fuel consumption in the mid-term by focusing strictly on the optimization of compression ignition internal combustion engines. However, the longer term solution should focus on the elimination of the emission of greenhouse gases which may be achievable using technologies such as hydrogen fuel cells.

To further advance the reduction of fuel consumption in the mining, construction and agricultural sectors, NRC-AST recommends that a series of fuel consumption tests be conducted on specific pieces of off-road equipment where the technology of interest is isolated and individually applied in order to verify the potential fuel savings of specific, individual fuel consumption reduction technologies or strategies.

NRC-AST also recommends that data be collected from in-service equipment in the mining, construction and agricultural sectors to identify typical operational profiles. These typical profiles or duty cycles could be used to develop standardized operational profiles, which could then be applied to calculations or laboratory tests to assess the real-life fuel savings that could be expected by implementing certain fuel consumption reduction technologies or strategies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Purpose

Environment Canada (EC) has retained the National Research Council Canada (NRC), as represented by the Automotive and Surface Transportation portfolio, hereafter known as NRC-AST, to continue the investigation of key recommendations arising from previously conducted NRC-AST research [1] which evaluated the fuel savings potential of various off-road engine technologies and fuel saving strategies.

The purpose of this study was to evaluate previously and newly identified fuel saving technologies or strategies which are applicable to the off-road sector. The resulting evaluation was used to provide details on which of the evaluated technologies and strategies could be applied to specific equipment within the mining, construction and agricultural sectors. Finally, where comparable equipment or machinery existed, a financial analysis was performed to determine the payback period associated with the use of a specific fuel saving technology or strategy.

1.2 Previous Research

Research previously performed by NRC-AST [1] focused on the identification and evaluation of fuel saving technologies and strategies that could be implemented in the off-road sector. The research was applied to the Environ/PSR database which contained census data of all off-road equipment found in Canada. The database was used to identify the largest fuel consuming fleets in Canada, generating a list of the top ten greenhouse gas emitters. A further analysis was performed to determine how the identified fuel saving technologies and strategies could be applied to the top ten fuel consuming off-road applications.

1.3 Scope

The research performed for this particular study primarily focused on fuel saving technologies or strategies that could be implemented on self-propelled vehicles in the mining, construction and agricultural off-road sectors operating within Canada. No consideration was given to increased operational efficiencies resulting in fuel consumption reductions due to improved operator effectiveness.

There were two main objectives associated with the research detailed within this report. Task 1 involved a literature review to identify any recently developed or improved fuel saving technologies or strategies that could be implemented on any form of off-road equipment, independent of the sector in which the equipment was operated. The newly identified fuel saving technologies and strategies were combined with those identified and evaluated in previous NRC research to update the qualitative application matrix for the top ten fuel consuming off-road applications. In addition, the first objective included a ranking of specific fuel consumption reduction technologies and strategies identified in the project proposal [2] in order of their potential to reduce fuel consumption in off-road applications.

Task 2 involved the matching of fuel saving technologies and strategies with specific equipment operating within the mining, construction and agricultural sectors. A quantification of the fuel savings to be expected with the implementation of specific fuel saving technologies and strategies was performed. In the absence of accurate census data, a fuel consumption reduction factor was developed. When combined with accurate census data, this fuel consumption reduction factor can be used to determine the total sector wide expected fuel savings associated with the implementation of specific fuel saving technologies and strategies. To further assess the viability of certain fuel saving technologies, individual case studies were performed to determine the payback period associated with their implementation.

1.4 Methodology

The research performed for this report consisted of two main areas of focus: the entire off-road sector and a subset of the off-road sector consisting of the mining, construction and agricultural sectors. An overview of the order in which the research was organized within this report may be seen in Figure 1.

Task 1 focused on all off-road sectors, as outlined in the project proposal and section 1.3. The three subtasks in Task 1 were all sequential in nature: the literature review allowed for the updating of the application matrix and then for a ranking of the available technologies.

Task 2 focused only on the mining, construction and agricultural sectors. The three subtasks in Task 2 were completed based upon the research performed in Task 1.

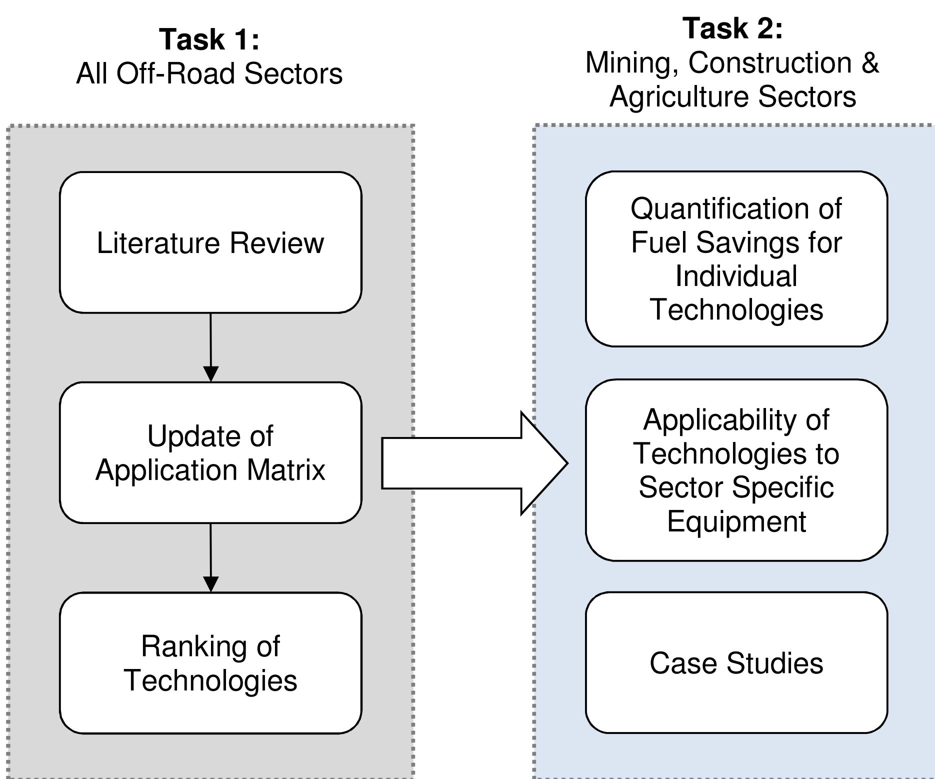

Figure 1: Methodology overview

1.5 Limitations

There are several limitations concerning the study undertaken. Firstly, the study relied upon the investigation of individual technologies and strategies to reduce fuel consumption in off-road vehicles. The intent was to quantify the fuel savings that could be achieved by implementing these individual technologies and strategies. However, these technologies and strategies are rarely implemented on an individual basis. As a result, there exists little data on the precise fuel savings associated with an individual technology or strategy. In addition, when these fuel saving technologies and strategies are implemented in combination with one another, the selected implementation combination is entirely at the discretion of the Original Equipment Manufacturer (OEM), purchaser, or operator, and the available combinations are essentially limitless. Moreover, the greatest gains in off-road equipment fuel consumption reductions are increasingly being realized by integrating one of these numerous technological combinations with control software, allowing for one of the integrated technologies to provide fuel consumption reductions during one operation and another of the integrated technologies to provide fuel consumption reductions during another operation, all on the same piece of equipment. Quantifying the precise benefits of individual technologies or strategies is not possible without highly tailored testing.

Secondly, the current overarching drive to reduce fuel consumption in the off-road equipment industry is solely based upon the monetary gains (or decrease in monetary expenditures) of the equipment owner. There are no regulations in place which restrict the amount of fuel that can be consumed by a particular piece of equipment performing a specific task. As a result, the data which could possibly be used to quantify fuel consumption reduction is often mixed with other cost-driven equipment improvements. For example, there is often a tendency to market off-road equipment in terms of its increase in productivity. However, an increase in productivity does not necessarily translate to a matching reduction in fuel consumption, as it may mean that more work is done for the same amount of fuel. The use of fuel economy, equipment efficiency and operator effectiveness as integrated and blended marketing tools results in a difficulty to extract the precise gains of one metric over another.

Thirdly, human factors were omitted from this study. Fuel conscious operation of off-road equipment is most likely the most effective way to realize large scale reductions in overall consumption. Although the technologies and strategies detailed in this report, if implemented, may provide overall reductions in off-road equipment fuel consumption, the end-user is ultimately responsible for optimizing any possible fuel savings.

Finally, an attempt was made to normalize the findings of this report across engine sizes and duty cycles. This methodology was employed due to the lack of availability of accurate census data in an attempt to provide value to the findings should these data become available. However, the most accurate and effective manner to evaluate the fuel saving capability of a specific technology, strategy, or combination thereof, is to have an identical task performed both with and without the use of said technological implementation. It is only through detailed fuel consumption testing that this data will become accurately quantifiable.

2 LITERATURE REVIEW

An extensive literature review was undertaken in an attempt to identify any fuel saving technologies or strategies for off-road equipment that have been developed or improved upon since the generation of the previous NRC report. The literature review focused on research performed between January 2012 and present day, but did not necessarily exclude research performed outside of that timeframe.

The following sections provide details on the individual technologies identified in the literature review as possessing potential for reducing the fuel consumption of off-road vehicles.

2.1 Displacement Controlled Hydraulic Actuation

The hydraulic system used on most modern mobile equipment incorporates one or more pressure controlled (load sensing) variable displacement hydraulic pumps, and control valves which restrict the flow of hydraulic fluid. One pump is usually shared by several actuators (cylinders or motors) which are often required to operate simultaneously, and the pump output must meet the pressure and flow requirements of the actuator performing the most demanding work. The excess pressure and flow is “throttled” by the control valves, resulting in significant energy loss in the form of heat. Such losses are the greatest contributor to system inefficiency for a multi-actuator system such as an excavator, which could account for 43% of the total energy consumed. [3]

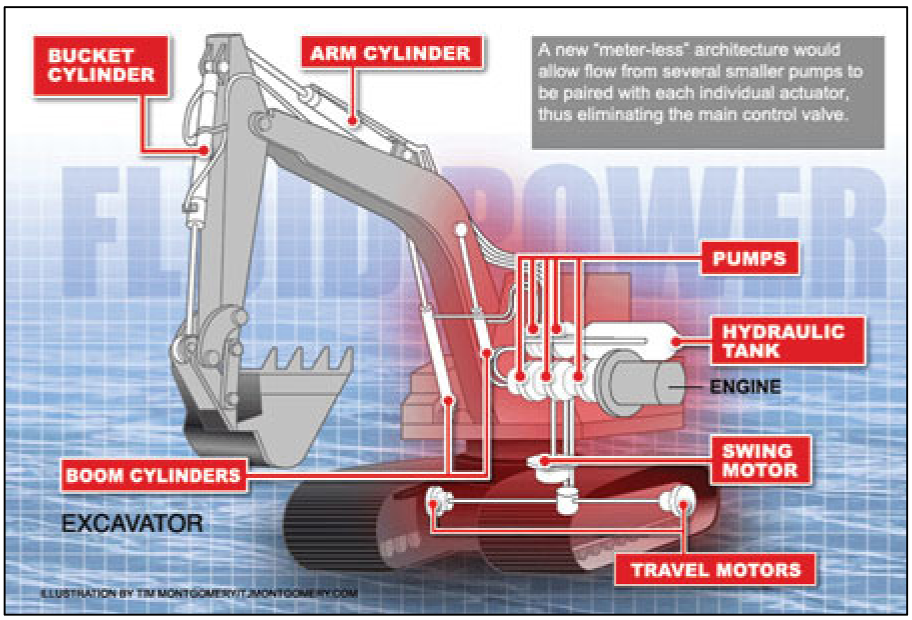

Figure 2: Displacement Controlled Hydraulic System Architecture [4]

Displacement controlled (DC) hydraulic actuation involves the direct control of each individual actuator with a dedicated hydraulic pump, providing the optimal amount of fluid power needed without the use of a valve to control the actuator power. The architecture for a DC hydraulic system on an excavator, which incorporates five hydraulic pumps, is shown in Figure 2. DC hydraulic actuation allows each pump to be optimized for the specific actuator requirements, further improving the system efficiency. However, it requires the integration of additional hydraulic pumps, which is often challenging due to space constraints, and it adds to the equipment cost. Since DC hydraulic actuation significantly reduces rejected heat, hydraulic cooling system requirements are reduced which may also result in reduced fuel consumption. [5] The overall impact on equipment weight is expected to be negligible.

DC hydraulic actuation also enables recuperation of potential or kinetic energy using over-centre pumps, where the pump can be used as a motor, driven by a load. Examples of such opportunities include lowering raised loads (e.g. loader or excavator bucket), or decelerating rotational motion such as the swing of an excavator body. Hydraulic accumulators can be used to store the recuperated energy, which can then be used to supplement pump power when required. An example of the use of hydraulic accumulators in an excavator is presented in Section 6.1.3.

DC hydraulic actuation has been demonstrated and implemented for the working hydraulic functions of several mobile machines, resulting in 15% fuel savings on a wheel loader, 20% fuel savings on a skid-steer loader, and 40% fuel savings on an excavator. Machine efficiency (i.e. the work that can be performed in a given amount of time) was also significantly increased. Using DC hydraulic actuation for the steering system of a wheel loader further reduced fuel consumption due to steering by 14.5%, and enabled “steer-by-wire” capability which could facilitate active safety features such as stability control, or remote or autonomous operation. [6] [7]

2.2 Microstructured Hydraulic Pump Surfaces

It has recently been discovered that the efficiency of a hydraulic pump can be significantly improved by employing “microstructured surfaces” instead of smooth surfaces, where moving parts are separated by a hydraulic fluid lubricating film. Surfaces such as pistons, cylinder walls, cylinder blocks and valve plates could be treated to incorporate features 1 µm high to reduce efficiency losses due to friction caused by the viscosity of hydraulic fluid.

Hydraulic pumps and motors have a maximum efficiency of approximately 90% when operating in their most efficient range, and their typical efficiency is usually much lower. Findings have shown that microstructured surfaces reduce losses due to friction as much as 57% when the pump operates at low output and about 10% when heavily loaded. [8]

2.3 Equipment Operating Modes

Mobile off-road equipment performs a variety of work activities under widely varied conditions. For example, a dozer may perform rough grade or fine grade on various soils, or stockpile functions; an excavator may perform clearing operations, excavate soil or move rock; and a wheel loader may move soil or load a truck. These duty cycles have varied power requirements (a percentage of full power), and the speed with which they are performed also affects the power required and the resulting fuel consumption. [9]

Based on the power requirements for a certain work activity, it is possible to optimize the engine operating parameters to maximize fuel efficiency. To realize this potential reduction in fuel consumption, OEMs have started to offer user selectable operating modes on equipment. For example, John Deere G-series excavators feature three productivity modes: “High Productivity” delivers more power and faster hydraulic response, “Power” delivers a balance of power, speed and fuel economy for normal application, and “Economy” reduces top speed and helps save fuel. There is also a “Power Boost” feature which provides a temporary increase in engine power, although it also results in an increase in fuel consumption. [10]

It should be noted, though, that the appropriate operating mode must be selected by the operator, and there may be a tendency to simply select “maximum power” at all times, especially if the operator is only concerned about productivity (and not fuel consumption). It is often the case that the operator is not the individual responsible for the cost of consumed fuel, reducing the incentive for the operator to use the most fuel efficient operating mode for the task being completed.

2.4 Reduction of HVAC Losses

In response to its identification in the project proposal [2], an attempt was made to identify technological advances in the reduction of losses associated with the operation of heating, ventilation and air conditioning (HVAC) equipment. However, the literature review did not reveal any new technologies or initiatives to reduce HVAC losses due to improvements in cabin sealing or insulation. Since much of the cabin is typically glass surfaces to provide necessary visibility, there may be advantages to incorporating glass treatments such as those used in building construction, like double glazing and tinting to increase the R-value and reflect sunlight.

Most of the attention given to reducing fuel consumption due to HVAC has been focused on idle reduction, which may be facilitated by electrically driven air conditioning compressors, and fuel-fired heaters. Electric defrosters could also be used to reduce idling for the purpose of clearing the operator's field of view.

2.5 Advanced Combustion Strategies

2.5.1 Low Temperature Combustion

Low-Temperature Combustion (LTC) is a flameless combustion strategy which occurs at in-cylinder temperatures that are lower than those normally experienced in conventional combustion engines. The LTC concept may be applied to gasoline, diesel or biofuel engines. However, engines with LTC capabilities are not yet readily available for purchase.

The LTC strategy covers a variety of advanced combustion methods including Homogeneous-Charge Compression Ignition (HCCI), Premixed-Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI).

Advanced combustion methods were discussed in detail within the Phase I NRC report [1]. However, the previous report focused mainly on the HCCI combustion strategy. The literature review performed in the current study revealed that advances have been made in other forms of LTC in the time since the previous report. Delphi and Hyundai are in the final stages of testing a LTC strategy in a 1.8 L Gasoline Direct-Injection Compression Ignition (GDCI) engine installed in a Hyundai Sonata. GDCI, a variation of PCCI, offers 25% to 40% improvements in engine efficiency. The implementation of the LTC strategy requires the use of a fully variable valve train, fast acting controlled cam phasers, and precise Exhaust Gas Recirculation (EGR) control. Piston cooling is accomplished through electronically controlled oil jets which may be deactivated during cold starts. [11]

2.5.2 Ultra Low Particulate Combustion

Ultra Low Particulate Combustion (ULPC) is an improved combustion strategy aimed at reducing emissions of particulate matter and oxides of nitrogen. However, recent studies have found that the use of such a combustion strategy has the potential to decrease overall fuel consumption as well. [12]

The ULPC combustion strategy improves the mixing of fuel and air in the main combustion chamber by matching the piston bowl geometry with injector nozzle spray angle. By optimizing these parameters, ULPC generates two combustion regions, one in the piston bowl and one above the piston bowl. The ULPC combustion strategy is most effective for off-road equipment having engines with lower operating speeds.

A bench test of a 2.4 L ULPC optimized engine operating at 2600 RPM not only produced emissions that met Tier 4 standards without any exhaust after treatment, but showed an decrease in fuel consumption of between 1% with advanced fuel injection to 5% with retarded fuel injection [12]. Bobcat has recently released a line of skid-steer loaders with ULPC optimized engines [13].

2.6 Hydrogen Fuel Cells

Fuel cells are a family of power generation devices which generate power by extracting energy from a fuel through electrochemical processes rather than through combustion. There are numerous forms of fuel cells available, each using a different combination of fuel, catalysts and electrolytes. The most common form of fuel cell fuel appearing in motive applications is hydrogen, mostly due to the energy extraction by-products being solely oxygen and water vapour. [14]

Despite being increasingly common in transit buses, locomotives and commercial forklift fleets, the use of fuel cells has had only limited entry in the off-road sector. New Holland has developed a 75 kW tractor as part of their Energy Independent Farm concept [15]. The concept involves farmers producing and storing their own hydrogen to power their vehicles through renewable resources such as wind and solar power. Although the concept would essentially eliminate the production of any greenhouse gases, there is a large financial investment associated with the fuel cell vehicles, as well as with the necessary hydrogen production and storage equipment. Despite being in operational use on a test farm in Turin, Italy, the New Holland hydrogen fuel cell tractor is not expected to be commercially available for the next 8 to 10 years [16].

There has also been some progress in the use of fuel cells in underground mining vehicles. Vehicle Projects LLC has developed a 160 kW fuel cell mine loader employing a 90 kW Polymer Electrolyte Membrane (PEM) fuel cell supplemented by a 70 kW battery system. It is reported that the developed system had similar performance capabilities to its 123 kW diesel equivalent, but there appears to be little industry uptake on the concept.

The current cost of hydrogen fuel cells prohibits their widespread use. However, 2020 targets have been established to meet a cost of 15 $/kW for high volume production which would make the use of hydrogen fuel cells more economically viable [17]. Another issue of concern with the use of hydrogen fuel cells is that of specific power (the power availability per mass) and power density (the power availability per volume). The current 2020 targets for automotive hydrogen fuel cells are a 650 W/kg specific power and a 850 W/L power density [17]. The 2017 targets for hydrogen storage tanks are 2.5 kWh/kg and 2.3 kWh/L [18].

If the above targets are met, a John Deere T670 agricultural combine requiring 280 kW of power would have a resulting fuel cell mass of roughly 430 kg and a resulting fuel cell volume of roughly 330 L (or occupying the volume of a cube with side lengths of 0.7 m). The hydrogen storage system required to operate the combine for eight hours would be 896 kg with a volume of 974 L. The overall system would weigh roughly 1500 kg and occupy a volume of 1300 L. Given that the base weight of this particular combine is 15,000 kg, this would not represent a significant weight gain especially when accounting for the fact that some of the increase in weight would be negated by removing the existing diesel engine. However, it should be noted that the above calculated hydrogen fuel cell system weight and volume only takes into account the base fuel cell and hydrogen storage requirements.

If similar calculations are to be performed for a CAT 797F mine haul vehicle with an engine size of roughly 3000 kW, the resultant hydrogen fuel cell would have a mass of roughly 4600 kg and occupy a volume of roughly 3500 L. The CAT 797F is equipped with a 3785 L fuel tank and a CAT C175-20 engine [19] which consumes 668 L/h at 75% load [20]. At 75% load, the CAT 797F can operate for roughly 5.7 hours before requiring refueling. To operate the vehicle for 5.7 hours between hydrogen tank refills using a hydrogen fuel cell, the hydrogen storage system would have a mass of roughly 6850 kg and occupy a volume of roughly 7,500 L. The base system for power generation and storage would have a total mass of roughly 11,500 kg and could occupy a volume of a cube with side lengths of 2.2 m.

Although fuel cells have tremendous potential to eliminate greenhouse gas emissions at the source of the motive power, there is a significant investment that must be made to incorporate their use. The associated cost of fuel cells is cited as one of the main deterrents of their use [14], although there are significant efforts being made to reduce the cost per kW and increase the overall power densities [21]. As the cost of such systems decrease and power densities increase, there is likely to be larger industry uptake.

2.7 Autonomous Control

The use of autonomous or semi-autonomous control allows for a more precise control of a piece of equipment by removing the human operator from the controls, either entirely or partially.

When analyzing autonomous control as a means to reduce fuel consumption, it is important to make a distinction between any realized reductions in fuel consumption and the increases in productivity and operational efficiency. Although it may be tempting to equate increases in efficiencies and productivity with decreases in fuel consumption, it is not necessarily accurate to equate them as such. An owner of a piece of equipment equipped with autonomous controls is not likely to let the vehicle sit idle after completing a task in less time, but is more likely to expand operations to increase overall productivity [22]. This would result in no overall net change in fuel consumption as the equipment would be operating for the same amount of time. In addition, the use of autonomous control to expand operations allows for the operation of multiple pieces of equipment at the same time with only one operator, possibly resulting in a net increase in fuel consumption if the number of operators is to be maintained constant.

The use of autonomous and semi-autonomous control using Global Positioning System (GPS) technology has been implemented in all three of the off-road sectors under consideration. In the agricultural sector, for example, semi-autonomous controls may be used to steer a tractor to maintain a preprogrammed course [23]. Kinze has also begun testing fully autonomous tractors to aid with harvesting [22].

In the construction sector, the use of semi-autonomous controls may be used to improve operator performance and increase output efficiency. For example, the use of CAT's stable blade control, a system designed to augment the operator's ability to control the blade of a dozer, is reported as a means to reduce operator effort and fatigue while increasing productivity in finish grading [24].

In the mining sector, fully autonomous dump trucks are being used to increase operational output and decrease operator costs by eliminating the driver from the vehicle. Komatsu's Autonomous Haulage System (AHS) allows for the driverless operation of their 930E mine haul dump trucks to move material from the site of excavation to the final processing or storage location [25].

Despite the availability of both autonomous and semi-autonomous vehicles and systems in the mining, construction and agricultural sectors, their benefit as a fuel saving technology, rather than operational improvement technology, relies on the removal of the vehicle operator. Similar gains in fuel efficiency could be achieved, perhaps more economically, through effective operator training. A study in the possible decrease in fuel consumption associated with autonomous and semi-autonomous control implementation would be a study into the decrease in fuel consumption associated with operator training, which is outside the scope of this report.

2.8 Electrification of Recreational Vehicles

Although the applicability of such vehicles to the sectors under consideration in this report is minimal or non-existent, in regards to addressing the updates made to Table 27 provided in the previous NRC research (Table 2 within this report), it is important to provide brief details as to the recent progress made in the area of electrification of recreational vehicles: there have been recent developments in the electrification of recreational vehicles such as off-road motorcycles and snowmobiles. For example, Zero Motorcycles offers a fully electric off-road motorcycle, the Zero DS [26]. In addition, CrossChasm has developed and tested a fully electric snowmobile that is currently in use in the Canadian arctic [27]. These two examples reveal an emerging trend in the electrification of recreational vehicles and the move towards zero tailpipe emissions.

2.9 Integration with Previous Research

The list of technologies and strategies for the reduction of fuel consumption in off-road vehicles identified within the literature review performed for this study is provided in Table 1. A quantified reduction in fuel consumption potential of the listed technologies is provided where it is available, but left as qualitative where this data is unavailable.

The fuel consumption reduction technologies and strategies identified in Table 1 may be combined with Table 26 from the previous NRC report on off-road emissions [1] to create a comprehensive list of available fuel consumption reduction technologies and strategies for the off-road sector.

Table 1: Available technologies and strategies for the reduction of fuel consumption

Technology/ Strategy	Option	Fuel Consumption Reduction (CO_2) Potential
Engine Technologies	Low temperature combustion	25% - 40%
	Ultra low particulate combustion	1% - 5%
Electrification/ Hybridization	Fuel cells	100%
Parasitic Losses	Displacement controlled hydraulic actuation	15% - 40%
	Microstructured hydraulic pump surfaces	Low
Intelligent controls	Equipment operating modes	Low

The complete list of technologies and strategies available by combining Table 1 and Table 26 from the previous NRC report was used to update the Qualitative Technology/Strategy-to-Application Matrix table presented within the previous NRC report (Table 27 in the previous NRC report [1]). The updated matrix may be found in Table 2, with the new entries presented in red lettering.

Table 2: Qualitative Technology/Strategy-to-Application Matrix

		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
Technology/Strategy[1]	Engine Technologies	• Turbocharging (3) • Turbo-compounding (2) • GDI (2) • LTC (3) • ULPC (3)	• Turbocharging (3) • Turbo-compounding (2) • GDI (2) • LTC (3) • ULPC (3)	• Cylinder deactivation (2) • VVT/VVL (3) • GDI (2) • LTC (3) • ULPC (3)	• Cylinder deactivation (3) • VVT/VVL (3) • GDI (2) • LTC (3) • ULPC (3)	• Advanced two-stroke (3) • 4-stroke (4) • GDI (3) • LTC (3) • ULPC (3)	• Advanced two-stroke (4) • 4-stroke (4) • GDI (3) • LTC (3) • ULPC (3)	• Turbocharging (4) • Turbo-compounding (4) • GDI (2) • LTC (4) • ULPC (4)	• Turbocharging (4) • Cylinder deactivation (3) • VVT/VVL (3) • GDI (2) • LTC (4) • ULPC (4)	• Turbocharging (4) • VVT/VVL (3) • GDI (2) • LTC (4) • ULPC (4)	• Turbocharging(4) • Cylinder deactivation (3) • VVT/VVL (3) • GDI (2) • LTC (4) • ULPC (4)
	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	• Fuel cells (2)	• Shore power (2) • Battery electric (1) • Fuel cells (2)	• Battery electric (2) • Hybrid-electric (2) • Fuel cells (2)	• Battery electric (2) • Hybrid-electric (3) • Fuel cells (4)	• Battery electric (2)	• Battery electric (2)	• Shore power (2) • Hybrid-electric (3) • Hydraulic hybrid (3) • Fuel cells (2)	• Battery electric (2) • Hybrid-electric (3) • Hydraulic hybrid (3) • Fuel cells (2)	• Shore power (2) • Hybrid-electric (4) • Hydraulic hybrid (3) • Fuel cells (3)	• Shore power (2) • Battery electric (2) • Hybrid-electric (2) • Fuel cells (3)
	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) • DC hydraulics (3) • Microstructured surfaces (3)	• 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) • DC hydraulics (3) • Microstructured surfaces (3)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3) • DC hydraulics (4) • Microstructured surfaces (4)	• Electrified accessories (3) • LED lighting (3) • 43V charge (3) • DC hydraulics (2) • Microstructured surfaces (4)
	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) • Operating modes (3)	* • Semi-autonomous control (2) • Operating modes (4)	* • Semi-autonomous control (2) • Operating modes (4)
	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

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

This page was intentionally left blank.

3 RANKING OF AVAILABLE TECHNOLOGIES

Each of the technologies and strategies listed within the project proposal as well as those identified in Table 1 were ranked based upon four separate criteria: reduction in fuel consumption, readiness of the technology for immediate use, the prevalence of the technology or strategy within commercially available equipment, and the ease of implementation of the technology or strategy. Each of these criteria were assigned a value from 1 to 5 and a weighted average was used to formulate the final ranking. The weighted average used gave reduction in fuel consumption a 40% weighting and the remaining criteria 20% weightings. The following sections provide the breakdown on how each criterion was used in the ranking as well as the results of the ranking exercise.

The complete list of fuel consumption reduction technologies under consideration is provided as follows:

- 42V charging system
- Advanced two stroke
- Cylinder deactivation
- CVT
- Displacement controlled hydraulic actuation
- Electrification
- Engine start/stop
- Fuel Cells
- Gasoline direct injection
- Hybridization
- LED lighting
- Light-weighting
- Low temperature combustion
- Low-viscosity synthetics
- Microstructured hydraulic pump surfaces
- Operating modes
- Shift strategies
- Tire pressure monitoring
- Turbo-charging
- Turbo-compounding
- Ultra low particulate combustion
- Variable valve timing

3.1 Reduction in Fuel Consumption

A higher reduction in fuel consumption for a particular technology or strategy was associated with a higher score in the ranking system. Table 3 provides the details on how the fuel consumption reduction technologies and strategies were ranked as it pertains to a reduction in fuel consumption.

Table 3: Reduction in fuel consumption ranking score and requirements

Assigned Score	Requirement
1	0-5% reduction in fuel consumption
2	5-10% reduction in fuel consumption
3	10-15% reduction in fuel consumption
4	15-20% reduction in fuel consumption
5	+20% reduction in fuel consumption

3.2 Implementation Readiness

A fuel consumption reduction technology or strategy that was still in early development was assigned a lower score than a technology or strategy that was readily available for implementation. Table 4 provides the details on how the fuel consumption reduction technologies and strategies were ranked as it pertains to implementation readiness.

Table 4: Implementation readiness ranking score and requirements

Assigned Score	Requirement
1	Conceptual or theoretical
2	Proven in simulation
3	Proof of concept built and tested
4	Limited availability for commercial purchase
5	Readily available for commercial purchase

3.3 Industry Prevalence

A fuel consumption reduction technology or strategy that was highly prevalent in commercially available equipment was given a lower score than those which were not yet present in commercially available equipment. The justification for this ranking is that fuel consumption reduction technologies or strategies already widely implemented will have a lower impact on reducing fuel consumption from current levels upon their complete implementation. Table 5 provides the details on how the fuel consumption reduction technologies and strategies were ranked as it pertains to industry prevalence.

Table 5: Industry prevalence ranking score and requirements

Assigned Score	Requirement
1	Implemented everywhere
2	Widely implemented
3	Moderately implemented
4	Limited implementation
5	Non-existent

3.4 Ease of Implementation

A fuel consumption reduction technology or strategy that was less easily implemented was given a lower score than those which were more easily implemented. Table 6 provides the details on how the fuel consumption reduction technologies and strategies were ranked as it pertains to ease of implementation.

Table 6: Ease of implementation ranking score and requirements

Assigned Score	Requirement
1	Extremely difficult to implement. Extreme reluctance of adoption within industry.
2	Highly difficult to implement. High reluctance of adoption within industry.
3	Moderately difficult to implement. Moderate reluctance of adoption within industry.
4	Relatively easy to implement. Low reluctance of adoption within industry.
5	Easily implemented. Wide acceptance within industry.

3.5 Resulting Technology/Strategy Ranking

The scores assigned for each category to each of the evaluated fuel consumption reduction technologies and strategies may be found in Table 7. The category scores were used to calculate a total score for the technology or strategy, using the weightings described within section 3. The resulting ranking of the evaluated fuel consumption reduction technologies and strategies may be found in Table 8.

It should be noted that the rankings are based upon the potential to reduce fuel consumption, and not the fuel savings that are already being realized from their implementation. For example, the use of turbo-charging falls low in the ranking due mainly to its already widespread implementation whereas low temperature combustion ranks very high in the list despite it not yet being a commercially viable option. The rankings may be thought of as a long-term potential to realize fuel savings based upon technology or strategy implementation considered only from this point forward.

Table 7: Scores assigned to technology/strategy for ranking purposes

Technology/ Strategy	Option	Reduction in Fuel Consumption	Implementation Readiness	Industry Prevalence	Ease of Implementation
Engine Technologies	Turbo-charging	1	5	1	5
	Turbo-compounding	1	5	2	4
	Cylinder deactivation	1	4	3	3
	Advanced two stroke	5	1	5	1
	Gasoline direct injection	2	4	3	4
	Variable valve timing, cam phasing	1	4	3	4
	Low temperature combustion	5	3	5	4
	Ultra low particulate combustion	1	2	5	4
Transmission Technologies	Shift strategies	2	5	2	4
	CVT	1	5	4	4
Electrification/ Hybridization	Fuel Cells	5	4	4	2
	Electrification	5	4	4	1
	Hybridization	5	4	3	3
Friction	Low-viscosity synthetics	1	5	2	5
Parasitic Losses	LED lighting	1	5	3	5
	42V charging system	1	3	5	3
	Displacement controlled hydraulic actuation	5	4	3	3
	Microstructured hydraulic pump surfaces	1	2	5	4
Anti-Idle	Engine start/stop	1	4	4	3
Intelligent Controls	Operating modes	2	5	2	4
Light-weighting and Other	Light-weighting	1	5	3	4
	Tire pressure monitoring	1	5	2	5

Table 8: Ranked fuel consumption reduction technologies and strategies

Ranking	Option	Score
1	Low temperature combustion	17.6
2	Hybridization	16.0
3	Displacement controlled hydraulic actuation	16.0
4	Fuel Cells	16.0
5	Electrification	15.2
6	Advanced two stroke	13.6
7	CVT	12.0
8	Shift strategies	12.0
9	Operating modes	12.0
10	LED lighting	12.0
11	Gasoline direct injection	12.0
12	Light-weighting	11.2
13	Low-viscosity synthetics	11.2
14	Tire pressure monitoring	11.2
15	Variable valve timing, cam phasing	10.4
16	Engine start/stop	10.4
17	42V charging system	10.4
18	Ultra low particulate combustion	10.4
19	Micro structured surfaces	10.4
20	Turbo-compounding	10.4
21	Turbo-charging	10.4
22	Cylinder deactivation	9.6

4 QUANTIFICATION OF AVAILABLE GHG SAVINGS

Based upon the results of the ranking performed in the previous section, the following sections provide the potential reductions in fuel consumption, and associated greenhouse gases, for each viable technology on a per kW·h basis.

4.1 Methodology of Quantification

In the absence of accurate census data describing the number and types of off-road equipment in use in the mining, construction and agricultural sectors, it is important to develop a means by which the magnitudes of possible fuel savings may be calculated. If accurate census data were to be made available, the methodology presented in this report will provide a fuel consumption reduction factor which may be used to calculate the fuel savings associated with the application of specific technologies. In order to generate this multiplication factor, it is important to know both the possible percent reduction in fuel consumption associated with a specific technology as well as the baseline fuel consumption rate of the equipment without the use of the specific technology.

4.1.1 Normalized Fuel Consumption Rate

In order to determine how much fuel the implementation of a certain technology or strategy will save, a normalized rate of fuel consumption must be stated. For diesel engines, several normalized rates of fuel consumption are available in the literature. Normalized fuel consumption rates of 228 g/kW·h [28], 233 g/kW·h [29] and 213 g/kW·h [30] have all been stated. For the purposes of this report, a normalized fuel consumption rate of 225 g/kW·h will be selected.

4.1.2 Fuel Consumption Reduction Factor

The fuel consumption reduction factor (FCRF) created for each specific technology was generated as shown in Equation (1). The percent reduction in fuel consumption shown in this equation pertains to the technology or strategy specific fuel consumption reduction.

$$FCRF = percent\ reduction\ in\ fuel\ consumption \cdot normalized\ fuel\ consumption\ rate \qquad (1)$$

4.1.3 Calculation of Available Fuel Savings

The fuel savings associated with the implementation of a specific fuel consumption reduction technology or strategy may be calculated using Equation (2). This equation provides the amount of fuel saved in litres for each piece of equipment implementing the technology or strategy. The use of the equation requires an assumption of the engine power usage rate, or load factor, of the equipment category in question. In the absence of accurate load factor data, suggested load factors for varying operating conditions may be found in Table 9.

$$fuel\ savings = \frac{FCRF \cdot engine\ size \cdot usage \cdot load\ factor}{fuel\ density} \qquad (2)$$

Table 9: Equipment usage rates and associated load factors [28]

Equipment Usage Rate	Load Factor
Low	0.38
Medium	0.54
High	0.70

4.2 Resulting Quantification

The results of the quantification using the methodology outlined in section 4.1 may be found in Table 10. The percentage reductions in fuel consumption associated with a particular technology or strategy were taken from Table 26 in the previous NRC report [1] and from Table 1. Only the fuel consumption reduction technologies and strategies for which there were known percentage reductions were included in Table 10. The data provided in Table 10 may be used, when combined with accurate census data, to calculate an approximate reduction in fuel consumption were the technology or strategy to be implemented in a particular piece of off-road equipment.

Table 10: Normalized quantification of fuel consumption reductions for evaluated technologies and strategies

Technology/ Strategy	Option	Percentage Reductions in Fuel Consumption		Fuel Consumption Reduction Factor	
		Low	High	Low (g/kW·h)	High (g/kW·h)
Engine Technologies	Turbo-charging	2%	5%	4.5	11.3
	Turbo-compounding	3%	5%	5.6	11.3
	Cylinder deactivation	2%	3%	4.5	6.8
	Advanced two stroke		30%		67.5
	Gasoline direct injection	2%	3%	4.5	6.8
	Variable valve timing, cam phasing	1%	7%	2.3	15.8
	Low temperature combustion	25%	40%	56.3	90.0
	Ultra low particulate combustion	1%	5%	2.3	11.3
Transmission Technologies	Shift strategies		7%		15.8
	CVT	3%	7%	6.8	15.8
Electrification/ Hybridization	Fuel Cells		100%		225.0
	Electrification		100%		225.0
	Hybridization	6%	70%	12.4	157.5
Friction	Low-viscosity synthetics	1%	2%	2.3	4.5
Parasitic Losses	LED lighting	2%	5%	4.5	11.3
	42V charging system	2%	5%	4.5	11.3
	Displacement controlled hydraulic actuation	15%	40%	33.8	90.0
Anti-Idle	Engine start/stop		3%		6.8
Light-weighting and Other	Light-weighting	1%	6%	2.3	14.2
	Tire pressure monitoring	2%	4%	4.5	9.0

5 APPLICABILITY OF TECHNOLOGIES TO SPECIFIC SECTORS

The following sections provide details on how the fuel consumption reduction technologies and strategies may be applied to specific off-road equipment types in the mining, construction and agricultural sectors. The complete list of fuel consumption reduction technologies and strategies considered in this report may be found at the beginning of section 3 on page 13.

5.1 Equipment Under Consideration

In order to generate a list of applicable equipment, North American industry reports were consulted to determine the major OEMs operating within the mining, construction and agricultural industries [31] [32] [33]. The industry reports revealed that the largest OEM market share in the mining sector is Caterpillar, owning approximately 21.1% of the market. In the construction sector, Deere & Company and Caterpillar own roughly 7.9% and 25.2% of the market, respectively, owning a combined market share of 33.1%. In the agricultural sector, Case New Holland (CNH) owns roughly 11.7% of the market and Deere & Company owns roughly 40.0% of the market, for a combined market share of 51.7%. These three companies – Caterpillar, Deere & Company and CNH – are the three largest providers of North American mining, construction and agricultural equipment. A survey of the product offerings of these three companies was performed and a list of the available equipment was compiled for each of the three sectors under consideration.

The complete list of equipment under consideration is included in subsequent sections.

5.1.1 Mining and Construction

The complete list of mining and construction equipment under consideration is provided below. The list was generated by surveying the product offerings of John Deere, Caterpillar and CNH.

- Articulated dump trucks
- Bore/drill rigs
- Cold planers
- Compact excavators
- Compact track loaders
- Compactors
- Crawler dozers
- Crawler loaders
- Draglines
- Excavators
- Graders
- Hydraulic mining shovels
- Loaders/backhoes
- Off-highway trucks
- Pavers
- Pipe layers
- Road reclaimers
- Rollers
- Rubber tired dozers
- Scrapers
- Skid steer loaders
- Skidders
- Surfacing equipment
- Trenchers
- Wheel loaders
- Wheeled excavators

5.1.2 Agriculture

The complete list of agricultural equipment under consideration is provided below. The list was generated by surveying the product offerings of John Deere, Caterpillar and CNH.

It should be noted that the tractor is the main source of motive power in the agricultural sector and that a majority of the required agricultural tasks are performed by connecting an attachment to the tractor's Power Take-Off (PTO). For example, baling, mowing, tilling and swathing are all performed with tractor attachments. Although there may exist specialized, self-propelled versions of equipment that perform these specific functions, they are not overly prevalent in the industry.

- Combines
- Compact tractors
- Four-wheel-drive tractors
- Harvester
- Row crop tractors
- Sprayers
- Tracked tractors
- Utility tractors

5.2 Engine Technologies

The engine technologies under consideration are as follows:

- Turbo-charging
- Turbo-compounding
- Cylinder deactivation
- Advanced two stroke
- Gasoline direct injection
- Variable valve timing
- Low temperature combustion
- Ultra low particulate combustion

Due to the widespread use of compression ignition engines, all of the evaluated fuel consumption reduction engine technologies, except for gasoline direct injection, will inherently apply to the off-road equipment used in the mining, construction and agricultural sectors. It is unlikely that gasoline engines will be employed in the off-road sector in replacement of diesel engines. Any shift away from the use of diesel fuel would likely be towards either an electrification/hybridization strategy or to the use of hydrogen fuel cells and not towards swapping one greenhouse gas producing fuel for another.

The largest gains in the reduction of fuel consumption of modern engines as it pertains to improved engine technology are to be realized from the further development of advanced combustion strategies. As outlined in previous research [1], the improvement of combustion efficiencies within the cylinder has been shown to reduce fuel consumption by as much as 15%. Further gains could be realized through the optimization of the piston bowl (1% to 5% reduction), as detailed in section 2.5.2, and through variable valve timing (1% to 4% reduction), turbo compounding (3% to 10% reduction) and cylinder deactivation (2% to 3% reduction). It is likely that the application of these technologies could be combined to realize reductions in fuel consumption by as much as 20% from the fuel consumption values of modern engines.

5.3 Transmission Technologies

The two fuel consumption reduction transmission technologies and strategies under consideration are CVT and shifting strategies.

The implementation of CVT in replacement of a conventional transmission will be of considerable benefit for off-road equipment which requires the application of varying engine loads or operates at varying speeds. Since this applies to all equipment under consideration in the mining, construction and agricultural sectors, it is assumed that CVTs could offer potential fuel savings for all considered equipment.

The optimization of shifting patterns as a fuel consumption reduction strategy will be most favourably employed in vehicles that operate from low to high speeds repeatedly during operational use.

Since the majority of agricultural equipment operates at a relatively constant speed, performing agricultural tasks over large swaths of open field, they are not likely to benefit greatly from the implementation of optimized shift strategies.

In terms of the mining and construction sector, the implementation of optimized shift strategies will have the greatest gains in fuel consumption reduction when used on equipment whose operational profile requires a cycle of acceleration and deceleration, for example, when a piece of equipment is required to pick up a load, transport that load some distance, drop off the load, and then return for another load. Therefore, the implementation of shifting strategies will be most effective for articulated dump trucks and off-highway trucks.

5.4 Electrification and Hybridization

The three fuel consumption reducing technologies or strategies under consideration are full electrification, hybridization and fuel cells.

Due to the nature of the environments in which they operate, off-road vehicles in the mining, construction and agricultural sectors do not lend themselves well to electrification. The equipment in these sectors is required to operate for long hours in locations that may or may not have access to electricity for recharging purposes. For example, operations in the mining sector are generally powered through the use of onsite diesel generators. In such an operation, there would not exist the additional power for vehicle charging without increasing the number of diesel generators, thereby negating any possible fuel consumption reductions. The long charging times associated with fully electric vehicles, compared to the time it takes to fill a conventional fuel tank, would be a significant deterrent for operators in these three sectors. Except possibly for niche markets, such as electric tractors for very small farms, there is little use for fully electric vehicles in the mining, construction and agricultural sectors. In addition, some of the equipment used in these three sectors is operated for three eight hour shifts a day, allowing no time for electrified systems to be charged.

The use of hydrogen fuel cells has been experimented with in agricultural tractors, as detailed in section 2.6. However, there are considerable costs associated with the implementation of hydrogen fuel cells which is currently precluding the use of such systems in practice. If the cost of hydrogen fuel cells were to decrease, they would become a viable alternative for many compression ignition and spark ignition engines. As costs decrease and reliability increases, there is no long term barrier to the widespread implementation of hydrogen fuel cell technology in all off-road equipment under consideration in the mining, construction and agriculture sectors.

Hybridization is gaining ground in the mining and construction sectors, being implemented in vehicles which have components that are repeatedly accelerated and decelerated, for example the boom of an excavator. Anytime a heavy component is decelerated, that energy may be recuperated and reused to accelerate that, or another, component. Although not all of the energy is recovered, that portion which is results in reduced overall fuel consumption. The use of this particular hybridization strategy is less effective for equipment operating at constant speeds.

Another method in which hybridization is being used pertains to the use of the onboard diesel engine as an electric generator, wherein the conventional drive train is removed and electric motors are used to power the vehicles' motion. This allows the engine to operate in a more efficient constant speed, resulting in reduced overall fuel consumption. The equipment operating in the mining and construction sectors which could benefit from the hybridization fuel consumption reduction strategy are listed as follows:

- Articulated dump trucks
- Cold planers
- Compact excavators
- Compact track loaders
- Compactors
- Crawler dozers
- Crawler loaders
- Draglines
- Excavators
- Graders
- Hydraulic mining shovels
- Loaders/backhoes
- Off-highway trucks
- Pipe layers
- Road reclaimers
- Rollers
- Rubber tired dozers
- Skid steer loaders
- Skidders
- Surfacing equipment
- Wheel loaders
- Wheeled excavators

The majority of the equipment in use in the agriculture sector operates at a relatively constant speed with little acceleration or deceleration. Not only do these operational characteristics not lend themselves to the capture and possible storage and re-use of dissipated energy during deceleration, but the constant speeds operations allow for the vehicle to optimized to operate at specific speeds, negating any usefulness of replacing a conventional driveline with a generator and electric motor type system. There were no hybridized tractors or other agricultural equipment found in the literature review.

5.5 Low Viscosity Synthetics

In a similar manner as the engine technology applications mentioned in section 5.2, any reduction in friction as a result of the use of low-viscosity synthetics will apply to any piece of equipment which uses an engine. Therefore, the use of the low viscosity synthetics is applicable for all considered pieces of equipment in the mining, construction and agricultural sectors.

5.6 Parasitic Losses

The technologies under consideration to reduce parasitic losses are LED lighting, 42V charging systems, displacement controlled hydraulic actuation and microstructured hydraulic pump surfaces. The expected fuel savings associated with the use of LED lighting and 42V charging systems may be applied to all equipment under consideration in the mining, construction and agricultural sectors.

The use of displacement controlled hydraulics and microstructured hydraulic pump surfaces is limited to those pieces of equipment which employ the use of hydraulics. The use of microstructured hydraulic pump surfaces can be employed anywhere that a hydraulic pump is used, which encompasses most of the mining, construction and agricultural equipment under consideration. The use of displacement controlled hydraulics is limited to equipment using hydraulic systems with multiple and simultaneous functions. The list of equipment operating in the mining and construction sectors to which displacement controlled hydraulics technologies may be applied is provided as follows:

- Compact excavators
- Compact track loaders
- Compactors
- Crawler loaders
- Excavators
- Hydraulic mining shovels
- Loaders/backhoes
- Skid steer loaders
- Wheel loaders
- Wheeled excavators

The use of displacement controlled hydraulics is of limited practicality in the agriculture sector.

5.7 Anti-Idle

The use of an anti-idle engine stop/start system will be the most effective in off-road equipment that may be left to idle at regular intervals. Although it is not ideal from a productivity standpoint to have a piece of machinery that is not operating at full capacity at all times, there inevitably occur instances where all equipment will stand idle. The use of an anti-idle system could therefore produce fuel savings in all pieces of considered equipment in the mining, construction and agricultural sectors.

However, the cost associated with implementing such a system may not be mitigated by the cost savings associated with the reduction in fuel consumption, especially with the increasing complexity of such systems as equipment size increases. The usefulness of such systems is heavily dependent upon how operators choose to use their equipment. The effective implementation of an anti-idle engine stop/start system is therefore more a result of the equipment duty cycle than it is of equipment type. Although having such systems available for purchase from OEMs would be beneficial, it is up to end users to decide, based upon their expected equipment duty cycle, whether including the system would be of net benefit to their operations.

5.8 Operating Modes

The use of operating modes to reduce fuel consumption is applicable to any piece of off-road equipment that has a set of relatively well known operating conditions. This is typically the case for the more versatile equipment; equipment that serves a variety of purposes. The list of equipment in the mining and construction sectors which could benefit from the availability of user selectable operating modes is as follows:

- Bore/drill rigs
- Compact excavators
- Compact track loaders
- Compactors
- Crawler dozers
- Crawler loaders
- Excavators
- Graders
- Loaders/backhoes
- Rubber tired dozers
- Scrapers
- Skid steer loaders
- Skidders
- Surfacing equipment
- Wheel loaders
- Wheeled excavators

The list of equipment in the agriculture sector which could benefit from the availability of user selectable operating modes is as follows:

- Combines
- Compact tractors
- Four-wheel-drive tractors
- Harvester
- Row crop tractors
- Tracked tractors
- Utility tractors

5.9 Other

5.9.1 Light-Weighting

The light-weighting of off-road equipment as a strategy to reduce fuel consumption would in theory be applicable to all pieces of equipment under consideration. If material could be removed, or if a different, less massive material could be used as a replacement, and the gross vehicle mass decreased with this removal of weight, fuel savings would result. However, it is likely that the removal of weight from a vehicle operating in the mining, construction and agricultural sectors would result in increased payloads being applied to the light-weighted vehicle, maintaining the same gross vehicle weight, but simply lowering the fraction of the gross vehicle weight consumed by the base vehicle.

In addition, there are some vehicles for which weight must exist as a form of counterbalance to offset loads placed on the vehicle. For example, agricultural tractors require differing counterbalance depending upon the implement they are employing or task they are undertaking. Excavators also require substantial counterbalance to offset the loads picked up by the bucket. These are two examples in which light-weighting would not be possible.

However, the light-weighting strategy could result in a reduction in material costs for the OEM if the light-weighting is a result of removing excess material. As design engineering capabilities increase through the effective implementation of computer modeling and simulation, weight reductions will be realized in all types of off-road equipment as a form of manufacturing costs savings, which in turn could result in reductions in overall fuel consumption if these gains were not used to carry excess load.

5.9.2 Tire Pressure Monitoring

The use of tire pressure monitoring systems is limited to pieces of equipment which have pneumatic tires. The list of equipment in the mining and construction sectors which could benefit from the use of tire pressure monitoring systems is as follows:

- Articulated dump trucks
- Graders
- Loaders/backhoes
- Off-highway trucks
- Road reclaimers
- Rubber tired dozers
- Scrapers
- Skid steer loaders
- Skidders
- Surfacing equipment
- Trenchers
- Wheel loaders
- Wheeled excavators

The list of equipment in the agriculture sector which could benefit from the use of tire pressure monitoring systems is as follows:

- Combines
- Harvester
- Sprayers
- Compact tractors
- Row crop tractors
- Utility tractors
- Four-wheel-drive tractors

6 CASE STUDIES

To further examine the costs associated with implementing the fuel consumption reduction strategies described within this report, and assess the payback period based on fuel savings, several case studies were undertaken. Case studies were limited to those equipment which are or were available for purchase both with and without the technology of interest.

Since actual fuel savings is dependent upon usage and load factor, an annual usage of 2000 hours was assumed, and both the low and high load factors detailed in Section 4.1.2 were used to calculate a range of fuel savings and payback periods. It is also assumed that coloured diesel will be used in the off-road equipment examined, which is less expensive than clear diesel since it is exempt from provincial road tax. The average provincial road tax in Canada is approximately 14.5 cents/litre. [34] The average retail price for clear diesel in Canada on March 11, 2014 was $1.454/litre [35], so for the purpose of calculating fuel savings, an average price of coloured diesel of $1.31/litre was assumed.

6.1 Hybridization

As defined in the Phase I NRC report [1], 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. Applied to off-road equipment used in the mining, construction and agricultural sectors, hybrid equipment could include those which use a diesel-electric drive system (whether they store energy or not), and those which recuperate energy using electric or hydraulic storage means. The following sections explore the potential fuel savings and payback periods of examples of such equipment.

6.1.1 John Deere 644K Hybrid Wheel Loader

In 2012, John Deere began selling the 644K Hybrid wheel loader alongside the 644K (non-hybrid) model. The list price of the 644K Hybrid was approximately $310,000, $53,000 more than the 644K. The average reported fuel consumption reduction was 25%. [36] The 644K Hybrid is shown in Figure 3.

Figure 3: John Deere 644K Hybrid Wheel Loader [37]

The 644K Hybrid uses a smaller engine (6.8 litre versus 9.0 litre), run at an operator selected constant speed between 900 and 1800 RPM, to drive an AC brushless generator. The power electronics supply power to the AC brushless motor, which drives a simplified three-speed transmission with no reverse clutch and no torque converter. The hybrid-electric drive efficiently recaptures energy to slow the loader when the operator releases the accelerator, and uses that energy to reduce the load on the engine to power hydraulics and auxiliary loads. No recaptured energy is stored – any excess is dissipated in a brake resistor. [37] [38]

Users report that the 644K Hybrid is easier to use and feels more powerful than the conventional 644K, and that greater productivity can be achieved, especially with a less-skilled operator. Since the engine runs at a constant speed (and the accelerator simply controls ground speed), full hydraulic power is immediately available. High torque is also available regardless of engine speed, since the electric motor generates near-maximum torque at low speeds. For activities such as V-pattern truck loading, it may be possible to completely eliminate shifting and braking. The noise level is reduced since the engine runs at a slower, constant speed (compared to the conventional 644K). Maintenance costs are expected to be reduced since there are fewer components requiring maintenance, reduced engine RPM and loading cycles, and reduced brake and tire wear. [39]

To determine the range of payback period for the 644K Hybrid (based solely on the reduction in fuel consumption), the average fuel consumption rate for the conventional 644K loader is used as the baseline. The nominal engine power for the 644K is 173 kW, so at a fuel consumption rate of 225 g/kW-h, as detailed in Section 4.1.1, and an assumed specific gravity of diesel fuel of 0.82 kg/litre, the baseline fuel consumption for the 644K is 31.9 litres/hour (at 100% load). The annual savings and payback period, assuming an annual usage of 2000 hours and a fuel price of $1.31/litre (for coloured diesel), for both a low and high load factor, are presented in Table 11.

Table 11: Payback Period – John Deere 644K Hybrid Wheel Loader

Load Factor	Savings		Payback Period (Years)
	Litres/Year	$/Year	
Low (0.38)	6,065	$7,944.51	6.7
High (0.70)	11,171	$14,634.63	3.6

6.1.2 **Caterpillar D7E Bulldozer:**

In 2009, Caterpillar introduced the D7E diesel-electric bulldozer, phasing out the comparable D7R Series II bulldozer in 2010. The list price of the D7E was $600,000, approximately $100,000 more than the obsolete D7R. [40] The average claimed fuel consumption reduction was 20%. [41] The D7E bulldozer is shown in Figure 4.

Figure 4: Caterpillar D7E Bulldozer [41]

The D7E bulldozer uses a smaller engine (9.3 litre versus 10.3 litre) to drive an AC generator, which generates the necessary AC power to run two brushless drive motors. An inverter provides DC current to run accessories including the engine water pump, lighting and HVAC. There is no transmission, as the required ground speed, direction and steering are achieved by the variable speed, reversible electric drive motors. The driveline is similar to that of a diesel-electric locomotive. [41]

The drivetrain of the D7E bulldozer comprises approximately 60% fewer moving parts than the D7R, contributing to longer life and reduced maintenance. The engine speed is maintained within a tight operating range of 1500-1800 RPM, which helps to extend engine life and improve fuel economy. The electric drivetrain improves manoeuvrability, contributing to improved bulldozer efficiency (measured in material moved per hour) of approximately 10%. [42]

To determine the range of payback period for the D7E bulldozer (based solely on the reduction in fuel consumption), the average fuel consumption rate for the D7R bulldozer is used as the baseline. The nominal engine power for the D7R is 179 kW, so at a fuel consumption rate of 225 g/kW-h, as detailed in Section 4.1.1, and an assumed specific gravity of diesel fuel of 0.82 kg/litre, the baseline fuel consumption for the D7R is 33.0 litres/hour (at 100% load). The annual savings and payback period, assuming an annual usage of 2000 hours and a fuel price of $1.31/litre (for coloured diesel), for both a low and high load factor, are presented in Table 12.

Table 12: Payback Period – Caterpillar D7E Bulldozer

Load Factor	Savings		Payback Period (Years)
	Litres/Year	$/Year	
Low (0.38)	5,020	$6,576.04	15.2
High (0.70)	9,247	$12,113.75	8.3

6.1.3 **Caterpillar 336E H Hybrid Excavator**

In 2013, Caterpillar began selling the 336E H hybrid excavator alongside the 336E (non-hybrid) model. The list price of the 336E H was $432,640, $35,400 more than the 336E. The average claimed fuel consumption reduction was 25%. [43] The 336E H hybrid excavator is shown in Figure 5.

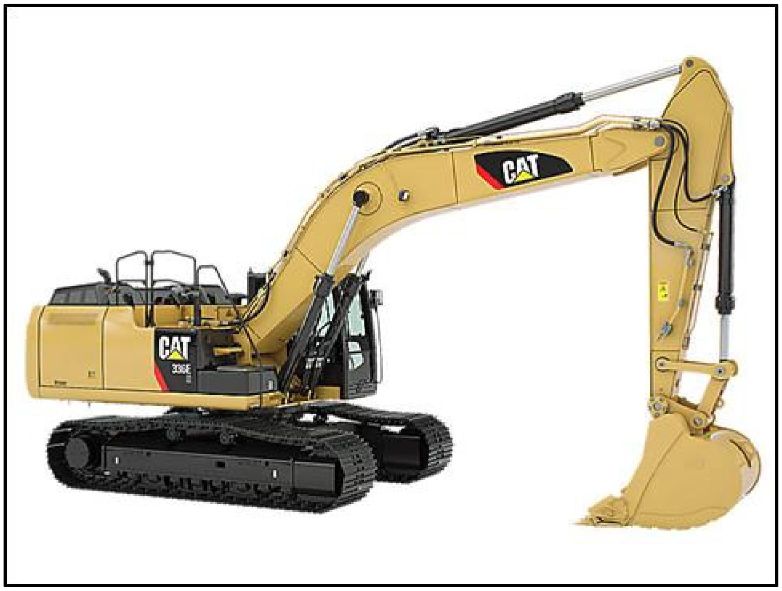

Figure 5: Caterpillar 336E H Hybrid Excavator [44]

The 336E H excavator uses the same 9.3 litre engine as the 336E model, configured to produce 213 kW versus 224 kW. It employs two nitrogen gas hydraulic accumulators that absorb energy from the swing, effectively braking the swing motion, and then using that stored energy to do work. The result is less load on the engine, leading to improved fuel efficiency. A specialized control system valve manages the flow of hydraulic fluid, and a specialized pump adjusts the hydraulic flow as required. [45]

The engine on the 336E H excavator operates at 1500 RPM versus 1800 RPM on the 336E model, which results in quieter operation and longer expected engine life. Operators report that it seems to respond faster and would likely lead to greater productivity. [46]

To determine the range of payback period for the 336E H hybrid excavator (based solely on the reduction in fuel consumption), the average fuel consumption rate for the 336E excavator is used as the baseline. The nominal engine power for the 336E is 224 kW, so at a fuel consumption rate of 225 g/kW-h, as detailed in Section 4.1.1, and an assumed specific gravity of diesel fuel of 0.82 kg/litre, the baseline fuel consumption for the 336E is 41.3 litres/hour (at 100% load). The annual savings and payback period, assuming an annual usage of 2000 hours and a fuel price of $1.31/litre (for coloured diesel), for both a low and high load factor, are presented in Table 13.

Table 13: Payback Period – Caterpillar 336E H Hybrid Excavator

Load Factor	Savings		Payback Period (Years)
	Litres/Year	$/Year	
Low (0.38)	7,852	$10,286.54	3.4
High (0.70)	14,465	$18,948.89	1.9

6.2 Continuously Variable Transmissions

While hydrostatic drive systems are common in mining, construction and agricultural equipment since they offer continuously variable gear ratios, they are typically less efficient than a mechanical drive system. The following section describes a wheel loader with an advanced powertrain which combines the variability of a hydraulic drive with the efficiency of a mechanical drive.

6.2.1 Caterpillar 966K XE Wheel Loader

In 2012, Caterpillar began selling the Cat 966K XE wheel loader, which incorporates an advanced powertrain system compared to its 966K sibling. The list price of the 966K XE was $474,000, $24,000 more than the 966K. [47] The average claimed fuel consumption reduction was 25%. [48] The 966K XE wheel loader is shown in Figure 6.

Figure 6: Caterpillar 966K Wheel Loader [49]

The 966K XE uses the same 9.3 litre engine as the 966K model, configured to produce 220 kW versus 199 kW. The 966K XE incorporates a CVT where a hydraulic pump and motor (variator unit) are used to achieve a smooth and continuous gear ratio change between engine speed and machine speed. Power is transmitted through both the variator unit and a parallel mechanical gear path, and that power is combined through a series of planetary gear sets in order maximize the transmission efficiency over a wide range of operating conditions. [48]

The advanced powertrain system on the 966K XE eliminates manual shifting. It automatically selects the suitable gear ratio for transport (roading) and pushing to load the bucket (loading). It facilitates frequent direction changes and varying torque requirements continually experienced by a wheel loader. It also permits the engine to operate at a lower speed, independent of ground speed.

To determine the range of payback period for the 966K XE wheel loader (based solely on the reduction in fuel consumption), the average fuel consumption rate for the 966K wheel loader is used as the baseline. The nominal engine power for the 966K is 199 kW, so at a fuel consumption rate of 225 g/kW-h, as detailed in Section 4.1.1, and an assumed specific gravity of diesel fuel of 0.82 kg/litre, the baseline fuel consumption for the 966K is 36.7 litres/hour (at 100% load). The annual savings and payback period, assuming an annual usage of 2000 hours and a fuel price of $1.31/litre (for coloured diesel), for both a low and high load factor, are presented in Table 14.

Table 14: Payback Period – Caterpillar 966K XE Wheel Loader

Load Factor	Savings		Payback Period (Years)
	Litres/Year	$/Year	
Low (0.38)	6,976	$9,138.49	2.6
High (0.70)	12,850	$16,834.06	1.4

7 DISCUSSION

7.1 Normalized Fuel Consumption Rate

The normalized fuel consumption rate detailed in Section 4.1.1 was selected based on values published in the literature. Given the recent advancements in diesel engine technology (detailed below), this value may be obsolete, and a current value might be lower. If this were the case, the fuel consumption reduction factors presented in Table 10 would be lower, and the payback periods presented in the case studies in Section 6 would be longer. Where actual fuel consumption data is available it should be used.

7.2 Measurement of Fuel Consumption Reductions

Throughout this report, the fuel consumption metric of g/kW·h was used to compare the effectiveness of the fuel consumption reduction technologies and strategies under consideration. However, if fuel consumption reduction regulations were to be implemented in the off-road sector, the g/kW·h measurement may not necessarily be the most appropriate metric. From an environmental standpoint, the primary goal for the reduction in fuel consumption is the reduction of emissions of greenhouse gases, namely CO_2. Therefore, a more appropriate metric may be g_{CO2}/kW·h, which is also used to measure particulate matter and NO_x emissions. It will be important to select an appropriate metric by which future off-road vehicles will be rated.

In addition to the selection of an appropriate fuel consumption metric, repeatable drive cycles for every type of off-road equipment will need to be created to allow for a standardized test method which is transferable across tested platforms. These drive cycles will need to be based upon real life equipment usage profiles to ensure realistic results.

Another important consideration which must be taken into account when considering the measurement of fuel consumption is whether only the engine should be tested or whether the entire vehicle should be tested. Given the various sizes, shapes and functions of off-road vehicles, testing the system as a whole may not be feasible. However, performing measurement tests only on the engine will negate any of the possible fuel savings attained through fuel consumption reduction technologies or strategies which do not act directly on the engine.

7.3 Return on Investment for Fuel Saving Technologies

Despite the high purchase price of large off-road equipment, equipment dealers report difficulty selling equipment with an optional premium for fuel saving technologies that cannot be reasonably recovered within 1-2 years. As detailed in the case studies in Section 6, the payback period is highly dependent upon the load factor, as well as the price of fuel and the annual usage. As fuel prices rise or usage increases, the payback period becomes shorter. A hybrid excavator, for example, is more appealing for forestry operations versus construction sites, since at a construction site an excavator is often idle, waiting for a dump truck or its next task.

The life expectancy of a piece of equipment also affects the acceptable payback period. For example, a bulldozer is typically kept in service much longer than a wheel loader, so a longer payback period may be acceptable. A new farm tractor, on the other hand, is often traded after a few years (according to a John Deere representative), so the acceptable payback period for optional fuel-saving features may be very short.

Note that there may be other motivation for adopting optional technologies that result in fuel savings, like hybridization, such as faster equipment response or simplified operation.

7.4 Fuel Consumption Reduction Due to Mandated Emissions Reduction

Regulations imposed on OEMs to reduce emissions from off-road engines has resulted in significant engine development and refinement. The improvements not only reduced emissions but also improved engine performance and efficiency, typically reducing fuel consumption as well.

Starting in 1996, the United States Environmental Protection Agency (U.S. EPA) enacted legislation to reduce oxides of nitrogen and particulate matter emissions from new compression ignition engines used in off-road equipment. Canada adopted regulations aligned with those of the U.S. in 2006. The regulations were applied in tiers which became more stringent, ultimately reducing emissions to near zero levels with the introduction of Tier 4 (final) regulations in 2014. A summary of the Tier 1-4 emissions limits for the 130-560 kW classification of off-road equipment, illustrating the significant reductions, is shown in Figure 7.

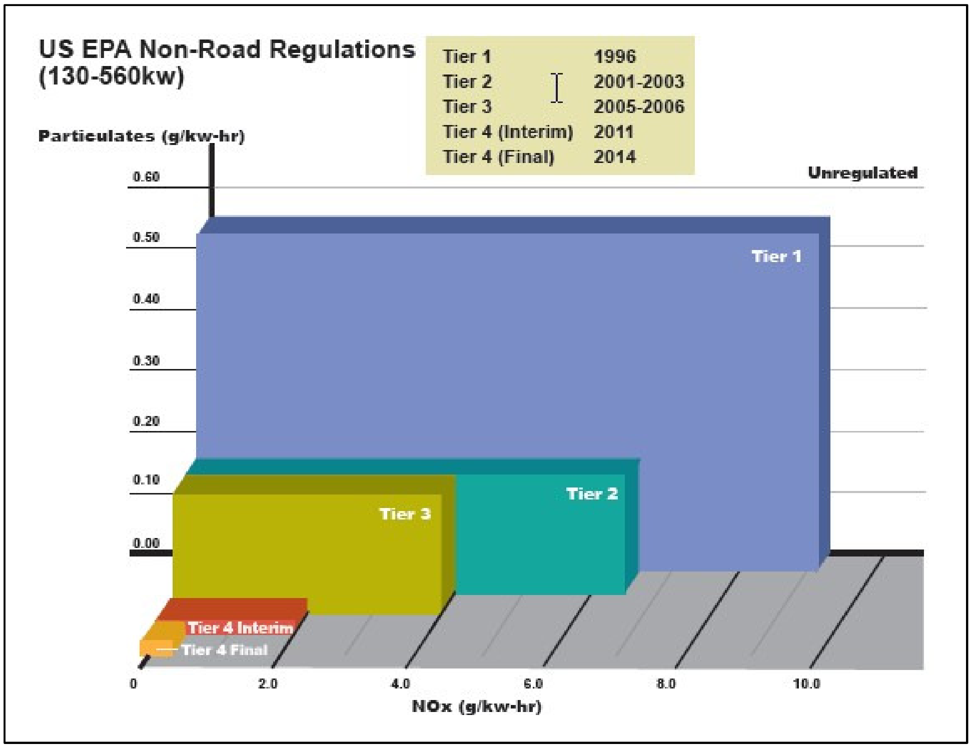

Figure 7: Summary of Tier 1-4 Emissions Limits for 130-560 kW Off-Road Equipment [50]

The mandated emissions reduction was achieved through the use of advanced technologies including electronic engine controls, high pressure fuel injection systems, and advanced turbocharging (in addition to exhaust after-treatment). Without the regulations, there would not likely have been the same push for technological development since there would not have been any direct benefit to the operators. Similarly, Corporate Average Fuel Economy (CAFE) regulations have led to technological advances and improved fuel efficiency for passenger cars and light trucks. At present there are no such regulations in place to reduce the fuel consumption of off-road engines, and it can be assumed that introducing such regulations would likely result in more fuel-efficient engines.

Since the off-road emissions regulations apply to new products only and do not apply retroactively to any existing equipment, there is no requirement or incentive (other than fuel savings, perhaps) for owners to purchase new equipment and retire old engines. It is not uncommon to still see tractors and combines from the 1950s and 1960s. [51] However, some construction projects have included consideration of the age and emissions performance of the fleet of machines to be used during the bid process. California has implemented regulations for the modernizing and upgrading of off-road machines and equipment in that state, where fleet average and Best Available Control Technology (BACT) requirements were slated to take effect on January 1, 2014 for large fleets (greater 3730 kW). The new requirements can be met by replacement of engines with newer technology, or acceptable upgrade through retrofit. [52] California also has legislation in place to limit unnecessary idling. So while further technological advances to improve fuel efficiency are possible, significant reductions in fuel consumption could also be achieved by promoting the replacement of older equipment/engines with newer ones.

7.5 Implications of Greenhouse Gas Regulations

The reduction of fuel consumption in an attempt to reduce the overall production of greenhouse gases in the mining, construction and agricultural sectors is of importance for a variety of reasons. Apart from the harmful environmental effects associated with the release of greenhouse gases, there is a necessity to reduce reliance on non-renewable resources as well as to reduce operating costs in the off-road sectors. The latter factor – the reduction of operating costs – is currently the principal driver for the implementation of fuel consumption reducing technologies and strategies. Although it may not be the most important long term consideration associated with the reduction in fuel consumption, the reduction of operating costs associated with fuel consumption is currently the only incentive for OEMs to research methods to reduce fuel consumption – as a means to generate purchasing incentive for owners and operators.

At present there are no existing regulations requiring OEMs to achieve specified fuel consumption targets for their off-road engines. It may be difficult to determine the effect on industry if such regulations were imposed, but if the implementation of the tiered reduction of regulated emissions is used as a road map, OEMs will invest heavily to meet the requirements in order to remain competitive in the market. If fuel consumption reduction regulations were introduced, it would be necessary to implement them in a manner that does not require OEMs to invest at such a rate that would threaten their ability to remain competitive in global markets.

This study has provided insights into the possible upper bounds of fuel consumption reduction regulations. It is possible, based upon the research, that OEMs could achieve a 20% reduction in fuel consumption by focusing only on the optimization of compression ignition internal combustion engines (as detailed in section 5.2). Although further reductions could be realized through the application of various electrification strategies, hybridization techniques, parasitic loss reductions, or similar improvements, the reduction of fuel consumption due to engine optimization represents the most universal approach to the reduction in greenhouse gas emissions: each piece of equipment using an internal combustion engine would benefit from these improvements.

Since the overarching goal is to reduce the emission of greenhouse gases, the reduction in fuel consumption through the optimization of the internal combustion engine should not be the long term solution. The 20% reduction in fuel consumption should be realized as a short to mid-term goal, within the next 10 to 15 years. The long term goal should focus on the elimination of the emission of greenhouse gases. The advances being made in the development of hydrogen fuel cells are indicating that this technology has excellent potential as a mid to long term solution. If the targets for fuel cell power density and specific power, as well as cost targets and hydrogen storage targets (as detailed in section 2.6) are achieved, the use of hydrogen fuel cells will become a viable alternative to diesel and gasoline internal combustion engines. This will of course require a large investment in hydrogen generation facilities as well as in the infrastructure required to transport and distribute hydrogen. It should also be noted that this study did not investigate the challenges associated with the establishment of a hydrogen supply chain of sufficient capacity to meet the needs of the off-road sector under consideration.

Although it may not be entirely necessary to regulate fuel consumption reduction to control greenhouse gas emissions from the off-road sector, since continually rising oil prices may create an external economic necessity for doing so, a short to mid-term fuel reduction target of 20% is likely achievable through engine optimization. Further reductions may be achievable through continued research and development, but they may only be realized once suitable regulations are implemented and OEMs invest in methods to achieve the fuel consumption reduction targets.

8 CONCLUSIONS

A thorough literature review was conducted to identify any recently developed or improved fuel saving technologies or strategies that could be implemented on any form of off-road equipment. The following were found to be the most relevant:

- displacement controlled hydraulic actuation
- equipment operating modes
- low temperature combustion
- ultra low particulate combustion
- hydrogen fuel cells

The qualitative technology/strategy-to-application matrix, presented in the previous phase of work [1], was updated to incorporate the technologies or strategies listed above. It was noted that low temperature combustion and ultra low particulate combustion were applicable to all sectors, and fuel cells were applicable to most sectors.

The technologies/strategies specifically listed in the project proposal [2], plus those identified during the literature review, were then ranked using four weighted criteria: reduction in fuel consumption, readiness of the technology or strategy for immediate use, the prevalence of the technology or strategy within commercially available equipment, and the ease of implementation of the technology or strategy. The top five technologies/strategies identified by the ranking exercise, and their ratings against the ranking criteria, are summarized in Table 15.

Table 15: Summary of top five technologies/strategies

Technology/ Strategy	Ranking	Reduction in Fuel Consumption	Implementation Readiness	Industry Prevalence	Ease of Implementation
low temperature combustion	1	>20%	Proof of concept built and tested	Non-existent	Relatively easy to implement. Low reluctance of adoption within industry.
hybridization	2	>20%	Limited availability for commercial purchase	Moderately implemented	Moderately difficult to implement. Moderate reluctance of adoption within industry.
DC hydraulic actuation	3	>20%	Limited availability for commercial purchase	Moderately implemented	Moderately difficult to implement. Moderate reluctance of adoption within industry.
fuel cells	4	>20% (100%)	Limited availability for commercial purchase	Limited implementation	Highly difficult to implement. High reluctance of adoption within industry.
electrification	5	>20%	Limited availability for commercial purchase	Limited implementation	Extremely difficult to implement. Extreme reluctance of adoption within industry.

Using potential fuel consumption reduction values from the literature review, and a normalized fuel consumption rate, the potential fuel savings for each of the technologies or strategies, applied to the mining, construction and agricultural sectors, was calculated. The applicability of each of the technologies or strategies to sector specific equipment was also evaluated.

It was concluded that there were no readily available technologies or strategies that could be easily implemented in isolation for the mining, construction and agricultural sectors, to achieve significant fuel consumption reduction. Recent engine development to meet strict emissions regulations naturally resulted in more fuel-efficient engines, incorporating proven engine technologies. Without regulations to drive further engine development to reduce fuel consumption, there is little incentive for OEMs to invest in the necessary research and development.

Several case studies were performed to investigate the fuel consumption reduction and the return on investment, for specific fuel consumption reduction technologies which are commercially available. The case studies were limited to those pieces of equipment which could be purchased with and without the specific technology. Given these constraints, the case studies were limited to three examples of hybridization and one example of CVT. Based on assumptions regarding usage and fuel cost, the payback period ranged from 1.4 to 15.2 years. Dealers reported general consumer reluctance to invest in such technologies, with interest limited to specific applications where the payback period would be relatively short.

It was noted that the most significant short-term reduction in fuel consumption would likely result from the replacement of older, less fuel efficient engines and equipment with modern ones incorporating the latest technologies. With suitable regulations in place, it is possible that OEMs could achieve a 20% reduction in fuel consumption in the mid-term by focusing strictly on the optimization of compression ignition internal combustion engines. The longer term solution, however, should focus on the elimination of the emission of greenhouse gases, which may be achievable using technologies such as hydrogen fuel cells.

9 RECOMMENDATIONS

To further advance the reduction of fuel consumption in the mining, construction and agricultural sectors, NRC-AST provides the following recommendations:

1. In order verify the potential fuel savings of specific (individual) fuel consumption reduction technologies or strategies, implemented on a specific piece of off-road equipment, a series of fuel consumption tests should be conducted where the technology of interest is isolated and individually applied to the equipment under test. This testing should be performed not simply on a test engine, but on a complete piece of test equipment performing identical tasks for each fuel consumption test.
2. Data should be collected from in-service equipment in the mining, construction and agricultural sectors to identify typical operational profiles. These typical profiles or duty cycles could be used to develop standardized operational profiles, which could then be applied to calculations or laboratory tests to assess the real-life fuel savings that could expected by implementing certain fuel consumption reduction technologies or strategies.

10 ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AHS	Autonomous Haulage System
AST	Automotive and Surface Transportation
CNH	Case New Holland
CVT	Continuously Variable Transmission
DC	Displacement Controlled
EC	Environment Canada
EGR	Exhaust Gas Recirculation
FCRF	Fuel Consumption Reduction Factor
GDCI	Gasoline Direct-Injection Engine
GPS	Global Positioning System
HCCI	Homogeneous-Charge Compression Ignition
HVAC	Heating, Ventilation and Air Conditioning
kg	kilogram
kW	kilowatt
L	litre
LED	Light Emitting Diode
LTC	Low Temperature Combustion
m	metre
NRC	National Research Council
OEM	Original Equipment Manufacturer
PCCI	Premixed-Charge Compression Ignition
PEM	Polymer Electrolyte Membrane
PTO	Power Take-Off
RCCI	Reactivity Controlled Compression Ignition
RPM	revolutions per minute
ULPC	Ultra Low Particulate Combustion
V	volt

11 REFERENCES

[1] C. Griffin, E. Toma, D. Chuang and J. Patten, "Environmental Study of Off-Road Engine Technologies," National Research Council Canada, Ottawa, Canada, 2012.

[2] National Research Council Canada, *NRC- Automotive & Surface Transportation Proposal - Off-Road Emissions - Phase II,* Ottawa: National Research Council Canada, 2013.

[3] N. Canter, "Improving Efficiency of Mobile Hydraulic Systems," October 2008. [Online]. Available: http://www.stle.org/assets/document/tech_beat_10-08.pdf. [Accessed 03 03 2014].

[4] M. Gannon, "CCEFP Features High-Efficiency Excavator," 16 Feb 2011. [Online]. Available: http://hydraulicspneumatics.com/200/IndZone/Construction/Article/False/86932/IndZone-Construction. [Accessed 03 03 2014].

[5] K. Heybroek, "Saving Energy in Construction Machinery Using Displacement Control Hydraulics - Concept Realization and Validation," Linköping Studies in Science and Technology, Linköping, 2008.

[6] N. Daher and M. Ivantysynova, "New Hydraulic Technology for Efficient Machine Steering," *RESOURCE Engineering and Technology for a Sustainable World,* pp. 17-19, January/February 2014.

[7] N. Daher and M. Ivantysynova, "Pump Controlled Steer-by-Wire System," SAE International, 2013.

[8] "More Efficient Hydraulic Systems Save Fuel," 16 12 2008. [Online]. Available: http://hydraulicspneumatics.com/200/TechZone/HydraulicPumpsM/Article/False/83398/TechZone-HydraulicPumpsM. [Accessed 25 02 2014].

[9] C. Frey, W. Rasdorf and P. Lewis, "Results of a Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment," Transportation Research Record, Raleigh, 2010.

[10] Raczon, Frank, "Work Modes, Fuel Savings Make Excavators Pay Off," 17 02 2014. [Online]. Available: http://www.constructionequipment.com/4060. [Accessed 27 02 2014].

[11] L. Brooke, "Delphi and Hyundai GDCI program aims to top diesel efficiency - SAE International," SAE International, 17 02 2014. [Online]. Available: http://articles.sae.org/12823/. [Accessed 26 02 2014].

[12] D. Yoo, D. Kim, W. Jung, N. Kim and D. Lee, "Optimization of Diesel Combustion System for Reducing PM to Meet Tier4-Final Emission Regulation without Diesel Particulate Filter," SAE International, Warrendale, PA, 2013.

[13] S. Smith, "Bobcat Launches Tier 4 500 Frame-Size Loaders with Non-DPF Emissions Solution," Bobcat Company, West Fargo, ND, 2013.

[14] S. Srinivasan, Fuel Cells - From Fundamentals to Applications, New York: Springer Science+Business Media LLC, 2006.

[15] New Holland Agriculture, "New Holland NH2 Hydrogen Powered Tractor," New Holland, Turin, Italy, 2009.

[16] J. Patrico, "Fuel Cell Tractor Still Cranking," The Progressive Farmer, 15 November 2012. [Online]. Available: http://www.dtnprogressivefarmer.com/dtnag/view/ag/printablePage.do?ID=BLOG_PRINTA

BLE_PAGE&bypassCache=true&pageLayout=v4&blogHandle=agequipment&blogEntryId=8a82c0bc3aca540d013b0517321e027c&articleTitle=Fuel+Cell+Tractor+Still+Cranking&editionName=DTNAgFre. [Accessed 10 March 2014].

[17] U.S. Department of Energy, "Fuel Cell Technologies Office: Multi-Year Research, Development, and Demonstration Plan," U.S. Department of Energy, Washington D.C., 2012.

[18] U.S. Department of Energy, "DOE Hydrogen and Fuel Cells Program: 2013 Annual Progress Report," U.S. Department of Energy, Washington, D.C., 2013.

[19] Caterpillar, "Cat | 797F Mining Truck | Caterpillar," Caterpillar, 2014. [Online]. Available: http://www.cat.com/en_US/products/new/equipment/off-highway-trucks/mining-trucks/18093014.html. [Accessed 20 March 2014].

[20] Caterpillar, "Caterpillar C175 Specifications," Caterpillar, 2012.

[21] Office of Energy Efficiency & Renewable Energy, "Roadmap and Technical White Papers," United States Department of Energy, Washington, DC, 2013.

[22] K. McMahon, "Kinze's autonomous tractor system tested in field by farmers," Farm Industry News, 12 November 2012. [Online]. Available: http://farmindustrynews.com/precision-guidance/kinze-s-autonomous-tractor-system-tested-field-farmers?page=1. [Accessed 12 March 2014].

[23] CNH America, *Precision Land Management: Farm With Precision,* New Holland: CNH America, 2013.

[24] Construction Equipment, "Earthmoving Report: CAT K2 Dozers Offer Finely Tuned Finish Grading," Construction Equipment, 28 February 2012. [Online]. Available: http://www.constructionequipment.com/earthmoving-report-cat-k2-dozers-offer-finely-tuned-finish-grading. [Accessed 17 March 2014].

[25] Komatsu, "Komatsu: Service and Solutions," Komatsu, 2005. [Online]. Available: http://www.komatsu.com/CompanyInfo/profile/product_supports/. [Accessed 17 March 2014].

[26] Zero Motorcycles, Inc., "Zero Motorcycles (Canada) || Zero DS Electric Motorcycle," Zero Motorcycles, Inc., 2014. [Online]. Available: http://www.zeromotorcycles.com/ca/zero-ds. [Accessed 7 March 2014].

[27] CrossChasm, "library.crosschasm.com," CrossChasm, 19 August 2013. [Online]. Available: library.crosschasm.com. [Accessed 10 March 2014].

[28] Food and Agriculture Organization of the United Nations, "Cost Control in Forest Harvesting and Road Construction," Food and Agriculture Organization of the United Nations, Rome, 1992.

[29] Diesel Service & Supply, "Approximate Diesel Generator Fuel Consumption Chart," Diesel Service & Supply, 2013. [Online]. Available: http://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx. [Accessed 4 03 2014].

[30] B. D. Hsu, Practical Diesel-Engine Combustion Analysis, Warrendale: Society of Automotive Engineers, 2002.

[31] J. Crompton, "Mining, Oil & Gas Machinery Manufacturing in the US," IBISWorld Inc, New York, 2013.

[32] J. Edwards, "Construction Machinery Manufacturing in the US," IBISWorld Inc, New York, 2014.

[33] O. Harrison, "Tractors & Agricultural Machinery Manufacturing in the US," IBISWorld Inc, New York, 2013.

[34] "Motor Fuel Taxes in Canada," Wikipedia, 05 March 2014. [Online]. Available: http://en.wikipedia.org/wiki/Motor_fuel_taxes_in_Canada#Diesel_tax_rates_across_Canada. [Accessed 11 March 2014].

[35] "Average Retail Prices for Diesel in Canada," Natural Resources Canada, [Online]. Available: http://www2.nrcan.gc.ca/eneene/sources/pripri/prices_byyear_e.cfm?ProductID=5. [Accessed 12 March 2014].

[36] M. G. Doyle, "John Deere Demos 644K Hybrid Wheel Loader, Discusses Price Premium, Fuel Savings," Equipment World, 21 June 2013. [Online]. Available: http://www.equipmentworld.com/john-deere-demos-644k-hybrid-wheel-loader-discusses-price-premium-fuel-savings-video/. [Accessed 07 March 2014].

[37] John Deere, "644K Hybrid Wheel Loader," John Deere, [Online]. Available: http://www.deere.com/wps/dcom/en_US/products/equipment/wheel_loaders/644k_hybrid/644k_hybrid.page. [Accessed 07 March 2014].

[38] Walt Moore, "Discovering Benefits of Electricity in 644K Hybrid Loader," 28 October 2013. [Online]. Available: http://www.constructionequipment.com/644k. [Accessed 7 March 2014].

[39] C. Bennink, "John Deere 644K Hybrid Electrifies Loader Operation," 17 May 2013. [Online]. Available: http://www.forconstructionpros.com/article/10894788/john-deere-644k-hybrid-electrifies-wheel-loader-operation. [Accessed 07 March 2014].

[40] T. VanHampton, "Cat Reveals Pricing of World's First Hybrid Dozer," 24 June 2009. [Online]. Available: http://enr.construction.com/products/equipment/2009/0624-CATRevealsHybridDozer.asp. [Accessed 10 March 2014].

[41] "D7E (U.S. Tier 4 Interim/EU Stage IIIB/Japan MLIT Step 4)," CAT, [Online]. Available: http://www.cat.com/en_US/products/new/equipment/dozers/medium-dozers/18429156.html. [Accessed 07 March 2014].

[42] Larry Stewart, "Caterpillar's D7E Electric Drive Redefines Dozer Productivity," 01 April 2008. [Online]. Available: http://www.constructionequipment.com/caterpillars-d7e-electric-drive-redefines-dozer-productivity. [Accessed 07 March 2014].

[43] "Expect More With Your CAT Excavator," CAT, [Online]. Available: http://www.catallday.com/hybrid/. [Accessed 10 March 2014].

[44] CAT, "336E H Hybrid," CAT, [Online]. Available: http://www.cat.com/en_US/products/new/equipment/excavators/large-excavators/18378156.html. [Accessed 07 March 2014].

[45] "GETTING INTO THE SWING - The Cat 336E H Cuts Cost, Not Power," CAT, [Online]. Available: http://www.catallday.com/hybrid/media/Cat336EH_Infographic_10-29-2013.pdf. [Accessed 10 March 2014].

[46] Walt Moore, "Caterpillar Hybrid Excavator Technology Sells Itself to Expert Operators," 03 May 2013. [Online]. Available: http://www.constructionequipment.com/336eh. [Accessed 10 March 2014].

[47] J. Thornton, Interviewee, *CAT Special Applications Manager.* [Interview]. 11 March 2014.

[48] "The New Cat® 966K XE: Efficient. Comfortable. Sustainable.," CAT, [Online]. Available: http://www.cat.com/en_US/news/press-releases/the-new-cat-sup-174sup966kxeefficientcomfortablesustainable.html. [Accessed 07 March 2014].

[49] CAT, "966K," CAT, [Online]. Available: http://www.cat.com/en_US/products/new/equipment/wheel-loaders/medium-wheel-loaders/18102895.html. [Accessed 07 March 2014].

[50] D. T. Forum, "Clean Diesel Technology for Off-Road Engines and Equipment: Tier 4 and

More," 2010. [Online]. Available: http://www.aem.org/PDF/DTF_Tier4WP_FIN.pdf. [Accessed 21 March 2014].

[51] Brian Bienkowski, "Dirty for Decades, Diesel Tractors, Bulldozers Get Cleaned Up," 21 March 2014. [Online]. Available: http://www.environmentalhealthnews.org/ehs/news/2014/mar/diesel-cleanup. [Accessed 25 March 2014].

[52] "In-Use Off-Road Diesel Vehicle Regulation," California Environmental Protection Agency Air Resources Board, 18 March 2014. [Online]. Available: http://www.arb.ca.gov/msprog/ordiesel/ordiesel.htm. [Accessed 24 March 2014].

12 ACKNOWLEDGEMENTS

The following NRC-AST personnel contributed to this project:

- Jeff Patten, project engineering support and management
- David Poisson, project manager