ULTRACAPACITOR KINETIC ENERGY RECOVERY SYSTEMS IN ROAD TRANSPORT VEHICLES. IS IT A VIABLE RETROFIT OPTION FOR REDUCING FUEL CONSUMPTION AND CO_2 EMISSIONS?

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ABSTRACT

With the cities of Cape Town and Johannesburg being signatories to the C40 Cities Climate Leadership Group, there is strong commitment to Green-House Gas (GHG) reduction in South Africa. Given the high contribution of road transport to total GHG production, the sector needs to make significant progress toward reductions. Road transport assets have a long lifespan as a result, solutions need to be found to reduce the fuel consumption and hence the GHG emissions of existing assets. Adgero (France) has developed a Kinetic Energy Recovery System (KERS) for trucks and trailers designed as a retrofit to reduce fuel consumption and emissions by recycling braking energy. The system uses a high efficiency electric motor to recover kinetic energy and then stores it in ultracapacitors. This energy is then used to provide acceleration to the vehicle thereby reducing fuel consumption and CO_2 emissions. Peri-urban simulations in an IVECO 12 ton delivery truck show a 32.19% reduction in fuel consumption and CO_2 emissions with a return on investment of 21.9% on fuel savings alone. This paper discusses KERS systems and presents early results of ultra-capacitor electric KERS systems in simulated peri-urban mission profiles. These systems are due for commercial release in 2018.

1 INTRODUCTION

In 1896 a Swedish Physicist, Svante Arrhenius, published a paper: “On the influence of Carbonic Acid in the air upon the temperature of the ground”. This paper drew attention to this change in our climate and was the first published study quantifying the contribution of Carbon Dioxide levels in the atmosphere to an increase in the temperature of the Earth, or what we now refer to as the greenhouse effect. He predicted that a doubling of the CO_2 content in the atmosphere would lead to a 5 °C rise in the temperature of our planet (Arrhenius,1896). The pre-industrial revolution level of $C0_2$ in the atmosphere was ~280ppm. The $C0_2$ content in the atmosphere passed 400ppm in 2015 (NASA, 2015).

The 2016 State of the Climate Report presented to the United Nations Climate Conference in Morocco November 2016 (CFACT, 2016) argues against the causal relationship between CO_2 levels in the atmosphere and global warming. That there is an increase in actual CO_2 levels, as well as the role of fossil fuels in this is however, generally accepted. The Intergovernmental Panel on Climate Change has set target limits of 1.5 °C, and 2.0 °C for differing future scenarios in an attempt to induce action around climate change (Intergovernmental Panel on Climate Change, 2014).

In Cape Town, transport accounts for 34% of CO_2 emissions (Cape Town, 2015). In Durban transport accounts for 39% of CO_2 emissions with road transport making up 23% of CO_2 emissions (Somazembe, 2017).

2 CURRENT ROAD TRANSPORT EFFICIENCY IMPROVEMENT OPTIONS

The Ricardo Review on Low Carbon Technologies in Heavy Goods Vehicles (Baker et al, 2009) reported the following improvements in HD truck efficiency as achievable:

- Low rolling resistance tyres 5% fuel efficiency improvement
- Platooning 7-20% fuel reduction achievable dependant on speed
- Driver training improves fuel consumption on average 10,1% (initially)
- Engine efficiency through reduced friction and auxiliaries 4 – 7%
- Waste heat recovery 6%
- Transmission technologies 7%
- Start/Stop systems 6% (urban cycle)
- Electric Hybrid with KERS 15 – 30%, typically 20%

From the above analysis of available technological advancements it is clear that there are significant CO_2 reduction benefits to be had in the electric hybrid/KERS technologies. It is further reported that on a scale of 1 to 10 (10 being most favourable) the CO_2 reduction potential of Electric Hybrid/KERS systems in urban cycles rates 9, cost of technology rates 2, and maturity of the technology rates 6. This means that while the CO_2 reduction benefit for urban duty cycles is close to maximum, cost is a significant barrier to implementation despite the technology having crossed its major challenges and approaching commercial maturity. This study was reported in 2009, and significant advances have been made in KERS since then, more especially in the electrical energy storage systems. It is also important to note that each one of the improvement studies were developed in isolation, and that combining the interventions does not necessarily lead to a summation of the expected results.

Table 1 shows the expected improvements that would actually be realised by heavy vehicle manufacturers by 2020 with 2014 as baseline (Breemersch & Vanherle, 2016). The study did not provide data for alternative powertrains as the data for this was unavailable from the manufacturers.

Table 1: Vehicle related measures' reduction potential for new vehicles (Breemersch & Vanherle, 2016)

	Long Haul	Regional
Engine Efficiency	5.0%	4.5%
Auxilliaries Management	1.5%	1.7%
Transmission	0.5%	0.5%
Alternative Powertrains	N/A	N/A
Axles	0.5%	0.5%
Driver Assistance System	2.5%	2.5%
Total OEM	9.67%	9.38%
Tyres	4.0%	3.0%
Aerodynamic Aids	4.0%	3.0%
Weight Reduction	0.5%	0.9%
Total Others	8.30%	6.76%

With vehicle manufacturers being slow to respond with alternative powertrains, the market is open for aftermarket technology providers to offer commercially viable solutions. An analysis of the fuel consumption reduction potential of current available technologies in the USA is presented in Table 2 (Jackson, 2011). This study demonstrates that a 40 to 50% fuel usage reduction is possible using new technologies. The study further quantifies the cost /benefit for these implementations with the truck tractor use case being the most expensive to implement at USD 1 731 per one % improvement. Despite its high cost, the truck tractor application provides a 7 year payback proposition. The role of hybrid technologies (including KERS) in reducing fuel consumption is significant, providing a 10 to 40% reduction. Improved commercial viability of these technologies would possibly result in a more widespread implementation which would drive down costs.

Table 1: Potential for fuel consumption reduction through aggressive deployment of new technologies (Jackson, 2011)

Category	Truck Tractor	Box Truck	Bucket Truck	Refuse	Bus	Coach	HD Pickup
Aerodynamics	11.5%	6%				8%	3%
Engine	20%	14%	14%	14%	14%	20%	23%
Weight Reduction	1.3%	4%	4%	1%	6.3%	1.1%	0.8%
Tyres	8%	3%	3%	2.5%	1.5%	3%	2%
Transmission	7%	4%	4%	4%	4%	4.5%	7.5%
Hybrid	10%	30%	40%	25%	35%		18%
Management and Coaching	6%						
Idle Reduction							
Sub-Total	49.3%	49.4%	51.3%	40.2%	50.4%	32.5%	43.2%
Added Weight (lb)	2500	1100	1050	1500	2000	1500	750
Adjusted Fuel Consumption	48.9%	47.1%	49.6%	38.4%	47.8%	32.0%	44.5%
Cost	$ 84600	$ 43120	$ 49870	$ 50800	$ 74400 $250400	$ 36350	$ 14710
$/% Benefit	$ 1731	$ 916	$ 1006	$ 1322	$ 1556	$ 1136	$ 331

In Europe, the CONVENIENT project aims to achieve a 30% fuel reduction in long-haul applications through a multi-technology implementation. KERS is expected to contribute 5-

7% to this goal (Bracco et al., 2016). In the South African context in particular, a comparison of hydrogen, hybrid and electric technologies reports that hybrid is the ideal technology until 20% saturation, at which point Battery Electric Vehicles (BEV) would be viable (Gajjar & Mondol, 2016).

3 KINETIC ENERGY RECOVERY SYSTEMS

In a vehicle powered by an internal combustion engine, braking is usually effected by means of a disc or drum brake. Friction is applied to convert kinetic energy to heat which is then dissipated (wasted). Most kinetic energy recovery systems work by applying an alternative form of braking which converts the kinetic energy into a form of energy which may be stored. This energy is then accumulated in a storage system and then when required, it is applied to generate motive force which displaces fuel usage (Tie & Tan, 2013). There is also a KERS type that converts suspension oscillations into electrical energy and stores it for use (Sliwinski, 2016).

Kinetic energy storage and recovery systems are not new, in fact in the 1950s the Gyrobus used an electric motor to spin up a 1.5 ton flywheel with diameter 1.6m to a speed of up to 3000 rpm (Proaktiva, 2008). This system allowed the bus to achieve a maximum speed of 55km/h and necessitated charging stations every 5km. The flywheel took 40 minutes to reach operational rpm at start up, but the recharging stations only required 2 to 5 minutes to restore maximum operational rpm. This vehicle could recover braking energy to recharge the flywheel.

In 2009, KERS rose to prominence due to its use into Formula One motor racing. These systems used an electric motor to capture braking energy which was then stored using lightweight flywheel systems to provide an extra 60 kW of power on demand to the driver (Cibulka, 2009). Alternative systems store the energy in batteries or capacitors. This renewed interest in KERS as a source of automotive efficiency.

Figure 1 shows the “Flybrid” KERS technology as used by Volvo in the Volvo S60 passenger vehicle with fuel efficiency improvements of 25% (Volvo, 2014). The system uses a lightweight carbon and steel flywheel spinning at up to 60 000 rpm.

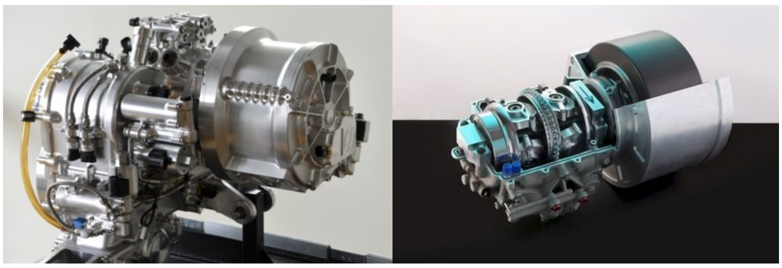

Figure 1: Flybrid flywheel KERS system as used in Volvo S60 (Volvo, 2014)

Table 3 shows the (estimated) potential of regenerative powertrain systems in goods vehicles and suggest that improvements in fuel consumption and carbon emissions of 8 to

12 % is possible in urban and regional delivery vehicles, and 3% to 5% in long-haul applications (Smokers & Van Zyl, 2016).

Table 2: Potential for Regenerative Energy in Road Transport
(Smokers, R; Van Zyl, 2016)

Effective Savings Potential	Service Delivery	City Distribution	Regional Delivery	Long Haul	Bus	Coach
Light Commercial vehicle	-10%					
Rigid Truck (Heavy)		-11%	-9%	-4%		
Rigid Truck (Medium)		-10%	-9%	-3%		
Rigid Truck (Light)		-8%	-8%	-3%		
Articulated Truck (Heavy)		-10%	-8%	-4%		
Articulated Truck (Light)		-10%	-8%	-3%		
Tractor Semitrailer (Heavy)		-12%	-10%	-5%		
Tractor Semitrailer (Light)		-10%	-8%	-3%		
Tractor Semitrailer (Other)		-11%	-9%	-4%		
Bus					-10%	-5%

There are a number of different types of KERS systems with the more popular being:

- Electric regenerative systems
  These systems use an electric motor to harness braking energy and store it in batteries or more recently, in ultracapacitors. When the vehicle needs propulsion assistance, this energy is used to drive the electric motors.

- Hydraulic systems
  These systems use hydraulic pumps to capture braking energy. This energy is stored in special high pressure accumulators and used to provide motive force when required. Usually the hydraulic pumps are reversible to function as a motor.

- Pneumatic systems
  These systems function similarly to the hydraulic systems, but use compressed air as the energy storage medium.

- Flywheel systems
  The flywheel system uses a set of gears to speed up a flywheel during the braking effort thus converting the braking energy to flywheel spin. The flywheel is usually housed in a near vacuum and uses ultra-low friction bearings. This allows the flywheel to continue spinning for extended periods. When the vehicle requires acceleration assistance, the gear set applies the flywheel energy to the drivetrain.

- Torsion bar systems
  These systems use a clutch and gear system to twist a torsion bar during braking and this energy is then released to propel the vehicle when required.

(Gabriel-Buenaventura & Azzopardi, 2015; Bhavsar et al., 2016; Kapoor & Parveen 2013)

A comparison of various KERS system component options reveals that capacitor based systems have higher efficiencies compared to other systems in KERS applications (Kapoor & Parveen, 2013). It was further proposed that super-capacitor KERS systems could offer as much as 40% fuel consumption benefit in passenger vehicles. This is a significant increase over the potential of KERS as suggested by the Ricardo Review (2009) and may be due to advances in the components used in the KERS technology.

4 THE ADGERO SYSTEM

French company Adgero has developed a KERS system for heavy goods vehicles that is based on a YASA motor and Skeleton Ultra Capacitors. This system uses a proprietary control system and is designed as a retrofit package to an existing diesel engine vehicle, or as fitment to a semi-trailer.

The Skeleton graphene ultracapacitors provide quicker charge and discharge rates than battery systems, longer lifespan with severe duty charge/discharge cycles and high power densities (Burke, 2010). The capacitance storage system has inherent round trip store and discharge efficiency advantage over battery chemical charge and discharge processes which result in a higher energy recovery yield than battery systems (Burke et al., 2014).

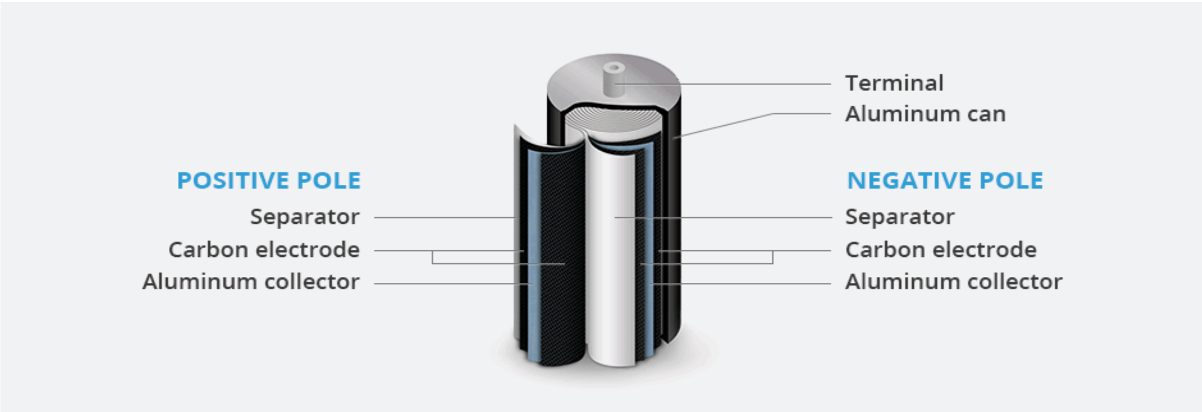

Figure 2: Skeleton Technologies Ultracapacitor

Benefits of Skeleton ultracapacitors:

- Lifespan of over 1 000 000 charge/discharge cycles
- Operating temperature range of -40 °C to +70 °C
- 30% more efficient than batteries
- 60 times the power density of batteries
- No harmful chemicals or toxic metals
- Low maintenance requirements

(Yadav & Sawarkar 2013; Burke et al. 2014)

The electric motor in this system is made by YASA in the UK. The YASA motor is a Yokeless And Segmented Armature motor originally developed as part of a DPhil research project at Oxford University (Woolmer, 2007).

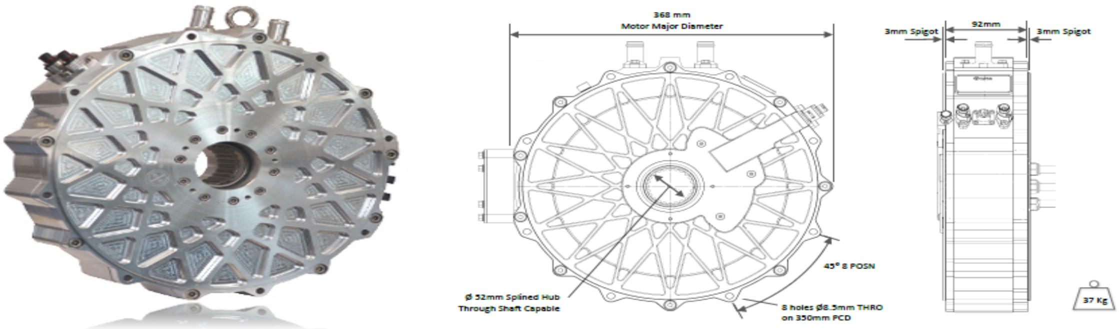

Figure 3: YASA motor (Woolmer, 2007)

Table 4: Characteristics of the YASA motor (Woolmer, 2007)

Peak torque at 450A (rms)	790 Nm
Peak Power at 700 VDC	200 kW
Peak Power at 400 VDC	100 kW
Continuous torque (40 deg C)	400 Nm
Continuous Power at 3000 rpm	70 kW
Speed	0-3250 rpm
Peak Efficiency	>95%
Mass	37 kg

The principal advantage of this motor is exceptional torque and power density. This results in a 200kW electric motor about the size of a conventional flywheel and weighing 37kg.

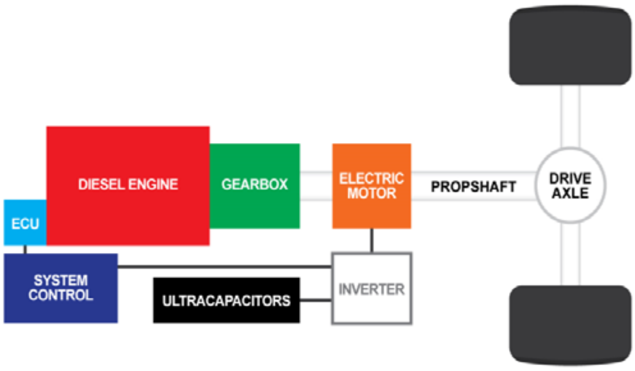

Figure 4: Layout diagram of Adgero KERS system in IVECO 12 ton rigid truck

The exceptional efficiency over conventional technology in both the electric motor with up to 95% peak efficiency (Woolmer, 2007) and the Skeleton Technologies Ultracapacitor energy storage modules provide a KERS solution superior to that predicted in the literature for (battery storage) kinetic regenerative systems.

Prototype Trials

Test vehicle: Iveco EUROCARGO 12 ton delivery vehicle (box truck)
Mission Profile: Peri-urban Delivery

Route: Bruntingthorpe Proving Grounds 6km peri-urban simulation with 6 stops

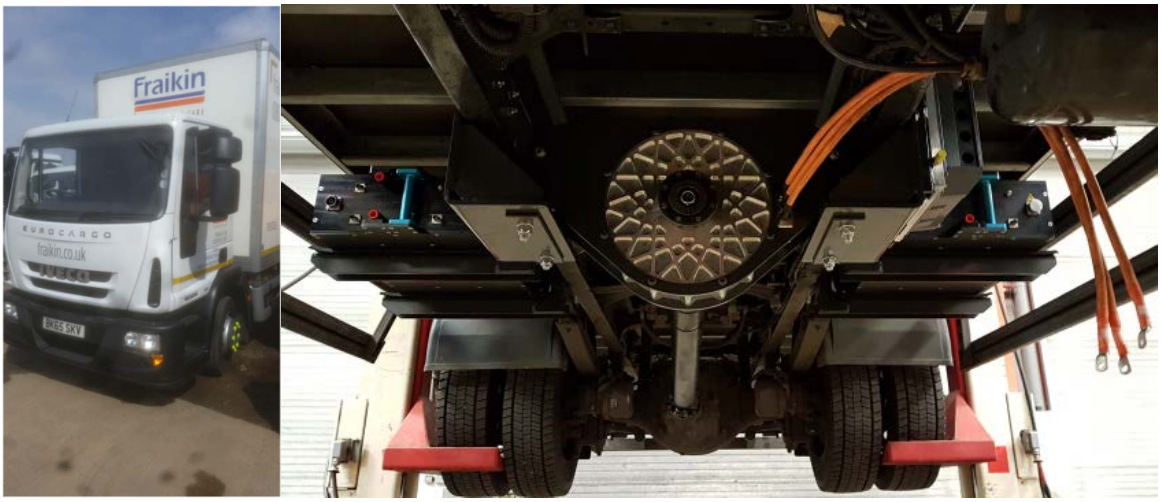

Figure 5: Adgero KERS system in IVECO 12t rigid truck

The YASA motor was fitted to the propshaft after the gearbox as shown in Figure5.

Table 5: Electrical characteristics of Adgero KERS system in IVECO 12t rigid truck

Energy Storage system data		
Capacity of Ultracapacitor Pack	356 Wh	1 282 kWs

Table 6: Fuel consumption in peri-urban 6km delivery cycle simulation at Bruntingthorpe Proving Ground

Configuration	Fuel Consumption (L)	Fuel Consumption L/100km	Fuel Consumption (MPG)	Fuel Consumption improvement from No KERS (%)
No KERS	1,84	29,92	9,44	N/A
KERS 500Nm slow cut-in	1,55	25,29	11,17	-15,47
KERS 750Nm slow cut-in	1,33	21,7	13,02	-27,47
KERS 750Nm medium cut-in	1,33	21,64	13,05	-27,67
KERS 750Nm medium cut-in	1,38	22,51	12,55	-24,77
KERS 750Nm quick cut-in	1,3	21,23	13,31	-29,04
KERS 750Nm quick cut-in	1,24	20,29	13,92	-32,19

The 6km peri-urban simulation conducted on 10 April 2017, and summarised in Table 6 shows a best improvement in fuel consumption of 32.19% over non-KERS operation. This is better than the 15-30% projections reported in the Ricardo Review (2009), as well as the 30% reported by Jackson (2011), and significantly better than the 8 to 12% proposed by Smokers and Van Zyl (2016).

These results represent the second prototype KERS system for the 12t rigid IVECO box truck and may be refined further through testing and modification, especially the control system software. Methodologies have been proposed for the design of energy storage systems in hybrid vehicles which may also be useful in optimisation (Wei et al. 2005).

5 PROPOSED LONG TERM STUDIES

Long term fleet trials have been proposed with Sainsbury's in the UK under the supervision of Imperial College London. The aim of these studies is to measure in various mission profiles and over an extended period the fuel consumption, CO_2 and NO_x of a test fleet of heavy goods vehicles. Due to the significant impact of acceleration events on NO_x emissions, it is expected that using electrical thrust to reduce the diesel combustion effort in acceleration events will have a pronounced positive effect in the reduction of NO_x emissions.

6 RETURN ON INVESTMENT

The expected system installed cost at commercialisation (mid 2018) is estimated at GBP 17 000. The Rate of Exchange GBP/Rand as at 02 March 2017 was R 17.25/GBP. The cost in Rand would be R293 250. For a base vehicle covering 5 000 km a month without KERS, annual fuel consumption is 17 952 litres. With a 32.19% fuel consumption saving, this would be a reduction of 5 779 litres per year. The March 2017 diesel price at the coast in South Africa was R 11.12 per litre (AA, 2017). The annual savings would be R 64 262, which yields a 21.9% return on investment. CO_2 reduction would be 15 285 kg per year. This is a simplistic financial model and return on investment is based on the fuel savings alone and ignores the savings in maintenance from reduced maintenance of the friction brake system or any other benefits.

7 CONCLUSIONS

Ultracapacitor based KERS systems can offer diesel fuel consumption reductions of up to 32.19% in peri-urban operating cycles. The fuel savings alone yield a 21.9% return on investment together with a 32.19% reduction in CO_2 emissions. This technology could provide significant benefit for diesel fleet operators seeking an emissions reduction with a positive return on investment without the charging infrastructure limitations and range restrictions of battery electric vehicle technologies whilst utilising their existing vehicles.

8 RECOMMENDATIONS

Road transport practitioners seeking to improve their emissions per ton km moved may consider ultracapacitor KERS as part of the "energy mix" in their fleet. This is particularly important for companies seeking to improve compliance to ISO, as well as RTMS certification where environmental sustainability is a serious consideration. South African cities, especially those in the Cities Climate Leadership Group, that are serious about emissions reduction targets need to create incentives for transport fleet operators to implement "green technologies". These cities should also create a Sustainability leader board where fleets, especially those associated with prominent retail brands, can volunteer to work toward emissions reduction targets of the city, and contribute results of their progress towards these targets so that the city can track the reductions in emissions inventories.

Policy-makers should consider the potential impact of these new technologies through the reduction of the cost per ton moved (with the long term impact of logistics efficiency on industrial cost-competiveness and hence job creation), as well as the environmental impact of lower emissions. The new technologies should be encouraged by providing incentives and tax rebates to improve the economic feasibility of sustainable road transport solutions. As an example, the State of New York provides a rebate voucher of US$ 40 000 for a hybrid truck purchase (New York State, 2016).

In the South African context, an incentive or tax rebate of 50% of the system cost would mean a payback on the investment in less than 3 years. This would be a strong catalyst for uptake of the new technology which would contribute to achieving targets of the C40 Climate Leadership Cities' reduction of emissions inventories. In addition, incubation of local intellectual property development around "green technologies" would become more viable with scaling up of use of these technologies in fleets resulting in new "Green Economy" skills development and new industries with potential for an increase in new jobs in South Africa.

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