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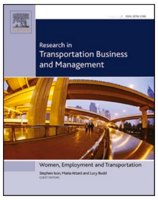

High-capacity coal trucks to reduce costs and emissions at South Africa's power utility

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ABSTRACT

South Africa's national power utility, Eskom, is under growing pressure to increase its power generation capacity in the face of national rolling blackouts while also containing costs, increasing revenue, and reducing its environmental impact. While the entity embarks on an ambitious $ 10 billion 2050 decarbonisation plan, there are short-term opportunities to save costs and emissions in parts of its business through relatively simple interventions. In this work, we investigate the transport of coal to Eskom's power stations. We focus on the approximately 30 million tonnes transported by road, where 'high-capacity vehicles' (HCVs) have already demonstrated significant productivity improvements in a national pilot project in South Africa. First, the current costs and emissions associated with the current transport activity are calculated, which amount to approximately ZAR 4 billion (US$250 m) and 230,000 t of CO2 respectively per year. A case is then presented for transitioning the coal transport fleet to 74-t high-capacity vehicles, which is calculated to save Eskom up to ZAR 248 million (US$15 m) and 35,000 t of CO2 each year. In addition, we show that the more road-friendly HCV fleet would result in a reduction in road damage valued at ZAR 50 million (US$3 m) per year. Ultimately, these cost figures represent savings to the South African taxpayer, as both Eskom and the road authorities are state entities. The precise cost benefit to Eskom, however, will depend on the nature of its coal supply contracts with local mines and transporters, but it is likely that market forces will enable these savings to be realised throughout the supply chain.

1. Introduction

South Africa's national power utility, Eskom, is facing several operational and business challenges. The impact of this is evident in the country's ongoing 'load-shedding' programme first introduced in 2007: a coordinated system of rotating power cuts ranging from two to four hours (typically) to prevent the grid from collapse due to a lack of available capacity. All the while, the utility is under heavy strain to increase its power generation capacity, contain costs and increase revenue, while also reducing its environmental impact. Ongoing construction of new coal-fired power stations (including the 4.8 GW Kusile power station which upon completion will be one of the largest coal-fired plants in the world) is looking to address the capacity issue. However, this raises concerns about the utility's ability to reduce its environmental impact. Eskom's own performance review for the period 2012–2018 reiterates some of these challenges, as shown in Fig. 1 (Eskom Holdings SOC Ltd, 2019).

Ninety percent (90%) of Eskom's generating capacity comes from the burning of coal (Eskom Holdings SOC Ltd, n.d.), with a reported 114 million tonnes of coal burned in the 2018/19 financial year. This resulted in the release of 221 million tonnes of CO$_2$ making it by far the country's largest emitter, accounting for 42% of the country's total emissions (Carbon Brief, 2018). This figure is assumed to only include 'scope 1' emissions, direct emissions as a result of its energy-production activities. Reducing its carbon footprint associated with primary generation is a monumental undertaking, and in July 2021 Eskom published a $10 billion decarbonisation plan to replace most of its coal-powered plants with renewables by 2050 (Sguazzin, 2021). Large shifts away from coal are not expected in the short term.

While Eskom embarks on its ambitious 2050 decarbonisation plan,

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there are short-term opportunities to save costs and emissions in parts of its business through a range of ‘low-hanging fruit’ interventions. One such example is in the transport of the (at least) 114 Mt. of coal from the mines to the power stations. While most power station coal is moved via conveyor and rail, around 30% is moved by road: the most expensive and carbon-intensive of the three transport modes, and the mode wherein the biggest opportunity for improvement lies.

‘High-capacity vehicles’ (HCVs) are a relatively ‘low-tech’ intervention proven in a number of trials and implementations around the world to significantly reduce road transport costs and emissions. HCVs are trucks or truck combinations which carry more freight than conventional vehicles through weight and dimension concessions, resulting in less fuel burn and associated costs and emissions for the same freight task, while also reducing the number of truck trips needed and associated road wear impact. In fact, HCVs have been trialled in South Africa since 2007 as part of the ‘Performance-Based Standards’ (PBS) pilot project, and since 2017 several vehicles involved in the trial have been transporting coal to power stations with promising results (Nordengen, Berman, et al., 2018). Eskom themselves have explicitly identified HCVs as one of the most economically competitive future freight transport options in South Africa (Eskom, 2019).

One of the South African PBS vehicles transporting power station coal is shown in Fig. 2. These vehicles possess additional axles and operate at a total mass of 74 t, 18 t more than the current 56-t vehicle mass limit in South Africa. The number of these coal trucks participating in the trial has been steadily growing, indicating increased investment from the transport operators. In addition, evidence supplied by several operators, suggests that the resultant savings with these vehicles present a good business case to the transporters (Steenkamp et al., 2021). The cost saving realised through the more efficient PBS trucks allows the operators to either increase profits, offer more competitive rates to clients, or both. Depending on the nature of the transport contracts and their negotiation between the mines, transporters and Eskom, it is foreseeable that Eskom will reap at least a portion of these savings, especially as the portion of PBS coal trucks in the fleet grows and lowers the average cost of coal transport by road.

In this paper, we assess the potential of high-capacity coal trucks to reduce costs and scope 3 emissions at Eskom. We consider a scenario in which all the approximately 2000 trucks transporting coal for power stations are transitioned from standard 56-t vehicles to 74-t PBS vehicles such as those already participating in the PBS pilot project. We also consider the indirect cost savings associated with the reduced road wear impact of the PBS vehicles.

Fig. 2. 74-t interlink transporting coal in the PBS pilot project.

2. Literature review and data collection

2.1. Power station coal and its transport

South Africa has roughly 3.5% of the world’s coal resources and produces 3.3% of the world’s annual coal production where, in 2016, 246 Mt. was mined (National coal strategy for South Africa, 2018). Of this, 28% was exported and 72% was sold domestically. Coal is used in three major sectors: electricity generation, industrial processes and manufacturing of gas and liquid fuels (e.g., at Sasol’s synthetic fuels production facility in Secunda). Fig. 3 shows the relative distribution of coal sales in South Africa. Most of the coal in South Africa goes towards energy production, i.e., to be burnt at Eskom’s coal-fired power stations.

In 2018/19, Eskom acquired 118 Mt. of coal (Eskom Holdings SOC Ltd, 2019) (of which 114 Mt. was burnt as noted earlier), and we can assume that all this required transport from mines to power stations. Due to the low value, high volume nature of coal, coal-fired power stations are mostly strategically located near major coal fields and coal mines, to minimise the coal transportation task in terms of cost and time. An illustration of the main North-East South African coal region is shown in Fig. 4.

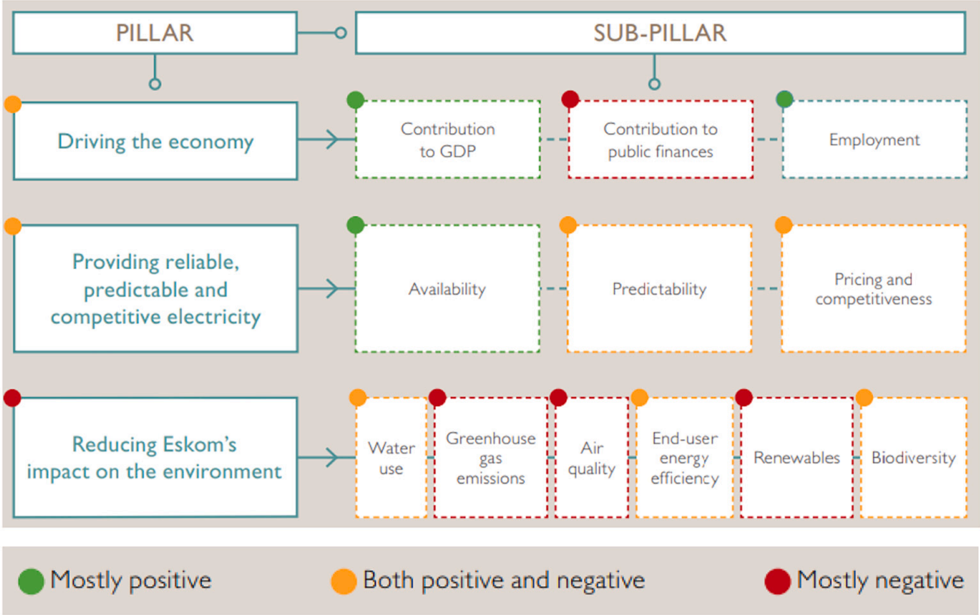


Fig. 1. Eskom Factor 2.0 outcomes, the first three pillars (Eskom Holdings SOC Ltd, 2019).

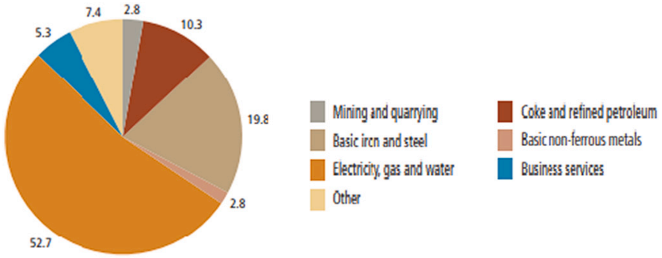


Fig. 3. South African coal demand from industries (National coal strategy for South Africa, 2018).

Eskom makes use of three transport modes to move coal from source to power station, namely conveyor, rail and road. The modal split by tonnes according to Eskom in 2015 (Solomons, 2015) (more recent data are not publicly available) is summarised in Fig. 5, with road accounting for 30% of the total. Although Eskom has expressed a desire to prioritise rail and conveyer (Khumalo, 2021) in future, road transport will realistically make up a similar proportion in the foreseeable future. The feasibility and business case for either conveyor, road or rail infrastructure investment would be determined by volume, contract duration, and distance amongst other factors. Conveyer transport is by far the cheapest mode per tonne-km (at around 20% the cost of road transport (Saxby & Elkink, 2010)), rail the next economical, and road haulage the

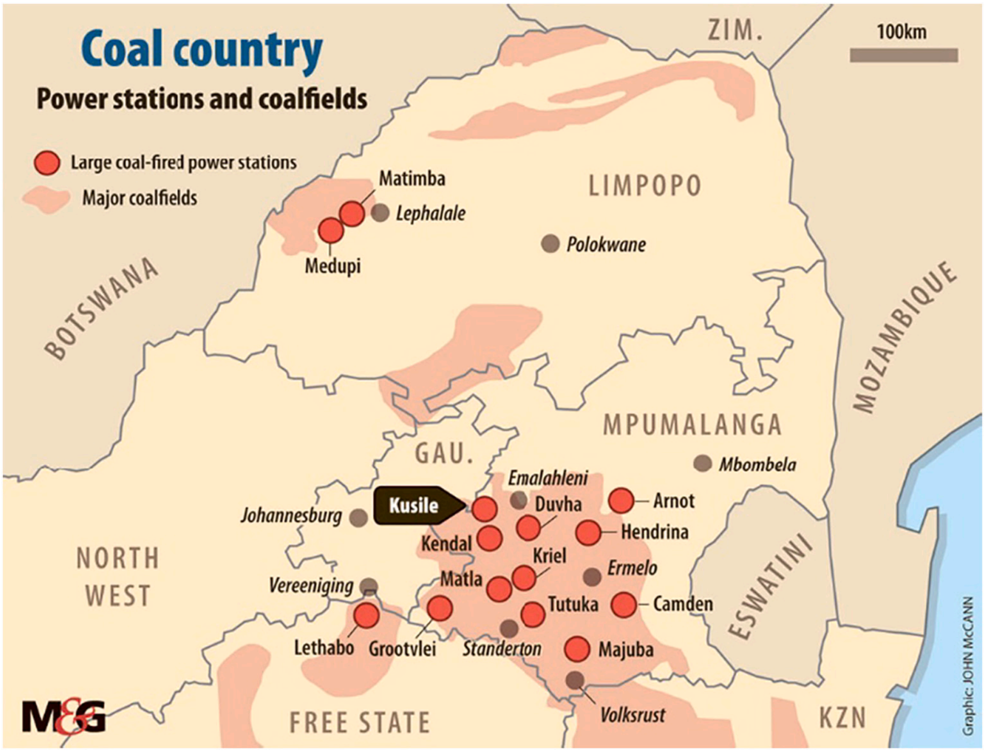


Fig. 4. Coal-fired power stations and coal sources in South Africa (Davie, 2019).

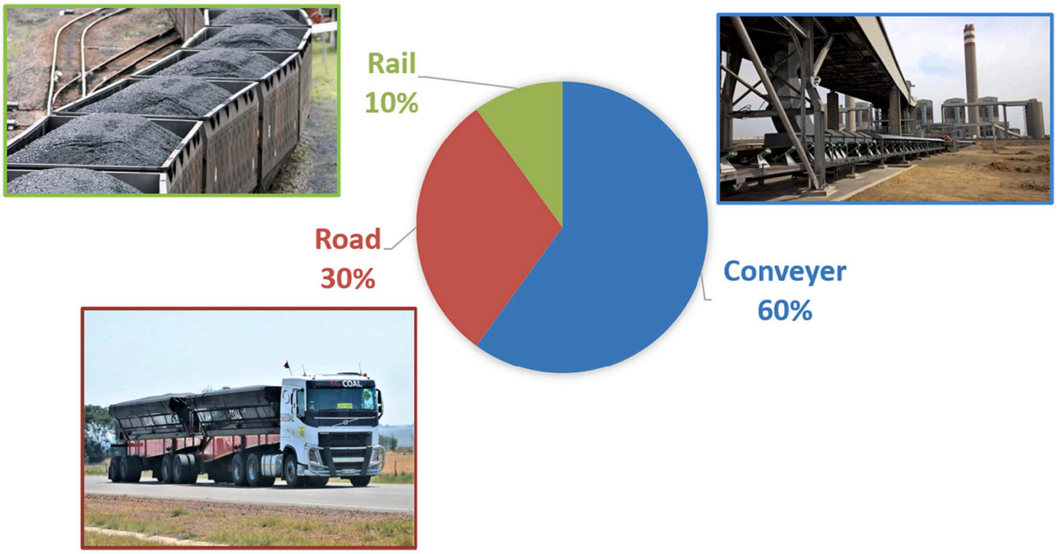


Fig. 5. Power station coal transport by mode (data from (Solomons, 2015)).

most expensive.

Conveyer systems are therefore used wherever possible, but are typically only feasible for lead distances less than around 5 km, but in some cases can be longer such as the 7 km from the Grootegeluk mine to the Medupi power station (Exarro, n.d.). Infrastructure constraints, service provision challenges, and flexibility mean that not all non-conveyer coal can be moved by the next best mode: rail. Eskom is trying to address some of these constraints to move more coal from road to rail and has an annual target of increased rail usage. However, these targets are not being met (Eskom Holdings SOC Ltd, 2019). In 2015 Eskom reported that it transports coal over about 3200 km of the Mpumalanga road network comprising 30 to 40 haulage routes, using a fleet of over 2000 trucks, travelling an average of 600,000 km/day (Solomons, 2015).

Costs associated with the purchase and transport of coal are published in the NERSA public hearing report of November 2017 (Eskom Holdings SOC Ltd, 2017). Fig. 6 shows a breakdown of the costs of coal for the 2017 financial year, as well as forecasts for 2018 and 2019. In 2017, 120 million tonnes of coal were purchased and transported, at a total cost of R 47 billion. Transport costs accounted for R 7 billion or about 15% of the total cost. For the purposes of this study, the 2018/19 tonnage of 118 Mt. and the 2017/18 cost of R 7 billion will be assumed, which will suffice for this comparative analysis.

Eskom obtains coal via two different contractual arrangements. In the first more common scenario, Eskom contracts directly with the coal mine for the purchase and delivery of coal and the mine is responsible for coal transport. In this case the mine would negotiate transport contracts, and transport cost would be included in the coal price offered to Eskom. In the second case, Eskom contracts directly with transport operators and so in this case would have direct input in negotiating the transport contract.

In either case, the baseline cost of this road freight transport task is estimated to be R 1.18/t-km (Braun, 2018) for a 56-t interlink combination at 50% utilisation, which is representative of the coal transport fleet. This includes the costs of capital, fuel, maintenance, tyres, and driver wages, but excludes operator profit. Fuel accounts for around 40% of total road freight transport costs (Havenga et al., 2016), and recent indications show that this could be closer to 45% and is growing. The public data collected which is most relevant for this study is summarised in Table 1.

Table 1
Summary of collected power station coal transport data.

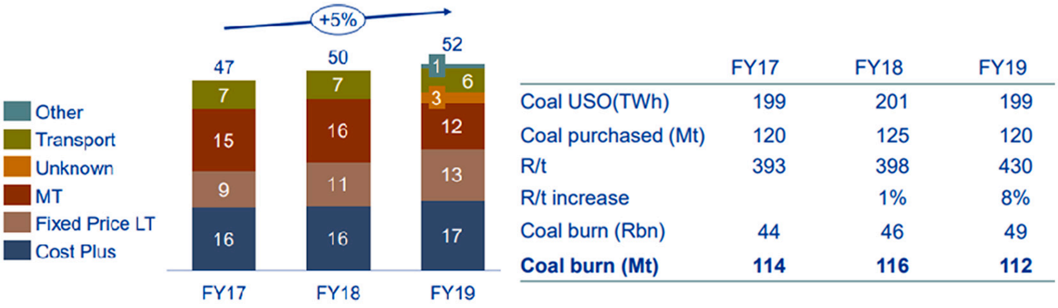
	Value	Source
Coal transported (tonnes/year)	118,000,000	Eskom (Eskom Holdings SOC Ltd, 2019) (2018/19 data)
…of which by road (tonnes/year)	35,400,000	Eskom (Eskom Holdings SOC Ltd, 2019) (Solomons, 2015) (30% of total)
Cost of coal transport (R/year)	R 7 billion	Eskom/NERSA (Eskom Holdings SOC Ltd, 2017) (2017 data, 2018 forecast)
Cost of coal transport (R/t-km)	R1.18	Fleetwatch (Braun, 2018) (56-t interlink at 50% util.)
Approximate fleet size (trucks)	2000	Eskom (Solomons, 2015)
Approximate number of haulage routes	35	Eskom (Solomons, 2015) (average of '30 to 40')
Approximate distance travelled (km/day)	600,000	Eskom (Solomons, 2015)
Fuel cost as a portion of transport costs	40%	Havenga et al. (Havenga et al., 2016)

2.2. High-capacity vehicles and the South African PBS pilot project

Globally, transport is a major contributor of carbon emissions, and in South Africa transport accounts for around 10% of the country's greenhouse gas emissions (DEA, 2019). Road transport accounts for approximately 90% of this figure, and of this heavy trucks such as those used to transport coal comprise 21% (DEA, 2014). While full battery electric vehicles (BEVs) seem to be the clear long-term solution to decarbonise passenger transport, heavy goods vehicles remain a challenge due to their significant power and range requirements. This is especially true in South Africa where 56-t vehicle combinations are commonplace. While several solutions are being investigated, including electric road systems, large battery trucks with megawatt charger systems, and fuel cell battery electric vehicles, it will be several decades before these are mainstream technologies even in developed countries, let alone in developing countries such as South Africa. Alternative solutions such as hybrid electric drivetrains and Liquid Natural Gas (LNG) have a role to play in the transition phase of road freight decarbonisation, but are not net zero carbon solutions for the long term.

'High-capacity vehicles' (HCVs) are vehicles which carry more freight than conventional vehicles through weight and dimension concessions. The use of HCVs to improve truck transport productivity and has been successfully trialled or implemented in several countries around the world including in Australia, New Zealand, Canada, and parts of Europe (Billing & Madill, 2010; de Pont & Taramoeroa, 2010; Kraaijenhagen et al., 2014; National Transport Commission, 2017). Such HCV programmes typically require assurances regarding the safe design of the trucks (e.g., through the use of performance-based standards), safe and professional management of the transport operation (e.g., through self-regulation schemes), as well as access control and vehicle monitoring operation (e.g., through intelligent access systems). These supporting frameworks have also proved successful. Note that the use of HCVs in an intervention which improves the overall efficiency of the vehicle and hence transport system as a whole, and is not dependent on a specific drivetrain technology. This is attractive in that it (a) reduces carbon emissions in current diesel HGV operations as part of a transition solution, and (b) can carry over into a zero-emission transport future to reduce clean energy consumption.

In South Africa, the National Department of Transport has supported a trial of HCVs since 2007. The pilot project is known as interchangeably as the 'Smart Truck' or 'Performance-Based Standards' (PBS) pilot project owing to the use of PBS to ensure safe HCV vehicle designs (Nordengen, de Saxe, et al., 2018). The vehicles operate on pre-approved routes assessed to be suitable and safe for the type of truck



	FY17	FY18	FY19
Coal USO(TWh)	199	201	199
Coal purchased (Mt)	120	125	120
R/t	393	398	430
R/t increase		1%	8%
Coal burn (Rbn)	44	46	49
Coal burn (Mt)	**114**	**116**	**112**

Fig. 6. Eskom cost breakdown 2017–19 (Eskom Holdings SOC Ltd, 2017).

and must undergo detailed assessments of low-speed and high-speed truck safety, road wear impact, and bridge loading impact against a set of strict standards before approval. Operators must also be accredited according to the Road Transport Management System (RTMS) to ensure that operations are managed according to industry best practice.

Monitoring data for the PBS vehicles have been collected by the CSIR on behalf of the Department of Transport since the beginning of the trial, along with data on conventional trucks in the same fleet, operated by the same transporters and performing the same freight tasks alongside the PBS trucks ('baseline' vehicles). Baseline vehicle data provides a benchmark against which to assess savings in several areas including fuel and emissions. The data is reported per vehicle per month and includes total distance travelled, total number of trips, total tonnes moved, and total fuel consumed. The raw data are collected by the operators own fleet management systems and summarised into monthly averages and totals for reporting to the CSIR.

The most recent published data on the project from early 2020 show an average on-road full duty-cycle fuel use and associated carbon reductions of 17% per tonne-km and a 23% reduction in truck trips compared to conventional baseline operations (de Saxe et al., 2020). In addition, the trial has demonstrated an average 13% reduction in road wear impact per tonne-km based, based on individual pavement loading analyses of all PBS and baseline vehicle designs coupled with the recorded monitoring data. At the time, the total fleet consisted of approximately 320 vehicles. The latest figure (August 2021) showed around 550 vehicles.

2.3. Road wear impact of heavy vehicles

The Mpumalanga road network where the majority of coal trucks operate is in a generally poor state, due to a combination of illegal vehicle overloading and a backlog of necessary road maintenance. Road condition data available from the Mpumalanga Road Asset Management System (RAMS) (Mpumalanga Road Assest Management System, 2019) shows of the road network used by coal haulage trucks, 16% is classified as in a 'Very Poor' condition and 34% in a 'Poor' condition. The full breakdown is given in Fig. 7. It is hence crucially important to ensure that the impact from heavy vehicles on this network is minimised. This can be achieved by a combination of proper loading control and through informed vehicle design.

Every vehicle design involved in the South African PBS pilot project vehicle must undergo a road wear impact assessment as part of the approval process. This helps to ensure that the vehicles are not causing any additional road wear impact compared to conventional vehicles, and in most cases cause significantly less road wear per tonne-km. This is in addition to there being no concessions on axle load limits compared to baseline vehicles. A reduction in road wear results in reduced road maintenance and construction costs due to the prolonged life of the infrastructure, and an associated reduction in emissions associated with road building and maintenance.

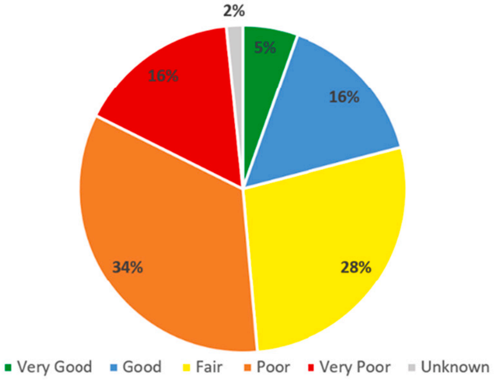


Fig. 7. Summary of the condition of the Mpumalanga road network according to the Mpumalanga RAMS (Mpumalanga Road Assest Management System, 2019).

PBS and baseline vehicles are assessed according to a 'Load Equivalency Factor' (LEF) per tonne-km, based on the South African mechanistic-empirical pavement analysis and design method used in South Africa since 1996 (de Beer et al., 2009). The LEF is an estimated ratio of critical pavement layer life relative to an accepted 'Standard Axle' (with a total weight of 80 kN and tyre pressure of 520 kPa). Eight representative South African pavement structures are assessed to obtain an average road wear impact result which can be compared across vehicles.

The LEF approach has been used to calculate road user charges for heavy vehicles in Namibia, using an appropriate cost per LEF-km figure (Kemp et al., 2018). In the Namibia study, this was derived from the Present Worth of Cost (PWOC) method from the South African pavement design manual (DoT, 1996). This method was then extended to the South African PBS pilot project, yielding a figure of ZAR 0.40 to ZAR 0.50 per LEF-km, based on a study of the N3 Gauteng to Durban freight corridor (Kemp, Steenkamp, & de Saxe, 2021). This method and the figure of ZAR 0.50/LEF-km will be applicable to the costing analysis in the current study.

2.4. Carbon reporting

The GLEC framework (Greene & Lewis, 2019), created by the Global Logistics Emissions Council, presents a standardised and widely-adopted industry standard for assessing the carbon footprint associated with large industrial activities with significant upstream and downstream components. The framework provides standardised techniques of approximation in instances when granular-level data are not available. The framework defines three 'scopes' of emissions as follows:

Scope 1 GHG emissions: 'Direct emissions from sources that are owned or controlled by the reporting organization.'

Scope 2 GHG emissions: 'Indirect emissions that are associated with energy that is transferred to and consumed by the entity.'

Scope 3 emissions: 'Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g., transmission and distribution losses) not covered in Scope 2, outsourced activities, waste disposal.'

The emissions associated with the transport of coal for Eskom fall under Scope 3. The GLEC framework describes several acceptable methods for estimating these emissions using either total fuel consumption data or total freight task data (in tonne-km). Furthermore, it is important to distinguish between 'tailpipe' emissions associated with the combustion of fuel in the vehicle's engine, and the indirect emissions associated with the supply chain of the fuel (i.e., its extraction, production, and distribution). These are referred to as 'Tank-to-Wheel' (TTW) and 'Well-to-Tank' (WTT) emissions respectively, and the entire emissions footprint of the fuel is the combination of the two, referred to as 'Well-to-Wheel' (WTW) emissions (Nocera & Cavallaro, 2017; Villante, Anatone, & De Vita, 2018). From a global emissions perspective, WTW is the true indication of emissions associated with a particular activity, but it is also useful to also know the TTW emissions as these have a significant impact on local air quality especially in urban areas.

The GLEC framework provides emission intensity factors for both TTW and WTW, denoted here as I_{TTW} and I_{WTW}, and these are summarised in Table 2. Note that figures for Africa are based on figures for Europe and South America with a 22% 'uplift factor'. Precise emissions intensity factors will depend on local freight activity (typical load factor and empty running), vehicle types, and the fuel supply chain, but accurate data for South Africa are not currently available. The GLEC framework provides several acceptable methods for estimating total tonne-km for an operation for the purpose of estimating carbon emissions within reasonable bounds of certainty.

Table 2
Emission intensity factors for truck transport (Greene & Lewis, 2019).

	I_{TTW} (g CO_2e/t-km)	I_{WTW} (g CO_2e/t-km)
Artic truck up to 60 t GVM (Heavy load, diesel fuel)	44[1] (54[2])	55[1] (67[2])
Artic truck up to 72 t GVM (Heavy load, diesel fuel)	38[1] (46[2])	48[1] (59[2])

TTW = TANK-TO-WHEEL, WTW = WELL-TO-WHEEL.

[1] Factors for Europe and South America.

[2] Factors scaled by a 22% uplift factor for the African region.

3. Analysis and results

3.1. Methodology and assumptions

In this study, we begin by analysing the available monitoring data for the existing PBS coal truck fleet and baseline vehicles to determine the difference in fuel consumption per tonne-km between the PBS and baseline vehicles and the typical lead distances for power station coal transport. Using the average lead distance and total volumes moved, we can then benchmark Eskom's existing road coal transport operations to ascertain the total freight task (in tonne-km) and calculate the costs and emissions associated with this activity. A cost of R 1.18 per tonne-km and the GLEC emission intensity factors are used for this purpose. The costs and emissions for a hypothetical fully-PBS fleet are then calculated using the known savings per tonne-km from the monitoring data. Finally, consideration is given to the additional indirect cost savings associated with a reduction of road wear impact. The following assumptions were made:

1. Eskom's own reported data are accurate, including data on modal split, coal tonnage, coal costs, and haulage routes. These are the only available sources for much of the required data, and so must be relied upon where necessary.
2. The effects of the road-to-rail initiative on coal volumes by road will not be significant in the short to medium term, and so we will exclude this from the analysis.
3. Eskom's reported data represent a fleet of conventional 56-t tandem interlink trucks, with no smaller tractor semi-trailer combinations in operation. This has been corroborated with Eskom, who have confirmed that the use of tractor semi-trailers for coal transport was phased out many years ago. The data is also presumed to exclude any significant portion of PBS vehicles at the time.
4. There is no back-hauling, resulting in a vehicle utilisation rate of 50%. This is representative of typical side-tipper mining transport operations in South Africa over the typical lead distances. Some new technologies such as modular bladders which permit the transport of liquids on the return leg of a side-tipper journey have been mooted but are not yet in use.
5. Given the lack of local data for South Africa, GLEC fuel emission intensity factors in g CO_2e/t-km for Europe and South America with a 22% upliftment factor for Africa are deemed to be suitable for use in this study.

3.2. Performance of the PBS coal trucks

At the time of data collection there were approximately 60 PBS truck combinations transporting coal to power stations within the PBS trial. The 60 PBS trucks represent 3% of the estimated trucks transporting coal for Eskom (Solomons, 2015). The first PBS coal trucks started operating in 2017, and the numbers have since grown. Fig. 8 shows a comparison of the PBS and 'baseline' truck combinations. Vehicle design information was provided by the operators and vehicle original equipment manufacturers. The baseline vehicle is a 56-t gross mass interlink combination (also known as a B-double), with tandem axle groups on the trailers, and is 22 m in length. The PBS combination is a 22-m 74-t gross mass interlink, with tridem axles on the trailers to support the additional load without exceeding axle load limits (and hence minimising impact on the road pavement).

The current gross mass and maximum length limits in South Africa are 56 t and 22 m respectively (DoT, 2003), and so the PBS combinations operate under special permit as part of the PBS pilot project allowing them to reach 74 t. Both PBS and baseline vehicles adhere to the maximum axle load limits prescribed in the National Road Traffic Act. Table 3 summarises the truck loading information. For both PBS and baseline operations, as is typical for bulk heavy transport, the trucks operate fully laden in one direction and unladen on the return trip yielding a 'utilisation' of 50%.

3.2.1. Monitoring data

Monitoring data have been supplied by the CSIR for the PBS coal trucks as well as the baseline vehicles up to the end of 2019. Neither the raw data nor the operators represented can be reproduced here for reasons of confidentiality. A summary of the monitoring data for baseline and PBS vehicles can be provided however, and this is given in Table 4 and Table 5. These data will be referred to as the 'sample data' (denoted by the subscript '(s)'), as they represent only a small sample of

Table 3
Comparison of mass data between PBS and conventional interlink vehicles.

	PBS	Baseline
Gross mass (tonnes)	74	56
Average payload (tonnes)	50	35

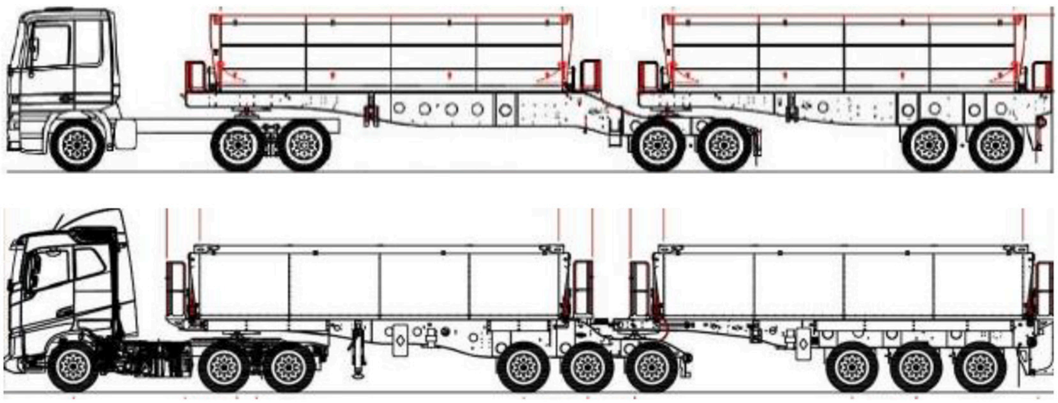


Fig. 8. Conventional 56-t tandem interlink side-tipper (baseline vehicle, top) and 74-t tridem interlink side-tipper (PBS vehicle, bottom) (both 22 m in length).

Table 4
Summarised monitoring data: baseline trucks.

	Volume (tonnes)	Distance (km)	Number of trips	Fuel used (litres)
2017	24,475	154,746	690	86,143
2018	27,219	192,047	778	104,401
2019	23,046	148,565	664	82,205
Totals	74,740	272,749	2132	272,749

Table 5
Summarised monitoring data: PBS trucks.

	Volume (tonnes)	Distance (km)	Number of trips	Fuel used (litres)
2017	703,266	1,033,731	14,866	714,434
2018	1,214,280	3,123,450	26,651	1,961,933
2019	797,799	6,200,432	17,594	3,655,540
Totals	2,715,346	6,331,907	59,111	6,331,907

the coal transport fleet. This is to differentiate it from the later calculated data which represents the entire power station coal transport fleet.

Note that the number of PBS vehicles and associated quantity of data in the sample dataset is notably smaller than that of the baseline vehicles. This is because the PBS vehicles are part of a limited government trial and represent a very small portion of the vehicles for those fleets operating in the trial. However, the data represents *all* PBS trucks and *all* baseline trucks of the *power station coal fleets participating in the trial*. There are other operators not participating in the trial (i.e., not operating PBS vehicles) and their data were not collected and are not included here.

The data provides sufficient information to estimate the overall average fuel consumption per tonne-km and the average lead distance in km (the one-way distance between the mine source and power station destination) for both PBS and baseline fleets. In this analysis we will work mostly on a tonne-km basis, as the data available is typically at a 'freight task' level. This is also in line with a common methodology for estimating Scope 3 carbon emissions prescribed by the GLEC framework.

The total freight task in tonne-kms (F_{tot}), average fuel consumption (R_{ave}), and average lead distance (D_{ave}) can be calculated from the total volume (V_{tot}), total distance (d_{tot}), total trips (T_{tot}) and total fuel consumed (L_{tot}). Baseline and PBS data are denoted by the subscripts 'bl' and 'pbs' respectively. The calculations are as follows:

$$F_{tot,bl(s)} = \frac{V_{tot,bl(s)} \cdot d_{tot,bl(s)}}{T_{tot,bl(s)}}, \quad F_{tot,pbs(s)} = \frac{V_{tot,pbs(s)} \cdot d_{tot,pbs(s)}}{T_{tot,pbs(s)}}$$

$$R_{ave,bl(s)} = \frac{L_{tot,bl(s)}}{F_{tot,bl(s)}}, \quad R_{ave,pbs(s)} = \frac{L_{tot,pbs(s)}}{F_{tot,pbs(s)}}$$

$$D_{ave,bl(s)} = \frac{1}{2} \cdot \frac{d_{tot,bl(s)}}{T_{tot,bl(s)}}, \quad D_{ave,pbs(s)} = \frac{1}{2} \cdot \frac{d_{tot,pbs(s)}}{T_{tot,pbs(s)}}$$

The 1/2 term in the lead distance calculation accounts for the 50% utilisation. Calculated results for tonne-kms and average lead distances are summarised in Table 6. Results are shown for each year in addition to the totals calculated over the entire dataset. On average, the PBS vehicles demonstrate a fuel consumption saving per tonne-km of (0.0157–0.0133) / 0.0157 = 15% over the baseline vehicles. The average lead distances over the three-year period are comparable for both fleets. Calculating an average lead distance for all operations (baseline and PBS) yields a result of 89 km. These findings are summarised in Table 7.

Table 6
Calculated tonne-kms and lead distances, baseline and PBS trucks.

	Baseline			PBS		
	$F_{tot(s)}$ (tonne-km)	$R_{ave(s)}$ (l/t-km)	$D_{ave(s)}$ (km)	$F_{tot(s)}$ (tonne-km)	$R_{ave(s)}$ (l/t-km)	$D_{ave(s)}$ (km)
2017	5,489,013	0.0157	112	48,902,755	0.0146	35
2018	6,718,991	0.0155	123	142,311,489	0.0138	59
2019	5,156,420	0.0159	112	281,158,494	0.0130	176
Totals	17,364,425	0.0157	116	472,372,737	0.0133	88

The 15% fuel saving compares well with the average 17% saving observed for the entire national PBS fleet (de Saxe et al., 2020). It also agrees well with the savings suggested by the data in Table 2, where the emission intensity factor reduces from 54 g CO2e/t-km for a GVM of 60 t to 46 g CO2e/t-km for a GVM of 72 t (a 14.8% reduction). In essence the saving is directly due to the increased payload capacity and could be calculated directly from the designed tare and payload masses of the vehicles. However, this would not account for in-service variations in loading (which are never perfect), and the value presented here represents validated on-the-ground operations.

A variation in lead distance is evident for the PBS data over the three years, potentially owing to the operators experimenting with routes for the few PBS vehicles. In calculating the lead distance using the sample data, the PBS data is more represented than the baseline data. As such, in the next section we use an alternative method to validate the lead distance for further analysis.

3.2.2. *Lead distance validation*

The above lead distance was calculated based only on the routes operating PBS vehicles and was potentially biased based on the larger proportion of PBS tonne-km in the sample dataset. Ideally, actual trip data from Eskom or coal transport companies would be used to get a more accurate understanding of lead distance, but these data are not available in the public domain. However, representative data from the GAIN Group's South Africa Freight Demand Model™ (FDM™) was made available for this study (GAIN Group, 2021). The model is a supply and demand gravity model for transportation freight flows and has been refined over the past decade rendering a robust, peer-reviewed model which quantifies freight movements per mode for 83 commodities between the 356 districts of South Africa, including international movements. The methodology used in the model is detailed in (Havenga & Simpson, 2018). Updated data for 2018 were obtained from the authors for this study.

Power station coal is one of the 83 commodities analysed and detailed in the FDM™. With the permission of the developers, power station volumes for conveyor, road and rail between specific origins and destinations were provided. The supply volumes for the model are triangulated from data sourced from annual reports by the Department of Minerals and Energy, financial reports published by coal mining companies, industry bodies and through publicly shared media reports. The power station coal demand volumes were compiled from Eskom data received in kind for historic years, which has been cross-referenced with power produced and production output yield factors and publicly shared media reports. Known flow volumes from actual rail volumes were received from Transnet Freight Rail (TFR) and included in the modelling process. Actual conveyor belt volumes were also supplied to the modellers by Eskom on an annual basis. The remaining road volumes were modelled through a gravity modelling process.

The modelled power station coal volumes and lead distances for each mode for 2018 are shown in Table 8. The resultant average lead distance for road haulage is 97.5 km, which agrees well with the figure of 89 km derived from the PBS monitoring data. Note the overall volume percentages, which are reasonably close to the 60/10/30 split quoted from 2015 earlier, which helps to suggest that this split has remained

Table 7
Calculated average fuel saving and lead distance.

Fuel saving (% litres per tonne-km)	15%
Average lead distance (all operations)	89 km

Table 8
Lead distance and volume per mode for South African power station coal in 2018.

Mode	Lead distance (km)	Volume		Approximate tonne-km	
		million tonnes	% of total	million tonne-km	% of total
Conveyor	3.0	75.9	64%	228	4%
Rail	275.0	8.7	7%	2393	41%
Road	97.5	33.3	28%	3247	55%
Totals		117.9	100%	5871	100%

approximately constant. Road transport accounts for the largest mode by tonne-km, at 55% of the total. The lead distance of 97.5 km will be used for further analysis.

The average road lead distance of 97.5 km is adequate for the required high-level freight task calculations. However, additional information which the FDM™ data provides offers more insight into the realities of the transport task. The actual lead distance can be slightly skewed from the actual modelled trips due to specific transport and coal mine contracts. In some instances, factors like coal grades required might mean that it is not always the coal mine nearest to the power station that would provide all of the volumes needed. Fig. 9 shows a scatter plot of all volumes across all modes with lead distance and tonnes indicated. The high-volume, short-distance conveyor belt volumes are clear on the left of the chart. The remaining road and rail volumes are isolated in the inset figure. This figure shows the typical lead distances and high volumes in the distance range of 50 to 200 kms, with typical annual volumes ranging between 100,000 t and 5 million tonnes. The average lead distance calculated from the data in Table 8, is the result from these individual modelled flows. The rail trip data, and hence remaining road trip data cannot be shown in isolation due to confidentiality agreements.

3.3. Costs and emissions: Benchmark

At this point in time, the necessary information is now available to calculate the cost and emissions of the current benchmark power station coal road transport operation. Here the term ‘benchmark’ represents the status quo: the entire fleet of vehicles currently transporting power station coal, in the form of the 56-t ‘baseline’ vehicle presented previously as part of the sample dataset study, assuming negligible or no PBS vehicles. Benchmark results are denoted by the subscript ‘bm’. First, the total freight task in tonne-km (F_{tot}) can be calculated using the total volume moved from Table 1 ($V_{tot,bm}$) and the average lead distance from Table 8 (D_{ave}) as follows:

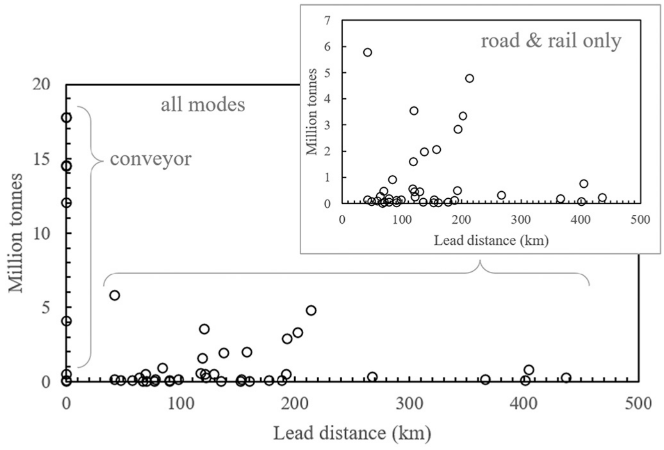


Fig. 9. Lead distance and volume of power station coal transport for all modes (from the FDM™).

$$F_{tot} = V_{tot,bm} \cdot D_{ave}$$

$$= (35,400,000 \text{ tonnes/year}) \cdot (97.5 \text{ km})$$

$$= 3,451,500,000 \text{ tonne-km/year}$$

The freight task is assumed to be independent of the type of vehicle used: it represents the total required movement of a fixed volume of commodity over a fixed selection of routes. This is not expected to change if the fleet transitions to PBS vehicles. The total cost of this operation (C_{bm}) can then be estimated using the cost per tonne-km for a 56-t truck at 50% utilisation from Table 1 ($c_{t\text{-}km}$):

$$C_{bm} = F_{tot} \cdot C_{t-km}$$

$$= (3,451,500,000 \text{ tonne-km/year}) \cdot (\text{R}1.18/\text{tonne-km})$$

$$= \text{R } 4,072,770,000/\text{year}$$

As a check, the calculated road transport cost of close to R 4 billion represents around 57% of the quoted total transport cost of R7 billion (Eskom Holdings SOC Ltd, 2017). Recall that road transport accounted for approximately 30% of the volume transported, but 55% of the tonne-kilometres (Table 8), and that road transport is the most expensive mode of road, rail and conveyor. Given this, the calculated result seems reasonable.

The calculated freight task (F_{tot}) can also be used to calculate the emissions associated with the benchmark transport task, using the GLEC emissions intensity factors in g CO2e/tonne-km (I_{TTW} and I_{WTW} in Table 2). The GLEC framework advises that the Europe and South America factors, are scaled by a 22% uplift factor for the African region for the case of articulated trucks up to 60 t GVM (heavy load, diesel fuel). Due to a lack of South African-specific factors, the factors and scaling recommended by GLEC were used. Until further work establishes factors specific to South Africa, there is some inherent uncertainty in the resultant CO2e figures reported, however this is not expected to differ significantly. The sensitivity to any difference would be linear, i.e., a 5% change in the emissions intensity factor would result in a 5% change in the calculated CO2e.

The total tank-to-wheel emissions and well-to wheel emissions of the benchmark transport task ($E_{bm,TTW}$ and $E_{bm,WTW}$ respectively) were calculated as follows:

$$E_{TTW,bm} = F_{tot} \cdot I_{TTW}$$

$$= (3,451,500,000 \text{ tonne-km/year}) \cdot (54 \text{ g CO2e/tonne-km})$$

$$= 186,381 \text{ tonnes CO2e/year}$$

$$E_{WTW,bm} = F_{tot} \cdot I_{WTW}$$

$$= (3,451,500,000 \text{ tonne-km/year}) \cdot (67 \text{ g CO2e/tonne-km})$$

$$= 231,251 \text{ tonnes CO2e/year}$$

It is also valuable to estimate the total number of truck trips and truck kilometres required for this freight task, as this has important implications for road wear impact and traffic on the roads utilised. The number of required return truck trips ($T_{tot,bm}$) can be calculated using the calculated freight volume ($V_{tot,bm}$) and the payload capacity of the standard 56-t vehicle from Table 3 ($M_{pl,bm}$). The total truck kilometres travelled ($d_{tot,bm}$) can then be estimated by multiplying the number of trips by the average lead distance (D_{ave}). The calculations are as follows:

$$T_{tot,bm} = V_{tot,bm} \cdot M_{pl,bm}$$

$$= (35,400,000 \text{ tonnes/year}) \cdot (35 \text{ tonnes})$$

$$= 1,011,429 \text{ trips/year}$$

$$d_{tot,bm} = T_{tot,bm} \cdot D_{ave}$$

$$= (1,011,429 \text{ trips/year}) \cdot (97.5 \text{ km}) \cdot 2$$

$$= 197,228,571 \text{ km/year}$$

3.4. *Cost and emissions: PBS scenario*

With the benchmark established, calculating the costs and emissions of a theoretical PBS fleet is straightforward. We calculated earlier from the PBS monitoring data a saving of 15% in fuel consumption per tonne-km for the PBS vehicles versus the baseline vehicles. This translates directly into a 15% reduction of associated carbon emissions from the burning of this fuel per tonne-km. We can hence estimate the carbon footprint of a full-PBS scenario using this saving if we assume that the freight task in tonne-km remains approximately constant in both the benchmark and PBS scenarios (i.e., $F_{tot,bm} = F_{tot,pbs} = F_{tot}$). This gives an annual PBS carbon footprint of 158,424 tCO2e (TTW) or 196,563 tCO2e (WTW), representing savings of 27,957 or 34,688 tCO2e respectively. Note that uncertainty in the emissions factor would impact the calculated CO2e figures for both baseline and PBS vehicles as discussed previously, but the percentage saving of 15% would be unaffected.

If we then assume that fuel accounts for 40% of transport costs for a typical transport operation of this nature (Havenga et al., 2016) (see Table 1), this translates into an overall cost saving of 15% × 40% = 6%. Applying this to the baseline data we get an annual PBS transport cost of R 3,828,403,800 representing a saving of R 244,366,200. This only accounts for fuel savings, and excludes other savings due to wear and tear, driver costs etc.

Finally the total number of truck trips and associated truck kilometres for the PBS scenario can be calculated as before, using the PBS payload per vehicle of $M_{pbs,pl} = 50$ t (Table 3). This is a 30% payload efficiency improvement over the baseline case, and yields figures of 708,000 trips/year and 138,060,000 km/year for the PBS case, representing savings of 303,429 trips/year and 59,168,571 km/year relative to the baseline.

3.5. *Road wear impact considerations*

So far, we have only considered the direct costs and emissions associated with the reduction in fuel use using high-capacity vehicles. We will now consider the indirect cost savings which can result from the reduced road wear impact of the PBS vehicles which has been observed in the South African pilot project. The method applied in the Namibia road user charge study (Kemp et al., 2018) was used, based on Load Equivalency Factors and the South African mechanistic-empirical pavement design method.

Fortunately, owing to the requirement that all vehicles participating in the South African PBS pilot project must undergo a road wear assessment, road wear impact performance of the coal vehicles in question are available for use in this study in the form of LEF/vehicle for both baseline and PBS vehicles in both laden and unladen scenarios. These anonymised data have been provided by the CSIR, though the original assessment reports are the confidential property of the industry participants. These assessments considered the same eight South African pavement structures used in (de Beer et al., 2009), and the reported LEF/vehicle represents the average value over all pavements.

Note that the LEF *per vehicle* is typically higher for the PBS vehicles due to the addition of additional load supported by an additional axle, but the overall LEF/t-km is typically lower due to the reduction in vehicle trips needed for the same freight task. Generally-speaking, carrying more freight with fewer vehicles yields a reduction in the overall road wear impact per unit of freight task (e.g., in tonne-km), provided individual axle or axle group loads are not significantly higher than the baseline case nor exceed regulated limits, and the overall tyre configuration (i.e., single versus dual tyres) is the same.

Using this approach, the road wear cost of a road transport operation can be estimated from the total distance travelled (d_{tot}), LEF per vehicle (LEF_{veh}) and the unit cost per LEF-km ($c_{LEF\text{-}km}$). The LEF per vehicle is dependent on the loading conditions (which results in different axle load inputs to the pavement), and so the laden and unladen journeys must be considered separately. With the assumption of 50% utilisation, the total journey distances reported in Table 4 and Table 5 can be split evenly into 50% laden and 50% unladen. The cost per LEF-km is independent of vehicle loading and so is the same for both scenarios. A unit cost of road damage of R0.50/LEF-km was used (Kemp et al., 2021). The costs calculation is summarised below, and the results are given in Table 9. The total saving is calculated to be around R 47 million per year, or 12% of the benchmark scenario.

$$C_{tot} = C_{laden} + C_{unladen}$$
$$= \left(d_{tot,laden} \cdot LEF_{veh,laden} \cdot c_{LEF\text{-}km}\right) + \left(d_{tot,unladen} \cdot LEF_{veh,unladen} \cdot c_{LEF\text{-}km}\right)$$

$$d_{tot,laden} = d_{tot,unladen} = \frac{d_{tot}}{2}$$

There is, of course, a reduction of carbon emissions associated with the reduction in road damage as the life of road assets is prolonged, which reduces the average annual demand for materials and construction activities. Some figures have been published for the typical carbon footprint of road pavement structures in South Africa over a 20- or 40-year life, in the range 100,000–700,000 kg CO2/lane-km (Blaauw & Maina, 2021). However, it is not trivial to determine the 'consumption' of road construction and maintenance emissions on a per vehicle level as has been done for costs using an LEF approach. As a first-order estimate, we can assume a comparable percentage reduction in line with the cost reduction: 12%. However, more detail on the traffic flows on the roads in question and the relative proportion of traffic which the coal trucks represent would be needed to fully quantify the emissions saved. This is considered beyond the scope of the current analysis and is recommended for future work.

3.6. *Cost of CO_2 emissions*

The monetization of CO_2 emissions is an active area of development, and many countries have introduced carbon taxes to help encourage businesses to lower their carbon footprint and to fund national carbon mitigation and adaptation efforts. However, the 'carbon price' associated with these taxes varies significantly between countries and it not necessarily reflective of the current and future costs associated with these emissions. Recent work has explored detailed methodologies for correctly accounting for these costs (Hickman et al., 2012; Kolosz & Grant-Muller, 2016; Nocera & Cavallaro, 2012), however there is no universally agreed approach to this and very limited data for South Africa. For the current study, the most applicable carbon price to use is

Table 9
Summary of road wear impact costs: PBS and baseline coal trucks.

	Distance (km/yr)	LEF per vehicle	Cost per LEF-km	Annual road wear cost
Baseline laden	98,614,286	6.46	R 0.50	R 318,524,143
Baseline unladen	98,614,286	1.50	R 0.50	R 73,960,714
Total (baseline)	**197,228,571**	–	–	**R 392,484,857**
PBS laden	69,030,000	8.37	R 0.50	R 288,890,550
PBS unladen	69,030,000	1.62	R 0.50	R 55,914,300
Total (PBS)	**138,060,000**	–	–	**R 344,804,850**
PBS saving:				R 47,680,007
PBS saving (%):				12%

that introduced by the South African government in 2019. This at least provides an indication of actual business-incurred costs associated with carbon emissions in South Africa at present, while noting that the actual costs are likely much higher.

South Africa introduced a carbon tax in 2019 at a rate of R 120 per tonne with increases by the 2% over the consumer price inflation index per year thereafter until December 2022 (Republic of South Africa, 2019). Given that the data and associated costs up to, 2019 have been used in this study, the initial rate of R 120/t can be used to calculate the associated carbon cost. This results in a WTW carbon cost of 231,251·120 = R 27,750,120/year (baseline) and 196,563·120 = R 23,587,560/year (PBS), a saving of R 4,162,560/year.

3.7. Summary

The calculated baseline and PBS scenario results and the savings associated with the PBS scenario are summarised in Table 10. Table 11 summarises just the costs of the transport task, both direct and indirect including those associated with road wear and carbon. For the savings, it was conservatively assumed that 50% of the transport cost savings would be passed on from the transporter to Eskom. An exact figure is difficult to predict and could reach closer to 100% depending on the competitive nature of the transport sector, profit margins, and the prevalence of PBS vehicles in the transport system. Nevertheless, 100% of the saving incurred by Eskom—a public entity—is considered to be a saving to the taxpayer. Road wear impact savings are assumed to be entirely a saving to the taxpayer, as road maintenance is a public service which in this case falls mostly to the provincial roads departments. Finally, the carbon tax savings were assumed to be entirely borne by Eskom, but again this is dependent on the nature of the transport contracts. All of this saving to Eskom is again considered a saving to the taxpayer. Other potentially monetizable aspects such as reduced crash risk due to the reduced number of trucks and improved vehicle designs have not been considered.

4. Discussion

The fuel-related cost saving of up to R 244 million/year is significant and represents a 6% saving on the total road transport cost or 3.5% of the total transport costs of R 7 billion. The actual savings may in fact be higher than this due to better turnaround times and driver costs as has been observed in some cases (Steenkamp et al., 2021). The portion of this cost saving which is ultimately passed on to Eskom is a matter for further investigation and will depend on several factors including Eskom's ability to negotiate new contracts with the mines and transporters, and the balance of coal contracts directly between Eskom and the mines, and those between Eskom and transporters. Initially, it is the transporter who realises the savings in the transport operations. However, ultimately much of or even most of this saving will be passed on to Eskom through the reduction of transport prices in the coal transport market in order for operators to remain competitive amongst each other for coal transport contracts.

Table 10
Comparison of direct costs, emissions and journeys: benchmark and PBS scenarios.

	Benchmark	PBS	Saving	
Cost of transport (R/year)	R 4,072,770,000	R 3,828,403,800	R 244,366,200	6%
TTW emissions (tonnes CO2/ year)	186,381	158,424	27,957	15%
WTW emissions (tonnes CO2/ year)	231,251	196,563	34,688	15%
Truck journeys (return trips/ year)	1,011,429	708,000	303,429	30%
Truck travel (km/ year)	197,228,571	138,060,000	59,168,571	30%

Some saving will need to be retained by the operators to justify the investment in new vehicles, such that the overall cost of ownership for them makes a good business case. Initial studies have indicated that these additional costs are small compared to the overall benefits (Steenkamp et al., 2021). A conservative estimate of 50% transfer of savings results in a R 122 million annual saving to Eskom and ultimately to the South African taxpayer. Eskom will also benefit from the improved stability of the transport providers, who will be operating under better business cases with improved profit margins. The current cost associated with South Africa's carbon tax is relatively small by comparison at around R 4 million, but this figure is expected to increase in future.

The additional road wear-related cost saving of R 48 million may not directly impact Eskom's balance sheet but is an additional cost saving to the taxpayer. There will of course be indirect benefits to Eskom and other road users over time due to improved road conditions for both coal transport and general traffic, which have both cost and safety implications. In total, there is scope for Eskom to save between R 126 million and R 248 million per year, and for the taxpayer to reap a saving of between R 174 and R 296 million.

The total truck trips and truck kilometres see the biggest reduction of 30%, with the PBS scenario resulting in 303,429 and 59,168,571 fewer trips and kilometres respectively each year. That is an average of 830 fewer truck trips a day, or 24 fewer truck trips per day per haulage route (assuming they are evenly spread across 35 haulage routes as per Table 1). This would likely be very noticeable to regular users of that road network. It will also reduce the logistic overheads at collection and delivery points owing to fewer vehicles needing to be positioned, loaded, and unloaded at the mines and power stations. Eskom's claimed 600,000 km per day of truck travel (Solomons, 2015) (see Table 1) implies 219 million km per year, which agrees well with the calculated 197 million km.

The 15% reduction in total emissions totalling close to 35,000 t per year, is significant in a transport context and is superior to the expected reduction potential of alternative decarbonisation interventions in the short term. However, the figure is small in the context of Eskom's total footprint of around 221 million tonnes where it represents a reduction of only 0.016% or around 0.008% of South Africa's total annual carbon emissions. In the broader context of road freight transport however, high-capacity vehicles present an attractive decarbonisation solution. According to (DEA, 2014), heavy duty vehicles in South Africa contribute around 14 million tonnes of CO2 (excluding indirect emissions). Even a few percent off this figure would be significant, taking into account the fact that HCVs may not be suitable for all current heavy duty vehicle operations.

The results are of course sensitive to the input data used, some of which may be subject to more uncertainty than others. It is valuable to review the results in the light of these sensitivities. The sensitivity of the results to the most important input values is summarised in Table 12. The possible variations are estimated based on sector knowledge and experience. The coal volumes reported by Eskom have little expected uncertainty, while the average lead distance (and hence total freight task in tonne-km) and LEF per vehicle are both considered to have around 20% uncertainty. The 22% upliftment factor incorporated into I_{WTW} and I_{TTW} is subject to further investigation as discussed earlier.

At the extremes in which all input parameters have been fully under- or fully over-estimated simultaneously, the total costs of both the baseline and PBS scenarios have an uncertainty of ±55% at its absolute maximum (15 + 20 + 5 + 15). Emissions uncertainty is at its most extreme ±40%. The total truck journey figures are almost certain as this is simply a function of the payload capacity of the vehicles. Total truck kilometres have a maximum ±25% uncertainty. Finally, road wear savings have at most an uncertainty of at most 25%. Note however that

Table 11
Comparison of direct and indirect costs and their implications for Eskom and the taxpayer.

Annual costs	Scenario		Savings relative to baseline		
	Benchmark	PBS	Total	Eskom	Taxpayer
Transport	R 4,072,770,000	R 3,828,403,800	R 244,366,200	R 122,183,100	R 122,183,100
Road wear impact	R 392,484,857	R 344,804,850	R 47,680,007	R -	R 47,680,007
Carbon (WTW)	R 27,750,120	R 23,587,560	R 4,162,560	R 4,162,560	R 4,162,560
TOTAL	**R 4,493,004,977**	**R 4,196,796,210**	**R 296,208,767**	**R 126,345,660**	**R 174,025,667**

Table 12
Sensitivity of baseline and PBS results to input data.

	c_{t-km}	D_{ave}	I_{WTW}	V_{tot}	Fuel % of costs	LEF_{veh}
Reference value	R1.18	97.5 km	67 g/t-km	35,4 Mt	40%	various
Possible variation (±)	±15%	±20%	±15%	±5%	±15%	±20%
Saving in cost of transport (R/yr)	±15%	±20%	–	±5%	±15%	–
Saving in WTW emissions (tonnes CO2/yr)	–	±20%	±15%	±5%	–	–
Saving in truck journeys (trips/yr)	–	–	–	±5%	–	–
Saving in truck travel (km/yr)	–	±20%	–	±5%	–	–
Saving in road wear cost (R/yr)	–	±20%	–	±5%	–	±20%

all the uncertainties affect the baseline and PBS *totals* in equal measures, and so the resultant calculated *savings* are significantly less sensitive, and the *percentage* savings have minimal uncertainty. Overall, there is no doubt that a PBS scenario would result in savings, and the reported savings are realistically accurate to within an estimated ±20% certainty.

5. Conclusions and future work

In this work, we have benchmarked the current costs and emissions associated with the transport of coal via road for power stations in South Africa, which amount to approximately R 4 billion and 230,000 t of CO2 respectively. A case was then presented for the use of high-capacity vehicles to reduce these costs and emissions, using 74-t vehicle combinations which have already been in use in the South African PBS pilot project for several years. If the entire fleet of trucks were replaced with these PBS combinations, approximately R 240 million and 35,000 t of CO2 would be saved each year. Further, such a transition would also yield a reduction in road damage valued at around R 50 million per year; this would also yield addition emission reductions which were not quantified in this work.

The business case to Eskom appears to be clear, but this is not simply a decision which Eskom has the power to make. The PBS scheme in South Africa is still in pilot project phase, and approval for the formalisation of the scheme is subject to decision by the Department of Transport. At the time of writing such a decision was still pending. If the scheme is approved, we can expect the coal transporters to react accordingly to the good business case presented and see a significant increase in participation possibly to the point of a full fleet replacement over a typical first-life vehicle replacement lifespan of 5 years. We can also expect some operators to experiment with larger vehicle combinations on appropriate routes which would further reduce costs and emissions in the system.

In addition to the business-related benefits, a transition to PBS coal trucks presents benefits to the South African public. These include reduced air pollution especially in residential areas located near coal mines and power stations, fewer trucks on the road with an associated reduction in crash risk, safer trucks on the road due to the PBS design process, reduced taxpayer expenditure on road maintenance due to the road wear impact improvements, and improved energy security due to the improved financial position of the country's electricity provider.

It should be noted that these recommendations and findings do not deny the value of the road-to-rail initiative. Moving more freight by rail in any industry where it is relevant must be encouraged and supported as much as possible, for the overall benefit to society and industry through lower costs and separation of heavy freight vehicles from passenger traffic. However, the migration to rail has faced several challenges over the recent years and continues to do so. This will also require substantial long term infrastructure investment, including in rail off-loading infrastructure at the power stations. While some freight may shift to rail in future, there will always be a need for a large proportion of freight to move on road. (This is not unique to South Africa.) And so, for whatever freight must be moved by road, initiatives such as this help to make road freight as efficient, safe and road friendly as possible. Specific flows between origin and destination pairs (as used to generate Fig. 9) can be studied to identify ideal opportunities for modal shift, but in some instances this is restricted by the availability of loading and unloading infrastructure for rail wagons and road trailers at the coal mines and/or power stations.

Recommendations for future work include the following:

- A study to determine appropriate carbon emission intensity factors for South African heavy goods vehicles
- A study to quantify the emissions impact associated with reductions in road wear impact, potentially through the determination of 'g CO2/LEF-km' factors for a range of pavement structures.
- Further investigation into the realities of the coal transport contracts between Eskom and the mines as well as directly between Eskom and transporters, and how a transition to PBS could be realised in practice.
- An exploration of public-private models of cost benefit sharing between Eskom and the mines and transporters, as well as between the Mpumalanga road authority and other third parties insofar as the reduced road wear impact is concerned.
- An investigation into modal shift opportunities for all origin destination combination pairs in the power station coal supply chain.

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