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Soot-free road transport in South Africa: A cost-benefit analysis of Euro VI heavy-duty vehicle standards

Authors: Yihao Xie, Francisco Posada, Arijit Sen

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Introduction

Ambient air pollution is a major risk factor for adverse health outcomes worldwide. Exposure to air pollutants is associated with millions of premature deaths each year from a wide range of health conditions, including stroke, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections (Stanaway et al., 2018). Black carbon (BC), or soot, is a component of $PM_{2.5}$ pollution, as well as a potent short-lived climate pollutant (SLCP) (Janssen et al., 2012).

The challenge of poor air quality acutely affects African nations, including South Africa. In 2019, 383,000 deaths were attributable to ambient fine particulate matter ($PM_{2.5}$) pollution in Africa, an increase of 7% from 2015, with the greatest increases occurring in the most highly developed African countries (Fisher et al., 2021). In South Africa, air pollution ranks as the number one environmental risk factor related to health, and is the 8th leading overall risk factor for deaths and disability in 2019 (Institute for Health Metrics and Evaluation, n.d.).

Transportation was responsible for 7% of deaths caused by exposure to $PM_{2.5}$ and ozone in 2015 in South Africa, and of these deaths, 48% are attributed to on-road diesel vehicles (Anenberg et al., 2019). Severely outdated vehicle emission standards have contributed to this deadly air pollution: the current HDV emission standards in South Africa are Euro II, first introduced in Europe more than 20 years ago and phased-out long ago there and in other major economies. South Africa has not updated its official emission standard regulations since adopting Euro II standards in 2006 (*Regulations Regarding Petroleum Products Specifications and Standards* 2006). Diesel engines that lack modern emission control devices produce $PM_{2.5}$, soot, nitrogen oxides (NO_X) and other pollutants in large quantities.

www.theicct.org

communications@theicct.org

twitter @theicct

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Unlike most markets in Sub-Saharan Africa, South Africa has a strong domestic vehicle manufacturing industry, and has banned the import of used vehicles, which are common in other African nations. This simplifies the regulation of environmental performance of vehicles in South Africa. In addition, South Africa's diesel fuel in the retail market is approaching the level of sulfur content required for Euro VI heavy-duty vehicle emission standards. The two factors combined put South Africa in a strong position to formally adopt Euro VI-equivalent and future HDV emission standards, thereby reducing air pollution and the health risks associated with it. Such leapfrogging has a precedent in India, where the government successfully jumped from Euro IV-equivalent to Euro VI-equivalent emission standards in 2020, under similar conditions of low sulfur diesel availability in the market (Shao, 2020). This study estimates the costs and benefits of adopting Euro VI standards in diesel HDVs in South Africa under different timelines of fuel quality and emission standard advancements. Based on the results, we also make policy recommendations that would reduce HDV emissions and improve air quality and public health in South Africa.

Background

Heavy-duty vehicle market

The heavy-duty vehicles market in South Africa was stable from 2016 through 2019 with around 27,000 vehicles sold per year. The market shrank in 2020 by 18.8% due to disruptions caused by Covid-19 (Lamprecht, 2021). Figure 1 below shows the sales of new HDVs in South Africa from 2016 to 2020 for four HDV segments: buses (with Gross Vehicle Weight Rating ≥ 8500 kg), medium commercial vehicles, MCVs (3501 kg ≤ GWVR ≤ 8500 kg), heavy commercial vehicles, HCVs (8501 kg ≤ GWVR ≤ 15000 kg), and extra-heavy commercial vehicles, XHCVs (GWVR ≥ 15001 kg). Diesel vehicles dominate South Africa's HDV market, representing nearly 100% of all new HDVs sold in 2020. In 2019 and 2020, imports accounted for around 1/5 of the total HDV sales in South Africa. On the other hand, less than 5% of HDVs produced in South Africa are exported, primarily to neighboring countries in the Southern African Development Community (SADC) region. This stands in stark contrast to light-duty vehicle production in South Africa, of which 64% were exported in 2020. The major manufacturers of buses and trucks in South Africa are mostly foreign brands, including Daimler (17% of the market in 2021), Isuzu (12%), Toyota (11%), and Volvo Truck (9%). These manufacturers each have a global presence and the technological expertise to produce Euro VI vehicles in other markets.

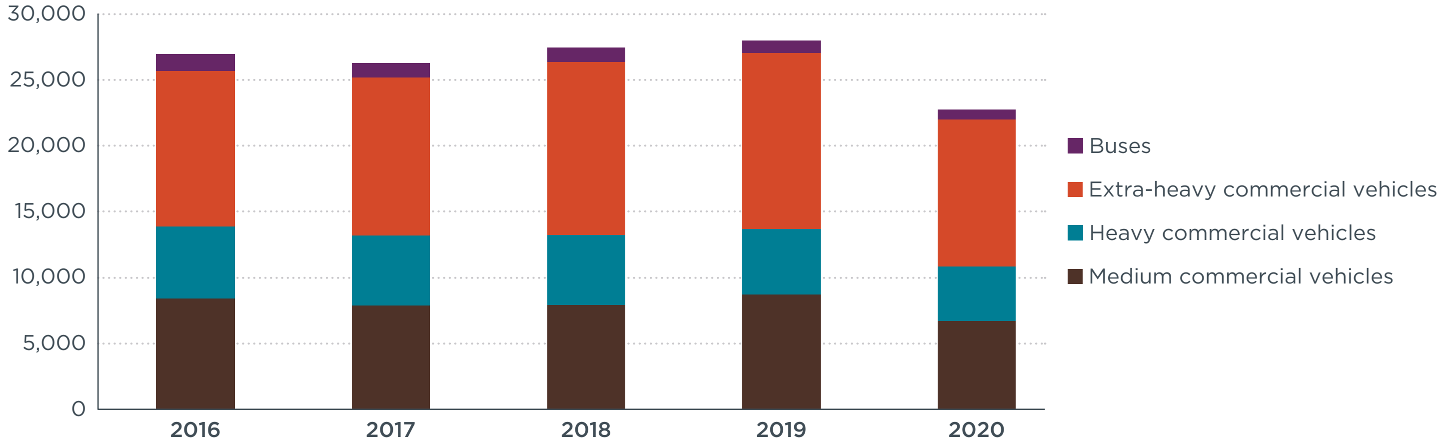

Figure 1. New HDV sales in South Africa, 2016-2020.
Source: Lamprecht (2021)

Heavy-duty vehicle emission standards

Figure 2 is a timeline showing the adoption of HDV emission standards in G20 economies. South Africa is the only nation still following the outdated Euro II standards, whereas all other G20 members have moved to more stringent heavy-duty emission standards, with an increasing number having implemented or being set to implement Euro VI standards (Miller and Jin 2019). According to industry experts and previous research, HDVs sold in South Africa have engine and aftertreatment technologies that can meet Euro III standards and beyond. This is especially true for buses sold today, which meet Euro V standards (Minjares et al., 2020). However, the production and sales of vehicles that exceed the current Euro II emission standards are not recorded in official or industry databases, because the current standards mandate only a Euro II level of performance.

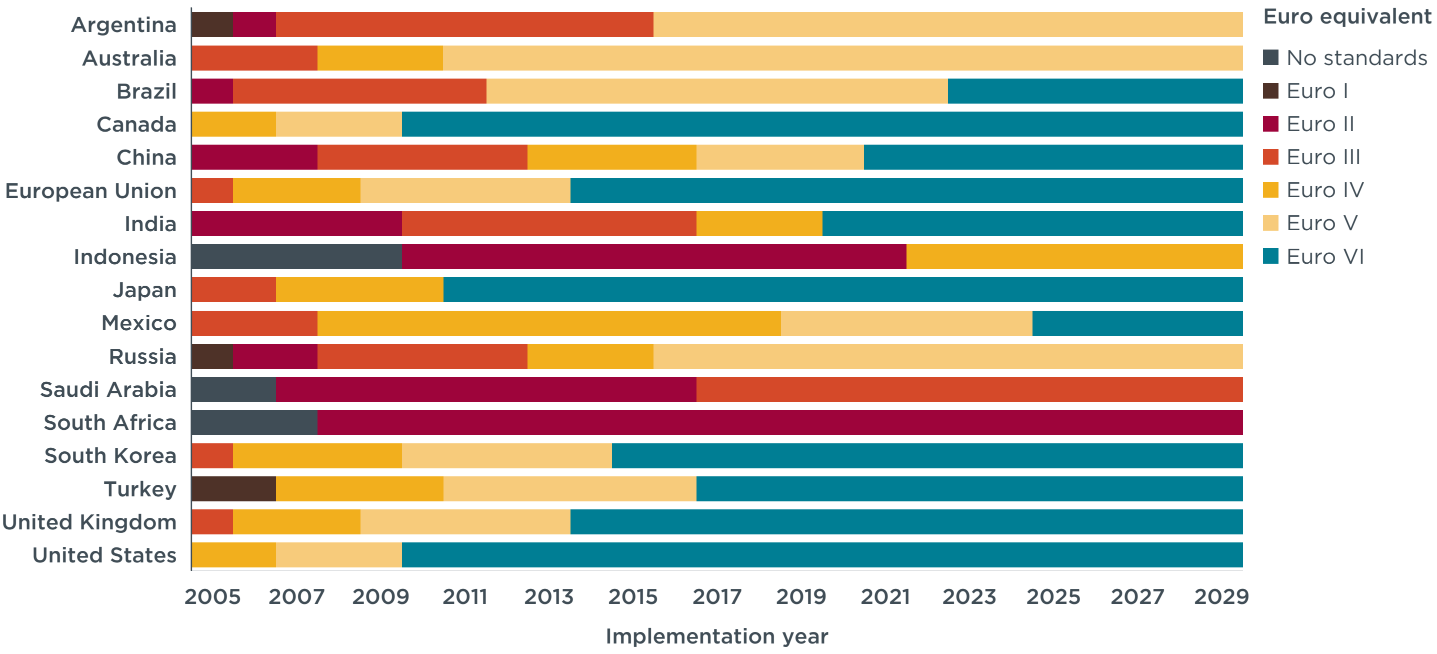

Figure 2. Implementation of heavy-duty diesel engine emission standards in G20 economies, listed alphabetically. *Source:* Miller and Jin (2019).

Diesel demand and quality

The vast majority of South Africa's diesel fuel has sulfur content lower than 50 ppm, which is suitable for Euro IV emission standards. In August 2021, South African regulators published new regulations that will limit diesel sulfur content to 10 ppm, effective in September 2023 (*Petroleum Products Act, 1977: Regulations Regarding Petroleum Products Specifications and Standards for Implementation* 2021).

Figure 3 shows that diesel consumption in South Africa rose steadily from 2010 to 2019, increasing by 23.5% over the period, then dipping in 2020 because of the Covid-19 pandemic (South African Petroleum Industry Association 2021a). Diesel with sulfur content of less than 50 ppm has also become the dominant diesel grade, with the latest market penetration at 97.5%. The rest of the diesel sold had a sulfur content of 500 ppm. At the same time, the volume of diesel net import has increased from 1.55 million tons in 2010, some 17.5% of annual diesel consumption, to more than 4.06 million tons in 2019, or 37.3% of annual diesel consumption ("SAPIA 2019 Annual Report," n.d.).

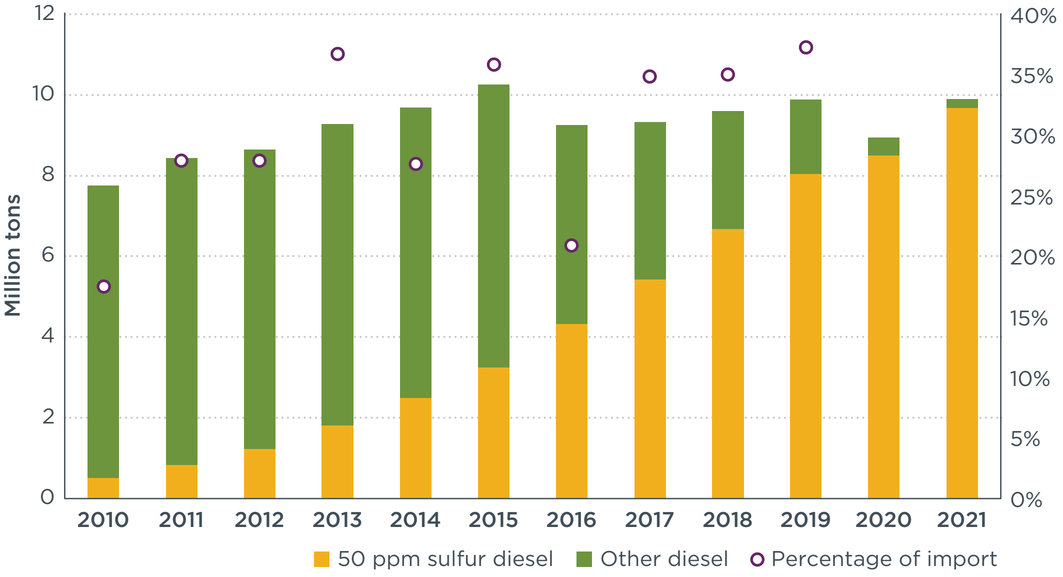

Figure 3. Diesel consumption and share of imported diesel in South Africa 2010-2021, million tons. *Source:* South African Petroleum Industry Association (2021).

While 10 ppm sulfur diesel is available for retail sale, it is not a regulated product in the South African market and its sales are not separately reported. Official information on fuel specification stops at 50 ppm, a sulfur level that meets Euro IV requirements. As a result, the calculated average diesel sulfur content of 60 ppm in 2021 is likely an overestimate because an unknown volume of 10 ppm sulfur diesel is embedded in 50 ppm sulfur diesel sales data.

Diesel fuel in the South African market comes from three sources: imported diesel, domestically refined petroleum diesel, and synthetic diesel made from natural gas and coal. South Africa's diesel imports come primarily from the Middle East, India, and Singapore ("The South African Energy Sector Report 2019," n.d.). According to a study conducted by SAPIA in 2019, all imported diesel fuels had less than 10 ppm sulfur content (South African Petroleum Industry Association 2021b). South Africa also imports most of its crude oil and does its own further refining. Domestically refined diesel from petroleum has a sulfur content of less than 50 ppm that meets the current sulfur limit (South African Petroleum Industry Association 2021b). Sasol Synfuels produces coal to liquid (CTL) synthetic diesel in Secunda, Mpumalanga, while another petroleum company, Petroleum Oil and Gas Corporation of South Africa (PetroSA) utilizes gas to liquid (GTL) to produce synthetic diesel in Mossel Bay, Western Cape. Both synthetic diesel products contain less than 10 ppm sulfur content.

Diesel quality in South Africa will likely improve in the future because of the deepening reliance on fuel imports. Two major refineries owned by Engen and Astron Energy in South Africa suffered fires and were shut down in 2020, limiting domestic supplies of petroleum diesel (Washington and Gupte 2021). The Engen refinery will not be restarted but instead converted to an import terminal, due to be completed in 2023 (Abudoun 2021). SASOL also cut output forecasts for its Secunda operations producing CTL fuels, including diesel ("Sasol Cuts Output Forecast for Secunda Operations amid Tight Coal Supplies | Reuters" 2021). With these changes in the local production of diesel fuel, SAPIA projects that imported fuel will meet at least 60% of the demand in the long run, which makes the September 2023 deadline for 10 ppm sulfur diesel easier to achieve.

Modeled policy scenarios

Standards for cleaner fuel are typically introduced just prior to, or in tandem with, cleaner vehicle emission standards (Miller 2019). To meet the Euro VI emission standards, diesel vehicles need 10 ppm sulfur diesel to allow the aftertreatment systems to function at the designed pollution conversion efficiency (Xie, Posada, & Minjares, 2020). The forthcoming limit of 10 ppm sulfur content in diesel fuel could potentially lead to rapid adoption of the most advanced Euro VI emission standards in South Africa.

In this context, our study evaluates the impact of advanced HDV emission standards in South Africa for three scenarios, along with a baseline scenario that continues the trajectory of current emission standards and announced fuel quality improvements. In all scenarios, South Africa implements the 10 ppm diesel sulfur content limit in 2023 as planned. The scenarios are outlined in Table 1 and include the following assumptions:

- **Baseline**: South Africa implements the planned 10 ppm sulfur diesel content limit in 2023 but maintains the current HDV emission standards. Without precise market share information by emission standard, we assume new vehicles in South Africa meet Euro III standards for trucks and Euro IV for buses from 2016 onward. This differs from the Euro II emission standards officially in place, but reflects our understanding of the market in practice, based on information provided by industry experts and government officials.
- **Incremental Transition to Euro VI**: South Africa implements Euro IV emission standards in 2024, followed by Euro VI standards in 2027.
- **Leapfrog to Euro VI**: South Africa implements Euro VI standards in 2024.
- **Beyond Euro VI**: South Africa implements Euro VI standards in 2024, then implements Euro VII-equivalent next-generation emission standards in 2030.[1]

To reduce the contribution of HDVs to air pollution and climate change, South Africa needs a suite of actions, including improving vehicle efficiency, shifting HDV passenger and freight activity to less energy-intensive modes, adopting zero-emission truck and bus technologies, and developing low-carbon fuels to provide renewable electricity for zero-emission vehicles. We focus only on emission standards in this study, however, and do not analyze the impact of these additional measures.

Table 1. Modeling scenarios and assumptions

Scenario	Diesel sulfur content	HDV emission standard
Baseline	60 ppm (average value for 2021), 10 ppm in 2023	Euro III for trucks; Euro IV for buses. No progression
Incremental Transition Euro IV – Euro VI		2024: Euro IV 2027: Euro VI
Leapfrog to Euro VI		2024: Euro VI
Beyond Euro VI		2024: Euro VI 2030: Euro VII-equivalent*

* Based on ICCT projections of emission factors of Euro VII standards

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[1] The European Commission is currently planning to adopt Euro VII emission standards for HDVs and Euro 7 emission standards for passenger vehicles. One goal of the Euro VII standard will be to tighten NO_x emissions under low-load and low-temperature conditions, and to reduce NO_x emissions by up to 90% compared to Euro VI limits. Euro 7/VII standards are expected to take effect between 2025 and 2030.

Modeling methods and data

Data on vehicle sales and stock, and on fuel sales and quality, were obtained from public reports (Department of Mineral Resources and Energy) and industry sources (SAPIA, National Association of Automobile Manufacturers of South Africa - NAAMSA), and from correspondence with experts and government agencies. HDV emissions of $PM_{2.5}$, BC, NO_x, and sulfur dioxide (SO_2) were derived using bottom-up fleet modeling in ICCT's roadmap model (ICCT, 2022). The health impact of emissions is evaluated using the ICCT's Fast Assessment of Transportation Emissions (FATE) model (ICCT, 2021). Finally, data on the costs of upgraded vehicle technology were sourced from previous ICCT studies, updated, and adjusted for South Africa's vehicle market (Ragon & Rodríguez, 2021; Posada, Chambliss, & Blumberg, 2016).

Projections of future HDV stock (Figure 4) in South Africa are sourced from the February 2021 version of the International Energy Agency Mobility Model (MoMo) and calibrated using actual sales data between 2016 and 2020 from the South Africa Automotive Industry Export Council. HDV sales and stock are both projected to grow in South Africa in the coming decades. By 2050, more than 358,000 new HDVs will be sold each year, contributing to a combined fleet size of more than 5 million vehicles (Figure 4). We assume the fuel efficiency of HDVs in South Africa will remain unchanged over the period of analysis because the country lacks HDV fuel efficiency standards. Growth in the vehicle fleet will also increase total energy consumption from South Africa's HDV activities in the same period. We assume that new HDV sales will be entirely diesel-powered in all scenarios, consistent with the reality of the market. Certain segments of the HDV market like urban buses may transition to battery-electric technologies but we do not model such changes in the absence of national targets or actions to support the adoption of zero-emission HDVs.

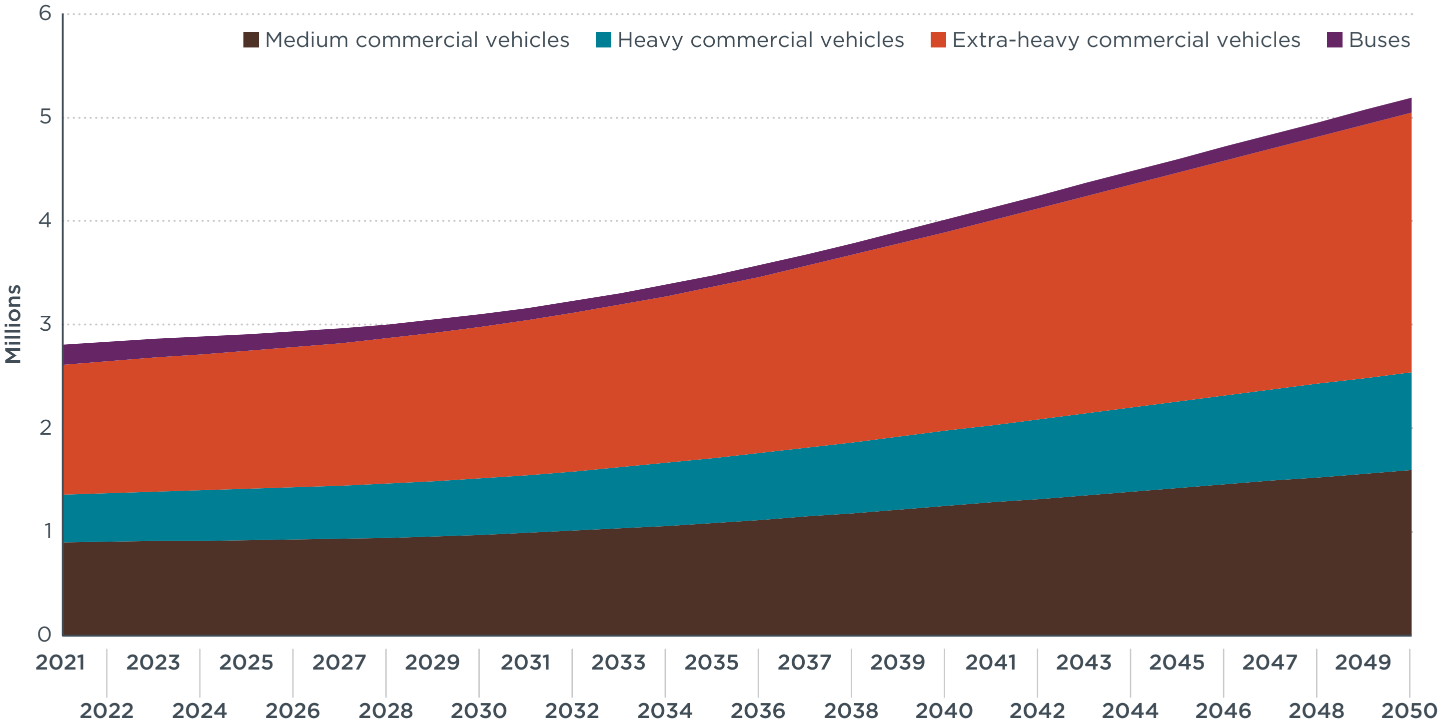

Figure 4. Projected HDV stock in South Africa by vehicle type, 2021-2050

Vehicle emission results

Figure 5 shows projected HDV tailpipe emissions of $PM_{2.5}$, NO_X, BC, and SO_2 between 2021 and 2050 in South Africa under each policy scenario.[2] In the baseline scenario, $PM_{2.5}$ falls with the availability of 10 ppm sulfur diesel in 2023 before picking up again with increased vehicle fleet size and activity. By 2050, the levels of $PM_{2.5}$, NO_X, and BC emissions will be 24.9%, 55.5%, and 25.3% higher compared to 2021 levels, respectively. The 10 ppm sulfur diesel limit under the baseline scenario leads to an 83% decrease in SO_2 emissions from 2022 to 2023 since there is less sulfur in the diesel to produce SO_2.

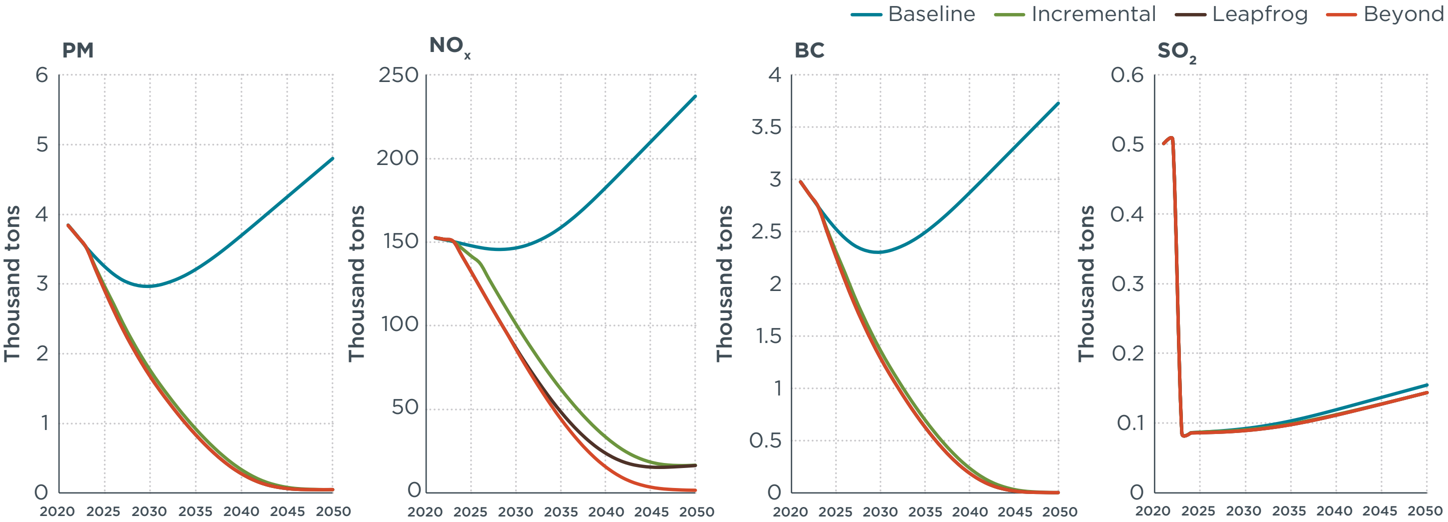

Figure 5. Annual tailpipe HDV emissions in South Africa, 2021-2050

Adopting modern emission standards can drastically reduce air pollution from South Africa's HDV activities. In the most conservative "Incremental Transition" scenario, emissions of $PM_{2.5}$, BC, and NO_X in 2050 would be reduced by 99.0%, 99.8%, and 93.0% compared to the baseline. "Leapfrog to Euro VI" would deliver even greater emission reductions in the near to mid-term, due to the earlier adoption of Euro VI standards, while annual emission levels in 2050 would be similar between these two scenarios.

The "Beyond Euro VI" scenario further reduces NO_X emissions by 89.0% in 2050 compared to the Leapfrog scenario, and by a staggering 99.2% compared to the baseline. With the proposed Euro VII standards assumed in this scenario, NO_X limits are nearly 10 times more stringent than the current Euro VI standards allow, which explains the plummeting NO_X emissions in our projection.

As Table 2 illustrates below, South Africa can more than halve its cumulative emissions of $PM_{2.5}$, NO_X, and BC over the 2021 to 2050 period under all three alternative policy scenarios. Compared to the Incremental scenario, early adoption of Euro VI under the Leapfrog scenario means a greater reduction of $PM_{2.5}$, BC, and SO_2 emissions. Accelerated adoption of Euro VI standards in 2024 avoids cumulative emissions of 72,500 tons of $PM_{2.5}$, 56,300 tons of BC, and 3.34 million tons of NO_X emissions between 2021 and 2050 from diesel HDVs, respectively. Transitioning to Euro VI in 2024 and following up with Euro VII-equivalent emission standards in 2030, i.e., the "Beyond Euro VI" scenario, would help South Africa achieve the greatest emission reductions, especially for NO_X.

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[2] Projection of $PM_{2.5}$ emissions in this study accounts for changes in emission control technologies and their emission factors, as well as the effects of sulfate emissions due to changes in diesel sulfur content over time.

Table 2. Reduction in cumulative emissions under alternative scenarios by 2050

	Cumulative emissions by 2050 under the **Baseline** scenario, kilotons	Cumulative emission reductions under **Incremental Transition** scenario relative to baseline	Cumulative emission reductions under **Leapfrog Transition** scenario relative to baseline	Cumulative emission reductions under **Beyond Euro VI** scenario relative to baseline
$PM_{2.5}$	108.7	64.7%	66.1%	66.1%
NO_X	5238.5	59.1%	63.8%	67.0%
BC	84.4	65.0%	66.7%	66.7%
SO_2	4.1	3.5%	4.0%	4.0%

Costs and benefits

Incremental vehicle technology and operating costs

More stringent emission standards require vehicle manufacturers to invest in emission control technologies. For example, when upgrading from a baseline of Euro III standards, HDVs that follow Euro IV and V standards are equipped with Selective Catalyst Reduction (SCR) systems to reduce NO_X emissions. The transition to Euro VI requires the addition of Diesel Particulate Filter (DPF) systems for $PM_{2.5}$ control in diesel vehicles. We model the incremental technology costs using ICCT studies that evaluated the costs of complying with stringent heavy-duty vehicle emission standards and adjusted for diesel HDVs sold in the South African market. The cost values for Euro III, Euro IV, Euro V, and Euro VI technologies were updated from HDV cost analyses performed in 2015 (Posada, Chambliss, & Blumberg, 2016). The update includes incorporation of recent and significant technology cost reductions due to the adoption of Euro VI standards in China and India. The estimated cost to meet Euro VII standards was based on projections of potential technologies that may be adopted by HDV manufacturers in the future (Ragon & Rodríguez, 2021); these are prices in Europe and may be higher than what South Africa experiences. The summary of cost per standard level for different vehicle types is presented in Table 3 below.

Table 3. Technology costs for new HDVs in South Africa, by emission standard and vehicle type, in U.S. dollars

Emission standard	**Bus**	**Medium commercial vehicle**	**Heavy commercial vehicle**	**Extra-heavy commercial vehicle**
Euro III	$220	$200	$210	$232
Euro IV/V	$2,225	$1,671	$2,084	$2,885
Euro VI	$3,588	$2,786	$3,347	$4,578
Euro VII*	$5,413	$3,698	$4,990	$7,576

*Estimated cost of potential technologies required to meet Euro VII standards

The incremental operating costs modeled in this analysis are the cost of servicing diesel particulate filters for Euro VI and later vehicles.[3] We do not model the cost of automotive urea (also known as AdBlue in Europe) consumption for the SCR systems used from Euro IV and beyond because these costs are likely offset by improved fuel efficiency in modern engines designed in the last decade to meet higher emission standards (Dallmann & Jin, 2020).[4]

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[3] The DPF traps particulate matter from the engine. The DPF burns the soot that is composed of carbon particles, and traps inorganic material that makes up a fraction of particulate matter in the exhaust. Unburnt inorganic material must be cleaned from the DPF every 200,000 km to avoid clogging the ceramic material; after that, the clean filter is placed back in the vehicle. The cleaning must be performed by the dealer or by properly trained technicians. The material collected should be treated as hazardous waste (HW) and handled according to the country's HW management regulations.

[4] The introduction of selective catalytic reduction systems (SCR) for NO_x control in Euro IV and newer engine designs has allowed manufacturers to calibrate engines for more efficient operation and thereby offset the cost penalties associated with urea refills. Furthermore, electronic engine controls, better fuel injection systems, and other engine developments offer greater fuel efficiency than Euro III and older engines designed and sold more than 30 years ago.

Health benefits and valuation

We used ICCT's FATE model to evaluate the burden of disease resulting from emissions of HDV exhaust pollutants in South Africa. Fleetwide HDV tailpipe emissions of BC, organic carbon, NH_3, NO_X, and SO_2, are used to estimate national population-weighted concentrations of $PM_{2.5}$ and O_3. We then calculate the health impacts of $PM_{2.5}$ and O_3 exposure following the "attributable fraction" approach. Detailed methodology can be found in Jin, et al. (2021) and ICCT (2021). We estimated the number of premature deaths and disability-adjusted life years (DALYs), i.e., the sum of years of life lost due to premature mortality and years of healthy life lost due to disability, that could be avoided through potential reductions of air pollution in South Africa. Social cost is thus expressed as health damage due to HDV tailpipe emissions, and benefits are avoided costs because of reduced HDV emissions in alternative scenarios. The monetary values of health benefits were estimated by multiplying the number of premature deaths by the Value of a Statistical Life (VSL)[5] of South Africa from 2021 to 2050, following the methodology in Viscusi and Masterman (2017).

All monetary costs and benefits in this analysis are adjusted with a 5% social discount rate to convert the damages to 2020 US dollars.

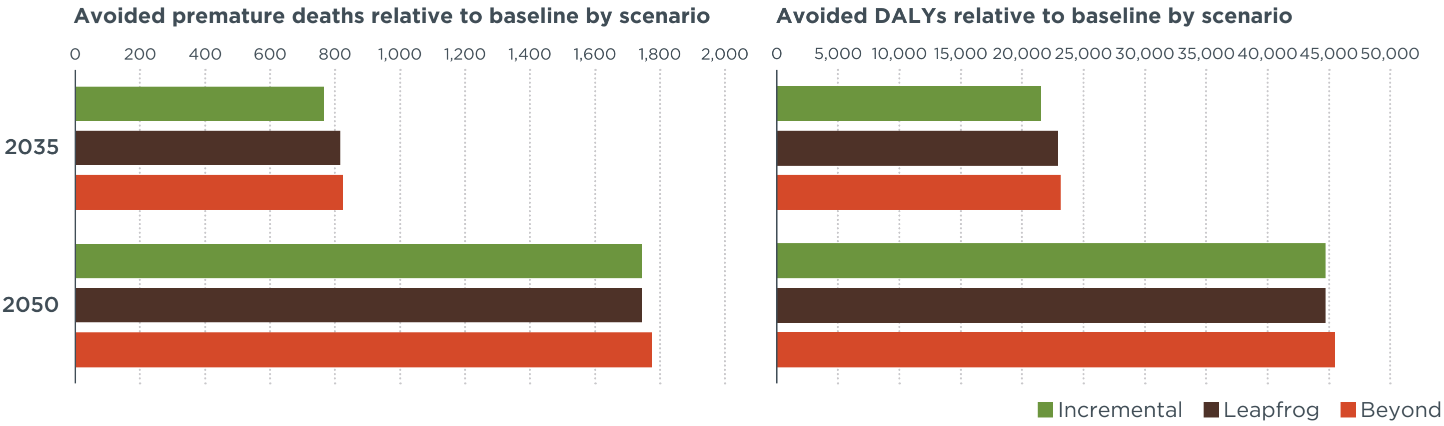

Figure 6. Avoided premature deaths and DALYs due to diesel HDV air pollution compared to baseline in 2035 and 2050

In this analysis, the alternative HDV policy scenarios and their resultant air pollutant reductions are associated with relatively modest changes in avoided premature deaths and DALYs in South Africa related to air quality, compared to the large total air pollution health burden in the country (Figure 6). In 2035, compared to the baseline scenario's average estimate of 33,200 deaths and 955,000 DALYs attributable to diesel HDV emissions of $PM_{2.5}$ and ozone, the Incremental scenario could avoid on average 766 premature deaths and 21,554 DALYs.[6] The avoided health damages scale over time, and by 2050, the Incremental scenario would avoid on average 1,742 premature deaths and 44,685 DALYs. Under the Leapfrog scenario, which sees South Africa implement Euro VI standards sooner in 2024, the country would avoid 815 deaths and 22,914 DALYs by 2035; by 2050 its effect on avoided deaths and DALYs is nearly identical to the Incremental scenario. Under the Beyond scenario, 823 premature deaths and 23,138 DALYs are avoided in 2035; in 2050 those numbers rise to 1,775 and 45,507 respectively.

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[5] The value of a statistical life (VSL) estimates willingness to pay for small reductions in mortality risk. It is often a critical parameter in cost-benefit policy analysis because it is a measure of the marginal cost of reducing exposure to pollutants.

[6] In addition to the estimates provided for the average forecast of future costs and benefits, the study also gave an estimate of the "5th percentile" and "95th percentile"—that is, the estimate that is between 5% and 95% of all forecasts in the concentration-response relationship of the health impact model. In other words, the estimates are expected to occur with 90% probability.

Table 4 compares the avoided cumulative health damages under three alternative policy scenarios between 2021 and 2050.

Table 4. Cumulative avoided premature deaths and DALYs in South Africa between 2021 and 2050

	Incremental	Leapfrog	Beyond Euro VI
Premature deaths	24,700 (14,200—42,100) *	25,500 (14,700—43,500)	25,900 (14,800—44,100)
DALYs	663,100 (383,800—1,146,600)	686,300 (397,500—1,185,100)	695,600 (402,500—1,201,700)

*Values in parentheses are 5th and 95th percentile estimates

Comparison of benefits and costs

Table 5 below compares the cumulative societal benefits and incremental costs in the alternative scenarios compared with the Baseline scenario. The social costs of HDV emissions in 2021 are estimated to be approximately $24.7 billion ($14.0 billion—$38.8 billion, 5th and 95th percentile). Between 2021 and 2050, the health benefits of improved HDV emission standards would far outstrip the incremental costs needed for compliance under all three scenarios. The greatest net benefit occurs under the Leapfrog scenario, where Euro VI HDV standards come into effect in 2024. The Leapfrog scenario confers a $400 million gain in net social benefit over the Incremental scenario that has a slower timeline for Euro VI adoption. While the Beyond Euro VI scenario is projected to deliver the greatest societal benefits, the net benefits would be lower than in the other two scenarios because of the technology investments needed for internal combustion engines that can meet next-generation emission standards.

Table 5. Present discounted (5%) cumulative value of costs and benefits from 2021 to 2050 compared with the Baseline scenario, in billion U.S. dollars

Variable	Incremental	Leapfrog	Beyond Euro VI
Incremental technology costs	1.56	1.66	2.46
incremental operating costs	0.07	0.09	0.09
Total incremental costs	1.63	1.75	2.55
Societal benefits	13.6 (7.9—23.1) *	14.2 (8.2—24.0)	14.4 (8.3 ~ 24.3)
Net benefits	12.0 (6.2—21.5)	12.4 (6.4—22.3)	11.8 (5.7 ~ 21.8)
Benefit-cost ratio	8.4 (4.8—14.2)	8.2 (4.7—13.7)	5.6 (3.3 ~ 9.6)

*Values in parentheses are 5th and 95th percentile estimates

Our analysis' valuation of net social benefits is highly likely to be an underestimate, for several reasons. First, our modeling does not capture non-fatal health impacts, such as pediatric asthma, which are known to be affected by exposure to nitrogen oxides like NO_2 (Anenberg et al., 2022). In the context of our study, the benefits of avoiding non-fatal health impacts would apply to lower NO_x Euro VII engines in the Beyond Euro VI scenario. The true extent of the health benefits in the Beyond Euro VI scenario is therefore not captured. Accounting for these effects might change whether Leapfrog or Beyond Euro VI has the greatest net benefits. Second, the climate benefit of reduced BC emission as an SLCP is not modeled in all scenarios.

Effects of potentially delaying improved fuel quality and tighter emission standards

The oil industry has expressed concerns about meeting the 10 ppm sulfur limit by September 2023. Government regulators and industry experts expect that the oil industry may push back the delivery of upgraded diesel by up to 5 years. Therefore, we include a separate analysis in our study to evaluate the effect of such a delay on vehicle emissions, and the attendant costs and benefits.

Delaying the fuel quality upgrade to 10 ppm sulfur diesel would set back implementation of Euro VI emission standards since 10 ppm sulfur diesel is a prerequisite for Euro VI aftertreatment technologies. Although this potential delay may temporarily save upgrading costs to petroleum refiners, hidden social damages would be incurred. Using as an example the Leapfrog scenario, which has the highest net social benefits, we demonstrate the impacts of delaying fuel quality upgrades and Euro VI adoption, summarized in Table 6.

Table 6. Timelines and assumptions under delayed scenarios

Scenario	Fuel quality	Vehicle emission standard
Original scenario	10 ppm sulfur diesel from 2023	Euro VI standards from 2024
5-year delay	10 ppm sulfur diesel from 2028	Euro VI standards from 2029

As a direct consequence of the fuel quality improvement delay, emission standard improvements would be delayed, resulting in additional HDV tailpipe emissions over the next three decades. Figure 7 below shows greater annual $PM_{2.5}$ and NO_X emissions in a delayed Euro VI scenario compared to the original Leapfrog scenario. In a scenario where 10 ppm sulfur diesel only becomes available in 2028 and Euro VI is adopted one year later, HDVs in South Africa will produce 30.3% higher cumulative $PM_{2.5}$ emissions and 26.7% higher cumulative NO_X emissions from 2021 to 2050. This is compared to a scenario where 10 ppm sulfur diesel and Euro VI standards are adopted five years earlier, in 2023 and 2024.

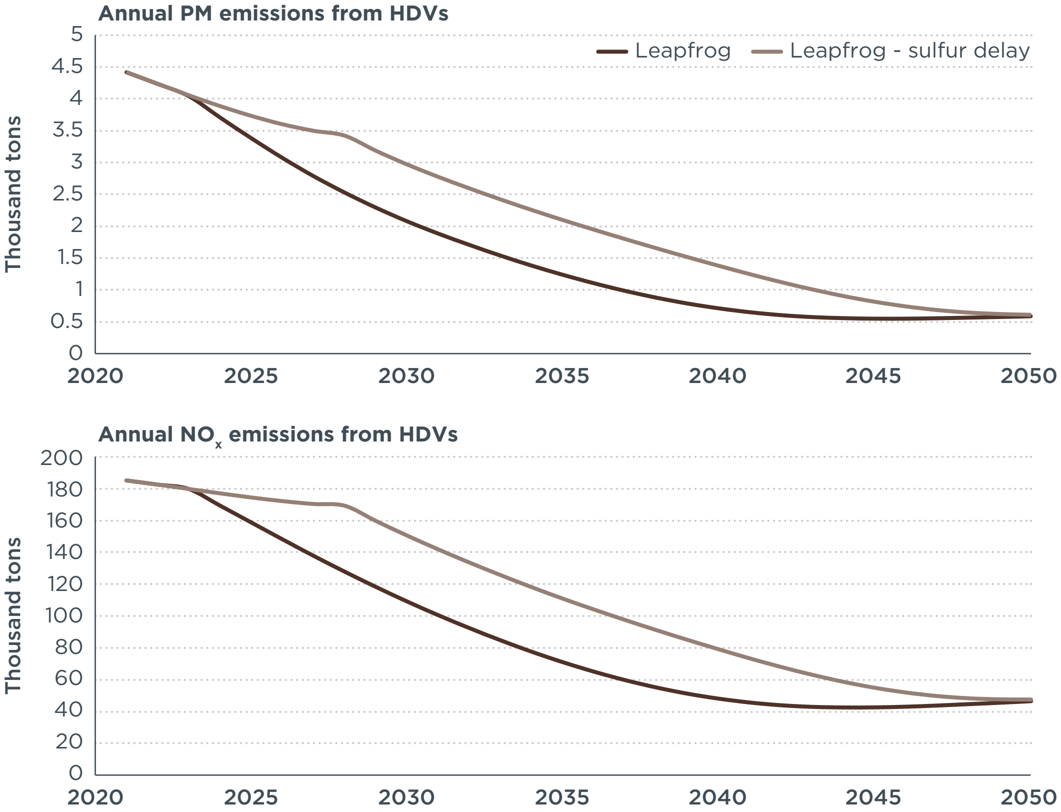

Figure 7. Additional $PM_{2.5}$ and NO_x emissions in delayed leapfrog scenario

Over the period 2021 to 2050, the average cumulative impact of a five-year delay in the implementation of 10 ppm sulfur diesel and Euro VI would be an additional 5,097 premature deaths and 143,047 DALYs. These health impacts are roughly a quarter of the health impact of the total South African HDV fleet exhaust emissions in 2021. While manufacturers may avoid investments in newer technologies for a few years under the delayed scenario, their cost savings are a fraction of the health damages to society. South Africa will suffer an additional nearly $3 billion of cumulative net societal damages over the course of three decades because of this delay.

Effect of biodiesel blend on tailpipe emissions

In 2015, South Africa introduced mandatory biofuel blending regulations that require fuel producers and retailers to buy and blend locally produced bioethanol and biodiesel, amounting to 2% and 5%, respectively, of market demand. No official statistics on biodiesel production and consumption in transport are available ("Implementation of Bioenergy in South Africa - 2021 Update", 2021). The status of the enforcement of the regulation is also unknown. The mandatory blending regulations were later integrated into a Biofuels Regulatory Framework in 2019 by the Department of Mineral Resources and Energy, whose overall target is 4.5% of biofuels by volume in the national liquid fuel mix (*South African Biofuels Regulatory Framework and National Biofuels Feedstock Protocol,* 2020).

This study did not quantitatively assess the impacts of biodiesel blend on diesel HDV tailpipe emissions and the associated health costs. An ICCT meta-analysis investigated the air quality impacts of biodiesel in the United States from literature in the past few decades (O'Malley & Searle, 2021). Based on the best available data, a 5% biodiesel blend from soybean feedstock (the feedstock most likely used by South Africa in its blending regulations) would increase NO_x emissions by 0.4% and decrease $PM_{2.5}$ emissions by 1.4% relative to conventional diesel of Euro V/VI standards. These differences in tailpipe emissions will likely translate to similar effects on health benefits under alternative policy scenarios where modern engine and aftertreatment technologies are introduced. The precise emission impacts will need to be measured using actual biodiesel fuels and vehicles in South Africa. Furthermore, the production of biodiesel from feedstock like soybeans could lead to land use changes that may increase air pollution and greenhouse gas emissions upstream, effects that policymakers will need to evaluate.

Implications for vehicle and fuel policies

We provide the following recommendations based on findings from this analysis:

Maintain the original timeline for diesel quality improvement. South Africa's plan to mandate 10 ppm sulfur diesel in 2023 is an important step that will enable subsequent policy actions that ensure soot-free engine standards. South Africa is well-positioned to switch to 10 ppm sulfur diesel nationwide, given the presence of unreported 10 ppm diesel already in circulation and the reliance on imports for diesel, which removes the need for refinery upgrades, a potential barrier to cleaner fuels.

Introduce Euro VI standards immediately after 10 ppm sulfur becomes available. South Africa's HDV emission standards currently lag, by a significant margin, those of other G20 economies. Improved diesel quality can facilitate a quick transition to Euro VI standards as early as 2024. As the Leapfrog to Euro VI scenario in our analysis shows, South Africa stands to reap the greatest net societal benefits if Euro VI standards are introduced immediately after the 10 ppm sulfur diesel requirement takes effect. South Africa should also be prepared for post-Euro VI standards that can deliver greater health benefits in the next decade.

Avoid delays, which have significant costs. The timing of fuel quality and vehicle emission standards is important. The net benefits of Euro VI to South Africa would fall by 24.0% with a 5-year delay in enforcement of a 10 ppm sulfur diesel standard. Worse yet, delaying the requirement would set back upgrades to emission standards and lead to additional premature deaths and welfare loss to society. The South African government should work with the petroleum industry to retain the already regulated schedule, and with HDV manufacturers to commit to a transition in vehicle emission standards following the fuel transition.

Conclusion

Our analysis finds that South Africa would enjoy substantial benefits in adopting Euro VI standards for its diesel HDV fleet. The announcement of a 10 ppm sulfur diesel requirement by 2023 provides a great window of opportunity for modern emission standards to sync with fuel quality improvements.

With a timeline of implementing Euro VI standards in 2024, the societal benefits associated with reduced HDV tailpipe emissions can outweigh the costs of technology advancements and operating expenses by a ratio of 8.2:1 (5% discounted) between 2021 and 2050. By contrast, delaying the implementation of 10 ppm sulfur diesel requirements or Euro VI standards will diminish the health benefits and lead to a net welfare loss for South Africa.

This analysis has not accounted for the possible benefits from electrification in the HDV fleet in South Africa. Future analyses could examine the potential air quality impacts and the costs and benefits of electrification in combination with Euro VII aftertreatment technologies, potential HDV fuel economy or CO_2 regulations, and fleet renewal.

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