Vehicle emissions are among the top contributors to Indonesia's air pollution (United Nations Children's Fund, 2018) and they contribute to elevated concentrations of $PM_{2.5}$, ozone, and nitrogen dioxide. A conservative estimate suggests that in 2015, 7,100 deaths were attributable to transportation tailpipe emissions of $PM_{2.5}$ and ozone in Indonesia, and globally, the top three contributors were on-road diesel vehicles, on-road non-diesel vehicles, and ships (Anenberg, Miller, Henze, Minjares, & Achakulwisut, 2019b). Diesel exhaust has been classified as a Class 1 human carcinogen (WHO, 2012).

To address emissions, the Indonesian government implemented Euro 2/II-equivalent vehicle emission standards for light-duty and heavy-duty vehicles in 2009 and 2010, respectively, and Euro 3-equivalent standards for motorcycles in 2013 (Ministry of Environment and Forestry [MoEF] Decree No. 4/2009 and MoEF Decree No. 10/2012). The country is now implementing Euro 4/IV-equivalent emission standards for light-duty and heavy-duty vehicles; they have applied to all gasoline vehicles since 2018 and will apply to all diesel vehicles beginning in 2021.

However, the fuel standards necessary to comply with Euro 4/IV requirements, including regulating sulfur content to 50 parts per million (ppm), are not in place. There are multiple grades of diesel fuel available on the market for which different limits apply. As presented in Table 1, the current fuel supply has sulfur content that varies from 300 ppm for diesel with cetane number (CN) 53 to 2,500 ppm for diesel CN 48, with diesel CN 48 dominating the market at more than 90%. Additionally, achieving compliance with diesel fuel sulfur limits has been a consistent issue.

Table 1. Diesel and gasoline sold in Indonesia

Fuel grade	Sulfur (ppm)	Other content limit	Market share
Diesel			
CN48 (Solar/BioSolar)	2,500	Unrestricted aromatics/polycyclic aromatic hydrocarbons	96.5%
CN51 (Dexlite)	1,200		2.7%
CN53 (Pertadex)	300		0.8%
Gasoline			
RON 88	500	Unrestricted benzene/aromatics	30.5%
RON 91	500	benzene 5%, aromatics 50%	68.3%
RON 95	500	benzene 5%, aromatics 40%	1.2%
RON 98 (Pertamax Turbo)	50	benzene 5%, aromatics 40%	

Note: Source is a study that compiled data about imported and consumed fuel that was commissioned by the International Council on Clean Transportation (ICCT) and conducted by M. Harjono (2019). The data was collected from the Handbook of Energy & Economic Statistics of Indonesia, published by the Ministry of Energy and Mineral Resources in 2016, 2017, and 2018, and several years of import statistics from Indonesia's Statistik Perfagangan Luar Negeri.

Indonesia's vehicle market is growing rapidly. Consequently, stringent fuel quality and vehicle emission standards will have substantial influence on the country's progress toward improving air quality and public health. The adoption of Euro 4/IV vehicle emission standards is essential to protect public health, but Euro 6/VI standards could achieve a further 90% reduction in $PM_{2.5}$ and nitrogen oxides (NO_x) from diesel vehicles compared with Euro 4/IV. Therefore, this study estimates the costs and benefits of advancing to Euro 6/VI standards in Indonesia, considering the current status of its market and the trends and policies affecting the vehicle fleet and fuel supply. Based on the results, we also make recommendations for policy in Indonesia that would reduce vehicle emissions and benefit air quality and public health.

for gasoline and diesel fuel, introducing emission standards for new vehicles, and establishing a roadside monitoring program (Resosudarmo, 2002). As illustrated in Figure 3, in 2003, the MoEF (Menlhk – Kementrian Lingkungan Hidup dan Kehutanan) issued a decree requiring that Euro 2/II-equivalent emission standards for motorcycles, cars, and heavy-duty vehicles be met in 2005 for new vehicle types and in 2007 for all new vehicles (MoEF Decree No.141/2003).[1] While the requirements were implemented on time for motorcycles and gasoline cars, the Euro II requirements for diesel cars and heavy-duty vehicles were not ultimately phased in until 2011 and 2010, respectively (MoEF Decree No.04/2009). Additionally, the mandate for current production vehicles (motorcycles, cars, and heavy-duty vehicles) to meet Euro 2/II standards was lifted entirely. In 2012, the MoEF required Euro 3-equivalent standards be met for all new types of motorcycles with engine displacement larger than 50cm^3 by 2013, and for all current production motorcycles by 2015 (MoEF Decree No.10/2012).

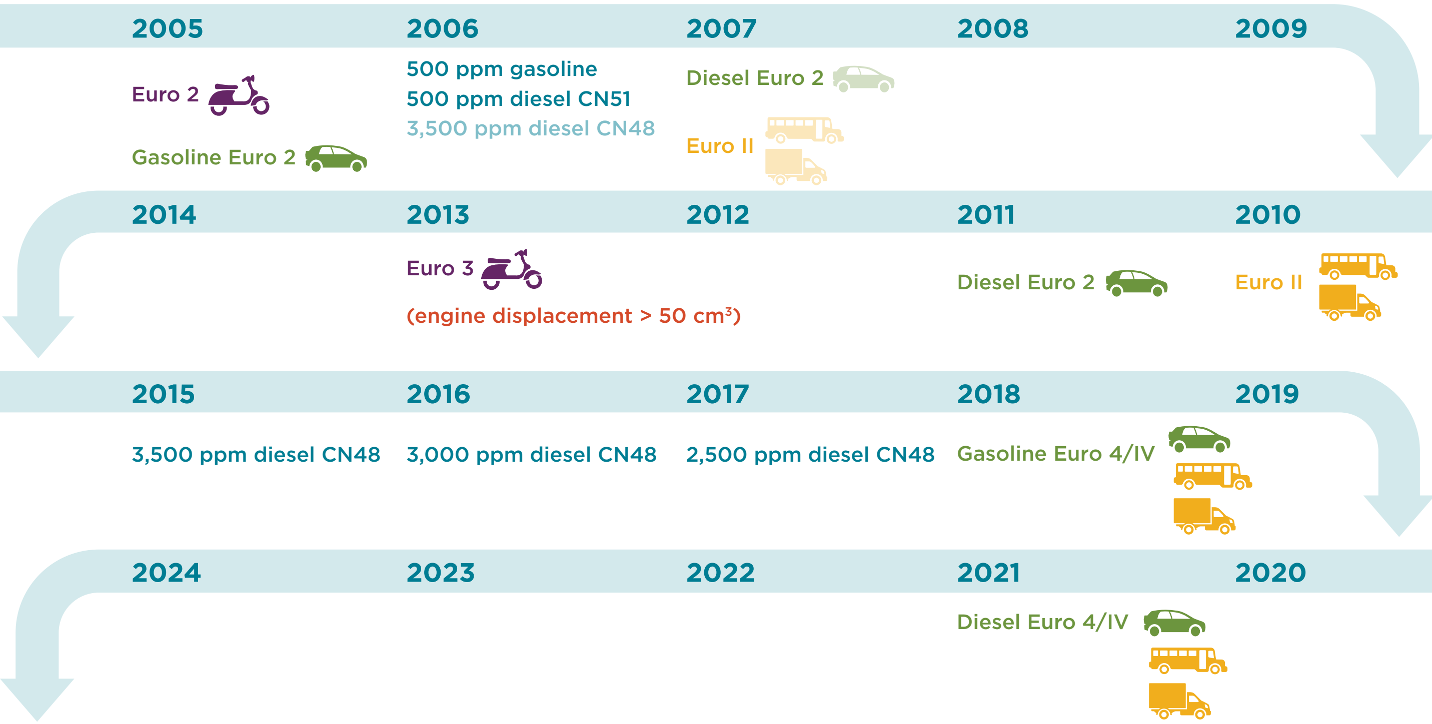

Figure 3. Timeline of Indonesia new vehicle emission standards and fuel sulfur content requirement. Note: Faded icons represent standards that were originally scheduled but then delayed.

In 2017, the MoEF adopted Euro 4/IV standards (No. P. 20/MENLHK/SETJEN/KUM. 1/3/2017) after retaining Euro 2/II standards for four-wheelers for approximately a decade. The regulation requires that all new gasoline vehicles meet Euro 4 emission standards as of September 2018 and all new diesel vehicles meet Euro 4/IV emission standards starting in April 2021. Other Association of Southeast Asian Nations (ASEAN) member states are also implementing Euro 4/IV standards; however, Indonesia lags Singapore, which has already implemented Euro 6/VI, and Thailand, which is expected to implement Euro 6/VI in 2023 (Figure 4).

1 Arabic numerals are used to refer to light-duty vehicle emission standards, while Roman numerals are used to refer to heavy-duty vehicle emission standards.

and Gas issued new fuel standards which lifted the requirements of 500 ppm sulfur fuel for diesel CN 48 and raised them to 3,500 ppm. A regulation adopted in 2013 eliminated the specification for unleaded gasoline but retained Euro 2 sulfur limits (SK 933/2013). The same regulation delayed implementation of the 3,500 ppm requirement for diesel fuel CN 48 to 2015. Finally, regulation SK 978/2013 set a 3,000 ppm limit by 2016 and a 2,500 ppm limit by 2017; it also added a 500 ppm target for 2021 and a 50 ppm target for 2025. Allowing gasoline with 500 ppm of sulfur does not comport with the Euro 4 vehicle standards that were phased in starting in 2018 because these standards require fuel with sulfur content of not more than 50 ppm.

Additionally, concerns remain regarding compliance with fuel quality standards (Safrudin, 2018). A 2011 evaluation of fuel quality in selected Indonesian cities found that neither the diesel nor the gasoline available at the pump was fully in compliance with the requirements set in 2006 (Safrudin, Krisnawati, & Mahalana, 2011). The sulfur content in the diesel fuel produced by local refineries varied from 300 ppm to 4,500 ppm, and the diesel sulfur content varied even between batches of fuel produced by the same refinery (Chambliss & Bandivadekar, 2014). If these compliance problems persist, they will hinder any governmental effort to enforce vehicle emission standards.

Some much cleaner or even Euro 4-qualified gasoline and diesel is already available in Indonesia. Shell has distributed gasoline and diesel fuel with 54 ppm sulfur content since 2016 and Pertamina began to produce and distribute gasoline and diesel fuel complying with Euro 4 standards in 2017 (Safrudin, 2018). Pertamina also made announcements regarding its timeline for upgrading to all 50 ppm gasoline, but with inconsistent timeline.

Modeled policy scenarios

As discussed above, fuel quality standards are an essential complement to stringent vehicle emission standards. Standards for cleaner fuel are typically introduced in conjunction with, or just prior to, cleaner vehicle standards (Miller, 2019). Of all fuel specifications, sulfur content is one of the most important factors that affects the performance of vehicle emission control systems. Lead, manganese, and other metal additives also have an effect. Fuels limited to 50 ppm sulfur for gasoline and diesel permit the introduction of Euro 4/IV standards, and limits of 10 ppm permit Euro 6/VI standards for light- and heavy-duty vehicles and Euro 5 for motorcycles.

It is recommended that modern vehicle emissions aftertreatment technologies such as diesel particulate filters (DPF), gasoline particulate filters, and selective catalytic reduction systems (SCR) operate with ultralow-sulfur fuel, i.e., less than 10–15 ppm sulfur. In gasoline, the presence of metallic additives such as tetraethyl lead and manganese impede the function of catalytic converters and undermine the effectiveness of investments in desulfurization that were intended to ensure these emission control technologies function properly (Minjares, Miller, & Nare, 2018). Some octane blending components, including benzene, are known carcinogens and should be strictly limited to no more than 1% (The National Institute for Occupational Safety and Health, 2014).

This study evaluates the impacts of advanced vehicle emission and fuel quality standards in Indonesia for two scenarios and a baseline without changes to already adopted standards. Table 3, below, has full details of these scenarios:

» **Baseline**: Assumes Indonesia successfully implements Euro 4/IV light-duty and heavy-duty emission standards and requires the matching fuel (50 ppm) for all gasoline grades by 2018 and for diesel grades by 2021.

» **Global Sulfur Strategy**: Assumes that Indonesia implements the CCAC's Global Sulfur Strategy (detailed in Miller & Jin, 2018) and requires Euro 6/VI emission standards for light-duty and heavy-duty vehicles, Euro 5 for motorcycles, and ultralow-sulfur fuel (10 ppm) by 2030.

» **Leapfrog**: Assumes that Indonesia follows the precedent set in India and skips Euro 5/V standards and moves directly to Euro 6/VI standards for all light-duty and heavy-duty vehicles, Euro 5 for motorcycles, and 10 ppm sulfur fuel requirements by 2023.

To achieve the maximum benefits for climate and public health, complementary actions to improve vehicle efficiency, reduce the need for travel, shift transport activity to less energy-intensive modes, and transition to zero-emission vehicles are needed, as well. However, analysis of such measures is outside the scope of this study.

Table 3. Modeling scenarios and assumptions

Scenario	4W vehicle	2W vehicle	Fuel sulfur content
Baseline	2005: Euro 2 LDV gasoline 2010: Euro II HDV 2011: Euro 2 LDV diesel 2018: Euro 4/IV gasoline 2021: Euro 4/IV diesel	2005: Euro 2 2013: Euro 3	2018: Diesel CN 53: 300 ppm Diesel CN 51: 1,200 ppm Diesel CN 48: 1,200-2,500 ppm Gasoline: 50 ppm 2021: 50 ppm diesel
Global Sulfur Strategy	2025: Euro 5/V 2030: Euro 6/VI	2020: Euro 4 2025: Euro 5	2030: 10 ppm
Leapfrog	2023: Euro 6/VI	2020: Euro 4 2023: Euro 5	2023: 10 ppm

Modeling methods and data

Vehicular emissions and health impacts for Indonesia were calculated using the method adopted for ICCT's global estimation (Miller & Jin, 2018; Miller & Jin, 2019). Emissions of $PM_{2.5}$, BC, NO_x, and SO_2 were derived using bottom-up fleet modeling, based on the forecast of Indonesia's vehicle market growth. Data on vehicle sales, stock, fuel blends and fuel quality were obtained from regional sources, including Badan Pusat Statistik—the Statistical Agency of Indonesia (2019), GAIKINDO—the Association of the Indonesian Motor Vehicle Industry (2019), AISI—the Indonesian Motorcycle Industry Association (2019), and interviews with key experts. Other data, including vehicle mileage and energy consumption, were calibrated to match the data from the International Energy Agency (Abergel et al., 2017; IEA, 2017). Data for the costs of upgraded vehicle technology were sourced from ICCT's previous studies, updated, and adjusted for Indonesia's vehicle market (Posada, Bandivadekar, & German, 2012; Posada, Chambliss, & Blumberg, 2016).

Future vehicle market

The vehicle market in Indonesia is expected to grow strongly in the coming decades, as shown in Figure 5. Sales of passenger cars are expected to reach 1.8 million annually by 2050, when the entire four-wheeler vehicle market is expected to reach 2.5 million in total annual sales. Annual sales of motorcycles are expected to be approximately 13 million soon after 2030 and slow down slightly afterward, once market saturation is reached. The sales projection used in the model is consistent with the studies from the IEA (Abergel et al., 2017; IEA, 2017).

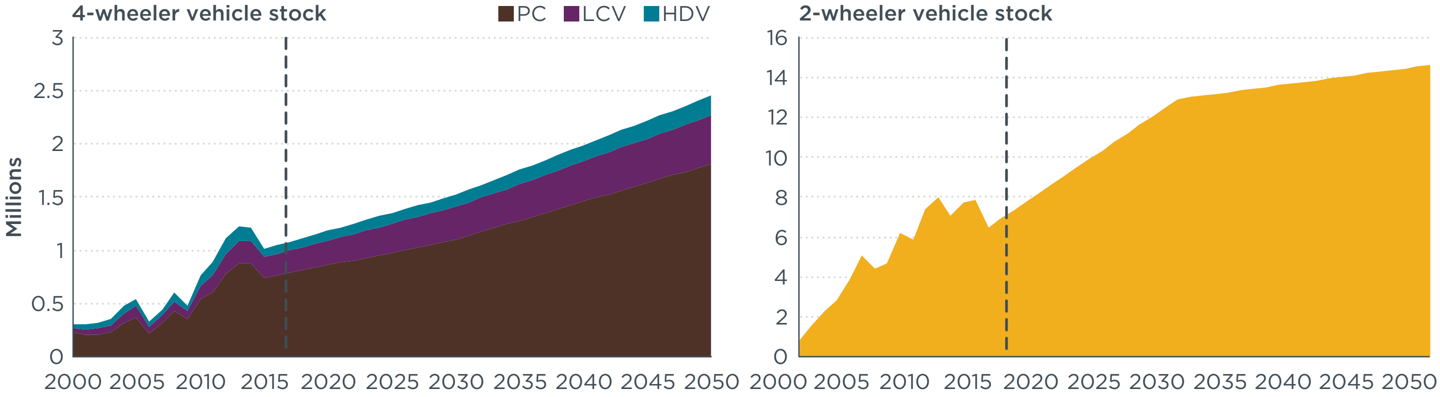

Figure 5. Historic and estimated future vehicle annual sales by category.
PC = passenger car; LCV = light commercial vehicle; and HDV = heavy-duty vehicle.

With this projection of vehicle market expansion, Indonesia is expected to be home to about 25 million four-wheeler vehicles and 156 million motorcycles by 2030.

Energy consumption and vehicle emissions results

In all three scenarios, and in line with the growing vehicle fleet, road transport energy consumption in Indonesia from 2020–2050 is projected to increase by a factor of 2.3 for gasoline and 1.8 for diesel. The demand for gasoline will reach almost 3,000 petajoules (PJ) in 2050, and this is expected to be about three times larger than diesel demand.

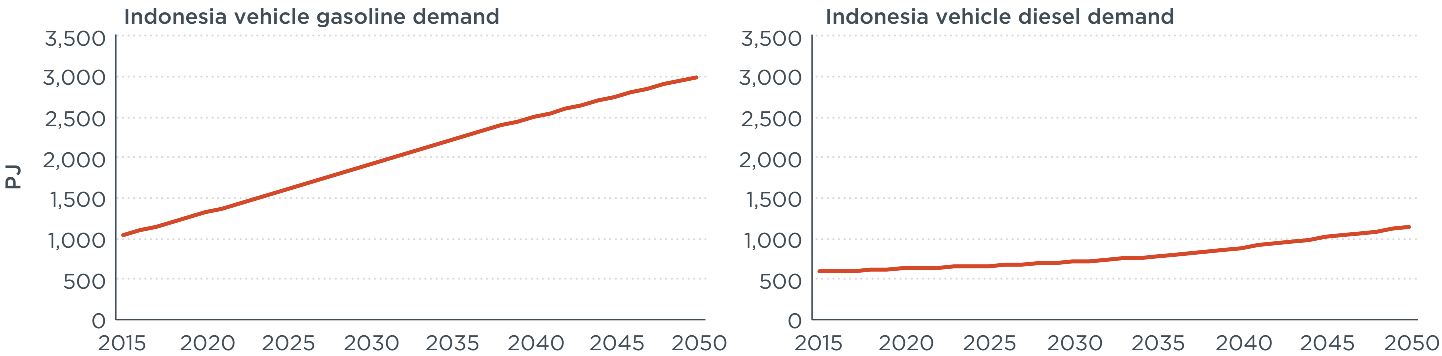

Figure 6. Annual vehicular fuel demand for gasoline and diesel

Figure 7 illustrates how the implementation of Euro 6/VI vehicle emission standards and aligned fuel standards simultaneously can greatly reduce emissions from vehicles in Indonesia. In the Baseline scenario, vehicle exhaust emissions of $PM_{2.5}$, BC, NO_x, SO_2, and other pollutants also decrease in the near-term, assuming successful implementation of the Euro 4/IV vehicle emission standards and 50 ppm fuel requirements. But with the rapid increase in the number of vehicles in Indonesia, total emissions from both gasoline and diesel vehicles increase soon after 2035. Only with the implementation of Euro 6/VI vehicle emission standards, Euro 5 for motorcycles, and ultralow-sulfur (10 ppm) fuel, as in the Global Sulfur Strategy and Leapfrog scenarios, can long-term emission reductions be achieved. The Leapfrog scenario, which involves the early adoption of Euro 6/VI and Euro 5 for motorcycles in 2023, yields additional savings that are particularly potent over the next 20 years but also last beyond 2050. Separating the emissions by gasoline and diesel illustrates the high contribution from diesel-powered engines, even though diesel fuel consumption is projected to be much lower than gasoline.

Figure 7. Vehicular (including motorcycles) exhaust emissions by fuel type and scenario, 2018–2050

Since the sulfur content of fuel is directly related to vehicular SO_2 emissions, improving fuel quality is the major lever to reduce SO_2 emissions. Transitioning to the exclusive sale of 50 ppm sulfur fuels in 2021, which is the baseline scenario, could reduce SO_2 by 95%. Further, transitioning to 10 ppm sulfur fuels in the Global Sulfur Strategy and Leapfrog scenarios could reduce SO_2 by another 80% in addition to the benefits from moving to 50 ppm fuel. The $PM_{2.5}$ emission reductions in Figure 7 also reflect the benefits of better quality fuels because they contain less sulfates.

Based on the model estimation, the implementation of Euro 4 standards for gasoline vehicles led to demand for about 60 PJ of 50 ppm gasoline in 2018. This is approximately 1.75 billion liters. However, the realized sales volumes of Ron 98, the 50 ppm Euro 4 gasoline, were only about 0.2–0.4 billion liters for 2018 (Harjono, 2019)—far from enough to support Euro 4 vehicle standards.

Given the high volume of motorcycles in Indonesia, the model estimates they will be responsible for about 30% of NO_x and 12% of PM emissions in 2050, even with Euro 5 standards implemented in 2023, as in the Leapfrog scenario. As shown in Table 4, this is higher than the 12% of NO_x and 6% of PM contribution of motorcycles today.

Table 4. Emission share by vehicle mode in selected years, Leapfrog scenario.

$PM_{2.5}$ share	2018	2025	2030	2050
Light-duty vehicles	19%	23%	27%	31%
Buses	2%	2%	2%	2%
Trucks	73%	68%	63%	55%
Motorcycles	6%	7%	8%	12%

NO_x share	2018	2025	2030	2050
Light-duty vehicles	21%	20%	21%	21%
Buses	2%	2%	2%	2%
Trucks	65%	63%	58%	48%
Motorcycles	12%	15%	19%	29%

The emission contribution from the heavy-duty truck fleet drops from 65% of NO_x and 73% of PM to 48% and 55%, respectively, by 2050 with the successful implementation of Euro VI standards in the Leapfrog scenario. This reduction of emissions volume and share from the heavy-duty truck fleet can only be achieved if qualified ultralow-sulfur fuel is available and proper maintenance keeps the aftertreatment equipment functioning.

Costs and benefits

Vehicle and fuel costs

The introduction of stringent emission standards compels manufacturers to invest in new emission control technology to comply. The application of this new technology creates incremental costs that are mainly attributable to the SCR systems for NO_x control and DPFs for PM control. We estimated the incremental costs by using ICCT's studies that evaluated the costs of complying with the stringent standards (Posada et al., 2012; Posada et al., 2016) and adjusting for Indonesia's economic context and vehicle market. As presented in Figure 8, the technology costs are more expensive for heavy-duty vehicles than for light-duty vehicles, and more expensive for diesel vehicles than gasoline ones.

The successful deployment of ultralow-sulfur fuel in the Indonesian market will require upgrading fuel quality standards for both domestic production and imported fuels. The incremental costs of importing or refining cleaner fuels are estimated to be 1.6¢ for 10 ppm gasoline and diesel when compared with 50 ppm fuel (MathPro, 2015). The incremental costs associated with improved vehicle emission standards also include operating costs, i.e., the costs of cleaner fuels, diesel exhaust fluid, and filter maintenance, and these were also evaluated. The operating costs are not shown in Figure 8, which focuses on costs associated with technology improvement only.

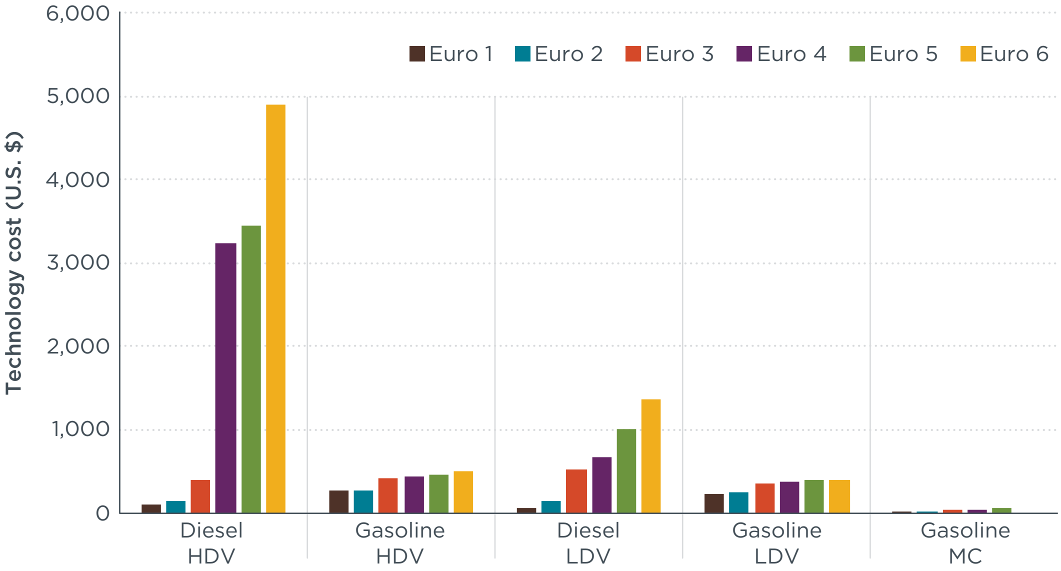

Figure 8. Technology costs for new vehicles in Indonesia, by emission standard

Value of health and climate benefits

The benefits of vehicle emission reductions, in the form of avoided social costs, were estimated using the economic valuation framework given in Shindell (2015) and detailed in a previous ICCT study (Miller, 2019). The social costs cover the pollutant-specific and time-dependent damages associated with emissions, including direct climate and health impacts, climate-related health damages, and the effects of ozone on reduced agricultural productivity. They are adjusted with a 5% social discount rate to convert the damages to present value terms (Miller, 2019).

The social costs of 2018 vehicle emissions are estimated to be approximately $19 billion ($9 billion–$32 billion, 5th and 95th percentile).[2] Compared with the baseline, the Euro 6/VI scenarios (Global Sulfur Strategy and Leapfrog scenarios) would reduce the societal damages of 2050 emissions by approximately 60%. Table 5 presents the cumulative benefits and costs in the Global Sulfur Strategy and Leapfrog scenarios compared with the Baseline scenario. There are substantial benefits to be obtained from implementing Euro 6/VI vehicle emission standards and ultralow-sulfur fuel.

Table 5. Present discounted (5%) cumulative value of costs and benefits from 2020 to 2050 compared with the Baseline scenario, in billion U.S. $

Variable	Global Sulfur Strategy	Leapfrog
Incremental Technology Costs	7.63	8.79
Incremental Operating Costs	2.82	4.00
Total Incremental Costs	10.5	12.8
Societal Benefits	91	118
Net Benefits	80.6	105
Benefit-Cost Ratio	8.7	9.2

2 In addition to the estimates provided are 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, or in other words the estimate that is expected to occur with 90% probability.

Comparison of costs and benefits

The investment in cleaner vehicles and fuels can yield tremendous social benefits, as presented in Table 5 and Figure 9 with 5th (low) and 95th (high) percentile estimates. Over the period from 2020 to 2050, implementation of Euro 6/VI fuel and vehicle standards in the Global Sulfur Strategy scenario would result in net societal benefits of $81 billion (5% discounted). The early adoption of the Euro 6/VI fuel and vehicle standards in the Leapfrog scenario would produce an additional $24 billion (5% discounted) in net societal benefits, with a benefit-to-cost ratio of 9.2:1 (5% discounted) when compared with the Baseline scenario.

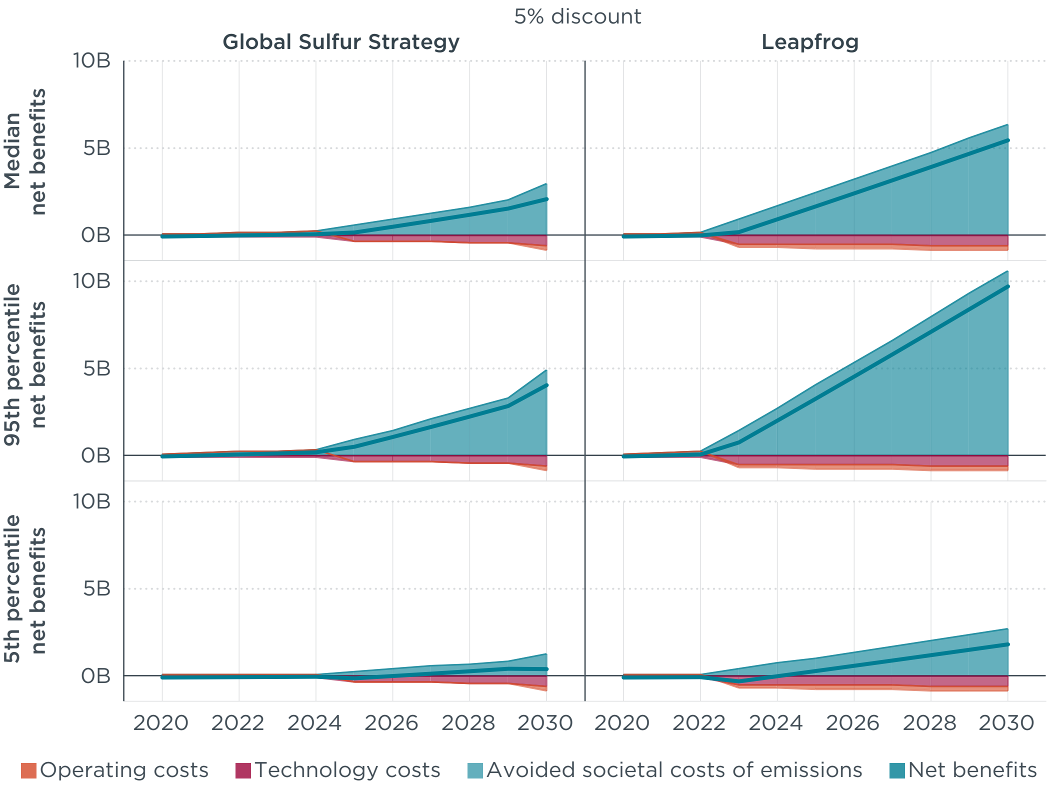

Figure 9. Net benefits of Global Sulfur Strategy and Leapfrog scenarios from 2020–2030 compared with baseline (B = billion 2019 U.S. dollars)

Implications for fuel policy

Based on the above results, it is suggested that Indonesia consider the following:

Both imported and domestically produced fuel will need to be brought up to standard

Indonesia is one of the few ASEAN countries that has not adopted standards for or committed to ultralow-sulfur fuel. With the Euro 4/IV emission standards being implemented for diesel engines and fuel in 2021, and potentially more stringent Euro 6/VI on the way, producing and importing sufficient fuel that meets ultralow-sulfur requirements (maximum 10-ppm) is essential to ensure the full implementation of the soot-free engine standards.

Stop the subsidy on dirty fuel

The pressing need for low- and ultralow-sulfur fuel raises great concerns about the potential for fueling Euro 4/IV vehicles and those designed to meet more advanced emission standards with unqualified fuel. The subsidy on dirtier fuel (e.g., Ron 88 gasoline and CN 48 diesel) leads to lower prices at the pump (Harjono, 2019) and this significantly increases the potential for mis-fueling. The issue is pressing, as Euro IV diesel vehicle standards are scheduled to take effect in 2021 and there is almost no Euro 4 diesel fuel are available on the market as of now. In cases of insufficient supply of 50 ppm sulfur diesel or mis-fueling because there is a cheaper fuel, the higher sulfur diesel fuel will damage the advanced emission control equipment required by Euro 4/IV and more advanced standards and result in limited or even no emission reduction benefits for those vehicles. Without revision of the government's position on requiring the matching fuel, there is a significant chance of mis-fueling with lower quality fuel.

Put additional attention on the impacts of promoting palm biodiesel

In addition to concerns about the quality of imported and locally produced diesel and gasoline fuel, Indonesia needs to address the impacts of aggressive palm biodiesel targets on vehicles equipped with Euro 4/IV and more advanced emission control technologies. The present target is 20% blending with palm biodiesel and that will increase to 30% in 2020 (Searle & Bitnere, 2018). Only about half of the 20% target is currently met, and a 10.2% blend level was reported in 2016 (U.S. Department of Agriculture Foreign Agricultural Service, 2017). Additionally, MEMR Regulation No. 12/2015 required a 30% blending target be met by 2020. The President of Indonesia, Joko Widodo, recently announced a new target of 100% biofuel blending in four years ("Forget blends," 2019). Such high biodiesel blending levels could damage vehicles, as discussed in Searle and Bitnere (2018).

With these biofuel blending targets announced, additional attention on vehicle and emission control equipment maintenance is needed. Searle and Bitnere (2018) found that biodiesel leads to increased vehicle maintenance costs, with more frequent replacement needed of components such as fuel filters, fuel injector nozzles, and seals, as well as potentially more costly components central to diesel engines. The study also found that using biodiesel might offset some of the benefits of introducing Euro 4/IV vehicle emission standards.

Prioritize regulating motorcycles and light-duty vehicles

The projected increase in the emission contribution from motorcycles, as shown above in Table 4, indicates that the current emission control strategy is not stringent enough for the growing motorcycle market. This calls for more aggressive and creative actions, including but not limited to aggressive electrification targets. These are feasible because of the lower battery capacity needs of motorcycles. The findings in the table also highlight similar concerns regarding the increasing $PM_{2.5}$ share from light-duty vehicles, which calls for prioritized policy attentions.

Conclusion

The results show substantial benefits for Indonesia in adopting the Euro 6/VI vehicle standards in conjunction with aligned fuel standards. Establishing a clear timeline for implementation and developing a supporting compliance program would help ensure that the maximum benefits are achieved. The already set Euro 4/IV vehicle standards lay the groundwork for Indonesia to reduce vehicle emissions, but the health benefits of Euro 4/IV are not as potent in the longer term. Euro 6/VI vehicle emission standards, along with the qualified ultralow-sulfur fuel, reduce all types of emissions for Indonesia even in the longer-term scenario that includes a rapidly growing vehicle market.

With a timeline of 2023 for implementing Euro 6/VI standards, the societal costs associated with vehicular emissions can outweigh the costs of transitioning to advanced vehicle technology and fuel upgrades by a ratio of 9.2:1 (5% discounted) between 2020 and 2050. This study also demonstrates the importance and the cost-effectiveness of implementing a 10 ppm fuel sulfur limit along with the vehicle standards. This could be achieved by switching to 50 ppm sulfur imports as soon as possible and then later tightening to 10 ppm while bringing refineries up to speed. But again, the emissions reductions and their associated improvements in public health and climate can only be achieved with qualified fuel available for all grades of fuel types.

Due to the large share of motorcycles in the fleet and their growing contribution to air pollution, there would also be significant benefit from prioritizing emission reductions from motorcycles. Early adoption of Euro 5 emission standards in 2023 does not provide the same level of emissions reduction as it does with four-wheeler vehicles, and electrification is an attractive complementary strategy, given that motorcycles are smaller and have lower battery capacity requirements. This analysis did not analyze the possible benefits from electrification, but future analyses could examine the potential impacts and the costs and benefits of electrification in combination with fleet renewal.

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