Guidance to Fuel Importing Countries for Reducing On-Road Fuel Sulfur Levels, Improving Vehicle Emission Standards

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CLIMATE & CLEAN AIR COALITION TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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MEMBERSHIP OF THE HEAVY-DUTY VEHICLES AND ENGINES INITIATIVE OF THE CLIMATE AND CLEAN AIR COALITION

The Government of the United States of America, the Government of Canada, the Government of Switzerland, UN Environment, the International Council on Clean Transportation

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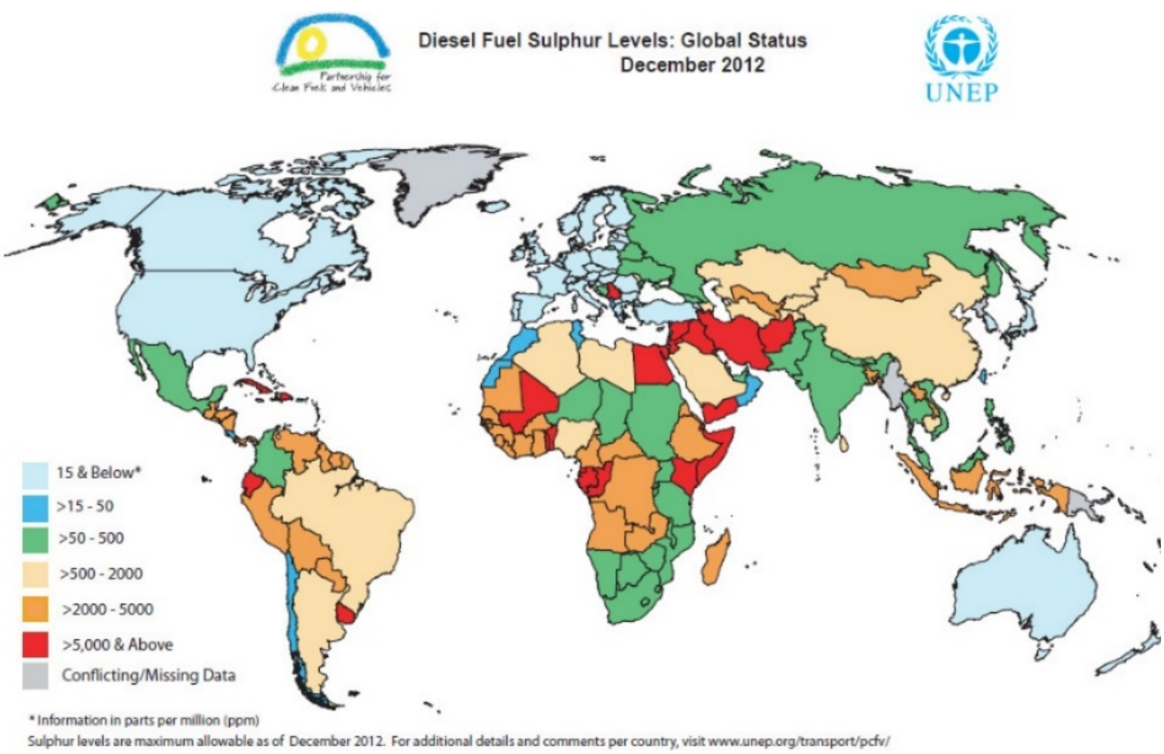
1. Introduction

In 2012, the Climate and Clean Air Coalition (CCAC) launched the Heavy-Duty Vehicles and Engines Initiative to *"virtually eliminate fine particle and black carbon emissions from new and existing heavy-duty diesel vehicles and engines through the introduction of low-sulfur fuels and vehicle emission standards."* Since 2012 there has been a steady progression to cleaner fuels and vehicles in many markets in Asia, Latin America, Africa and Eastern Europe (Figure 1). However, improvements in both fuel refining and importing markets need to be sustained through the next decade to realise the full air quality and climate change mitigation potential of cleaner fuels and vehicles.

In 2016, the Heavy-Duty Vehicles and Engines Initiative released the Global Strategy to Introduce Low-sulfur Fuels and Cleaner Diesel Vehicles[1] – the first global plan to achieve a 99% reduction in particulate matter (PM) and black carbon (BC) emissions from the global on-road diesel vehicle fleet (CCAC, 2016). In December 2016, 36 countries recognized and fully endorsed the Global Strategy's approach and targets in the Marrakech Communique.[2]

Figure 1. Global Diesel Fuel Sulfur Levels: 2012 vs. 2018[3]



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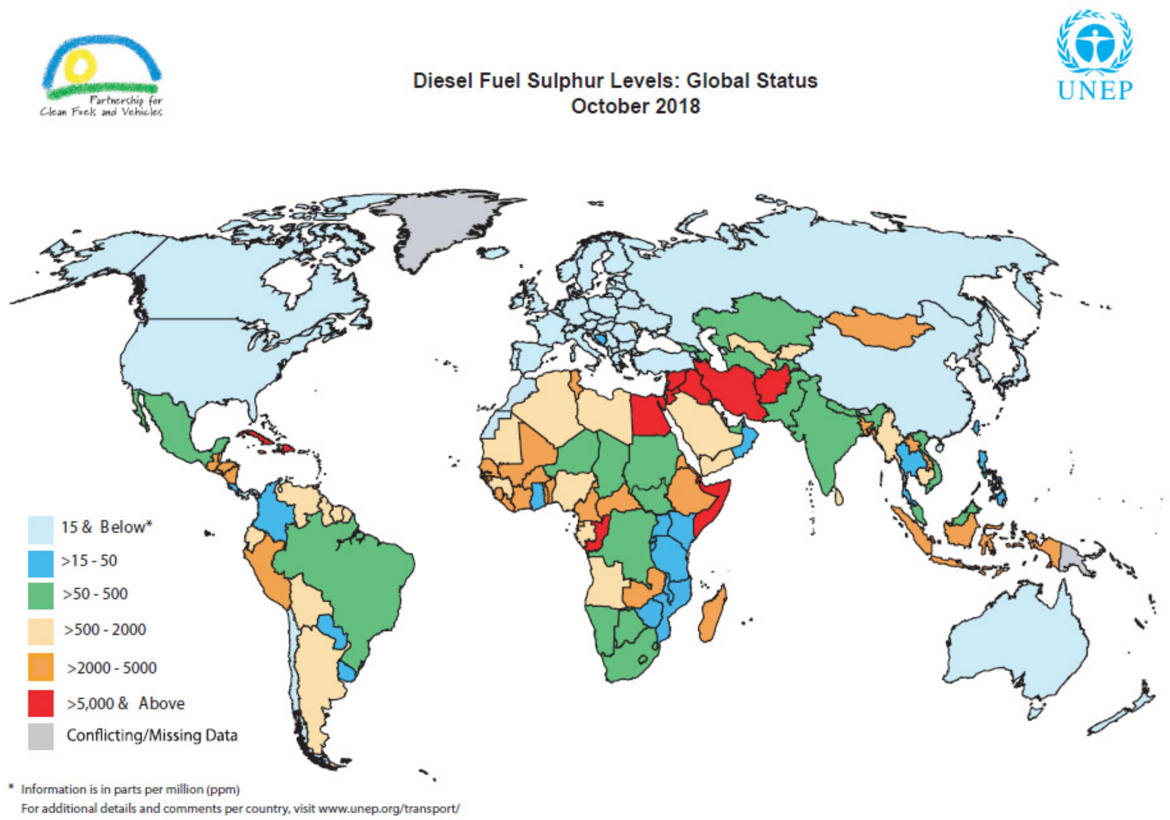
[1] http://www.ccacoalition.org/en/activity/global-sulfur-strategy
[2] http://www.ccacoalition.org/en/resources/marrakech-communique
[3] https://www.unenvironment.org/explore-topics/transport/what-we-do/partnership-clean-fuels-and-vehicles/sulphur-campaign



The Global Strategy's targets are ambitious, but achievable: low-sulfur diesel (50 ppm) phased in for most countries by 2020 and for all remaining countries by 2025, followed by ultralow-sulfur fuel (10 ppm) for the majority of global on-road fuel supply by 2030. For fuel importing countries, the ability to source low and ultralow-sulfur fuels from the international market means that these standards could be adopted even more quickly.

The challenges facing fuel importing and fuel refining countries are diverse and complex. This document deals specifically with the issues facing fuel importing markets. Because they are reliant on fuel imports, these countries and sub-regions can act quickly to adopt new low-sulfur fuel standards. Fuel importing countries make up the largest group of countries analyzed in the Global Strategy and are key to driving forward the regional and global demand for low-sulfur fuels – and, in turn, investments for cleaner fuels in refining countries. However, the transition to low-sulfur fuel standards can be more challenging for refining countries since considerable investments must be mobilized to upgrade refineries.[4]

Sulfur in fuel is problematic because it leads to increased air pollution. This occurs directly through emissions of harmful sulfur compounds such as sulfates, and indirectly by inhibiting the effectiveness of modern emission control devices. The largest public benefits achievable through sulfur control are health related, but many of the constituents of $PM_{2.5}$ also have an effect on climate change. One component in particular of $PM_{2.5}$, black carbon, is a potent climate forcer that absorbs sunlight and releases heat, causing warming. Because black carbon only has a life in the atmosphere of less than a week, it is a so-called short-lived

[4] http://www.ccacoalition.org/en/activity/global-sulfur-strategy

climate pollutant. Reducing emissions of short-lived climate pollutants like black carbon has a direct and immediate impact on climate change, and can therefore be a valuable complement to reducing CO_2 emissions as a tool to limit climate change.

Diesel exhaust, especially the particulate matter emissions from older technology engines, is a known human carcinogen that directly contributes to air pollution-related health impacts. And diesel black carbon itself is an ultrafine particle that may operate as a universal carrier of a wide variety of toxins directly to the lungs and into the bloodstream. Diesel engines account for approximately 30 percent of all anthropogenic emissions of black carbon, with 75 percent of diesel particulate matter coming from older technology (pre-Euro VI or US 2007) engines.

Actions to control diesel exhaust emissions, particularly black carbon, can reduce the health impacts of outdoor air pollution and contribute to a 0.5 degree avoided warming by 2050. The CCAC Scientific Advisory Panel has demonstrated that 0.5 degrees C average warming can be avoided in 2050 through a combination of measures to control short-lived climate pollutants. Among these is a 75 percent reduction in black carbon emissions by 2030 (from 2010 levels).

Black carbon associated with diesel combustion can be controlled using diesel particulate filters required by Euro 6/VI (U.S. 2010) (or 'soot-free') emission standards; but these devices are only effective with low, or ideally ultralow, sulfur fuels (Bond et al., 2013). The *Global Progress Report Towards Soot-Free Diesel Engines in 2018* of the Heavy-Duty Vehicles Initiative has shown that a 75 percent reduction in black carbon emissions by 2030, the target set by the CCAC Scientific Advisory Panel, can be met in the global transportation fleet if all new heavy-duty vehicles are soot-free (Euro VI/ U.S. 2010) by 2025 (ICCT 2018).

Euro VI-equivalent emissions standards that require particulate filters (filter-forcing standards) are the most effective option for controlling diesel black carbon, reducing $PM_{2.5}$ emissions by 99% and black carbon by over 99%. Low-sulfur fuels also reduce emissions from existing in-use vehicles, allowing them to perform better and cleaner (See Box 1).

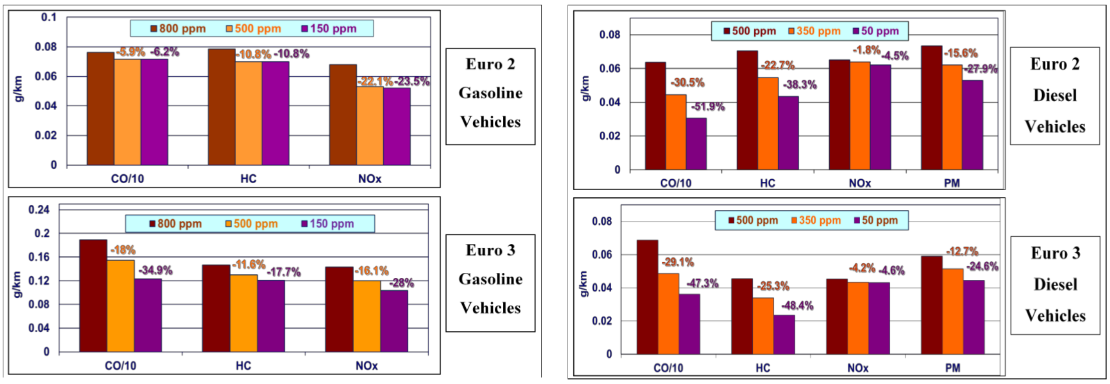
Research clearly shows that air pollution, especially $PM_{2.5}$, poses a serious threat to human health. The recent systematic analysis for the Global Burden of Disease Study 2015 showed that $PM_{2.5}$ contributed to 4.2 million early deaths worldwide for the year 2015 (the Global Burden of Disease Study 2015 Risk Factors Collaborators, 2016 and Cohen, et al., 2017). The deaths were from heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections. Exposure to $PM_{2.5}$ was the 5th highest ranking risk factor for death globally in 2015 among 79 risk factors analyzed, whereas ozone was the 33rd highest ranking risk factor (Figure 2) (Health Effect Institute and Institute for Health Metrics and Evaluation, 2017). The impact of $PM_{2.5}$ on human health will continue to increase if fuel desulfurization does not accelerate. Therefore, there is an urgent need to reduce ambient air concentrations of $PM_{2.5}$ from various sources.

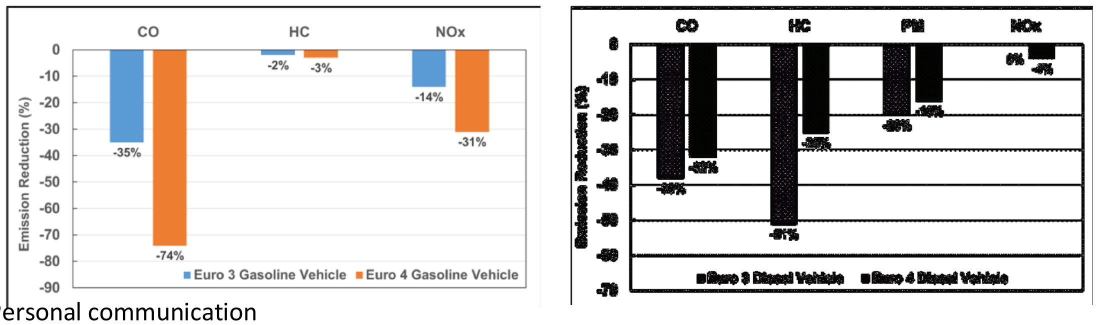
Box 1: Immediate Near-Term Air Quality Benefits from Improved Emissions for In-Use Vehicles Using Low-sulfur Fuels

Low-sulfur fuels also reduce emissions from existing in-use vehicles and make them perform better and cleaner, even without emission control devices. For those existing in-use vehicles equipped with emission control devices such as catalysts and filters, emissions are generally improved if sulfur levels are lowered.

It was demonstrated that emissions of CO, HC and NOx from in-use vehicles were significantly lowered with a switch to lower sulfur fuels (see below, Pollution Control Department of Thailand, 2018).[1] Particulate matter emissions from diesel vehicles were also found to be lower even without PM emission control devices.

For fuel importing countries, shifting from importing high-sulfur fuels to low-sulfur (<50 ppm) or ultralow-sulfur (<10 ppm) fuels will provide immediate emission reductions from existing on-road, in-use vehicle fleets – improving air quality and short-lived climate pollutants in the short term. In order to obtain the maximum emission reduction benefits in the near-term, a direct shift to ultralow-sulfur (<10 ppm) fuels maximizes benefits by enabling the use of filter technology and Euro 6/VI (U.S. 2010) standards.

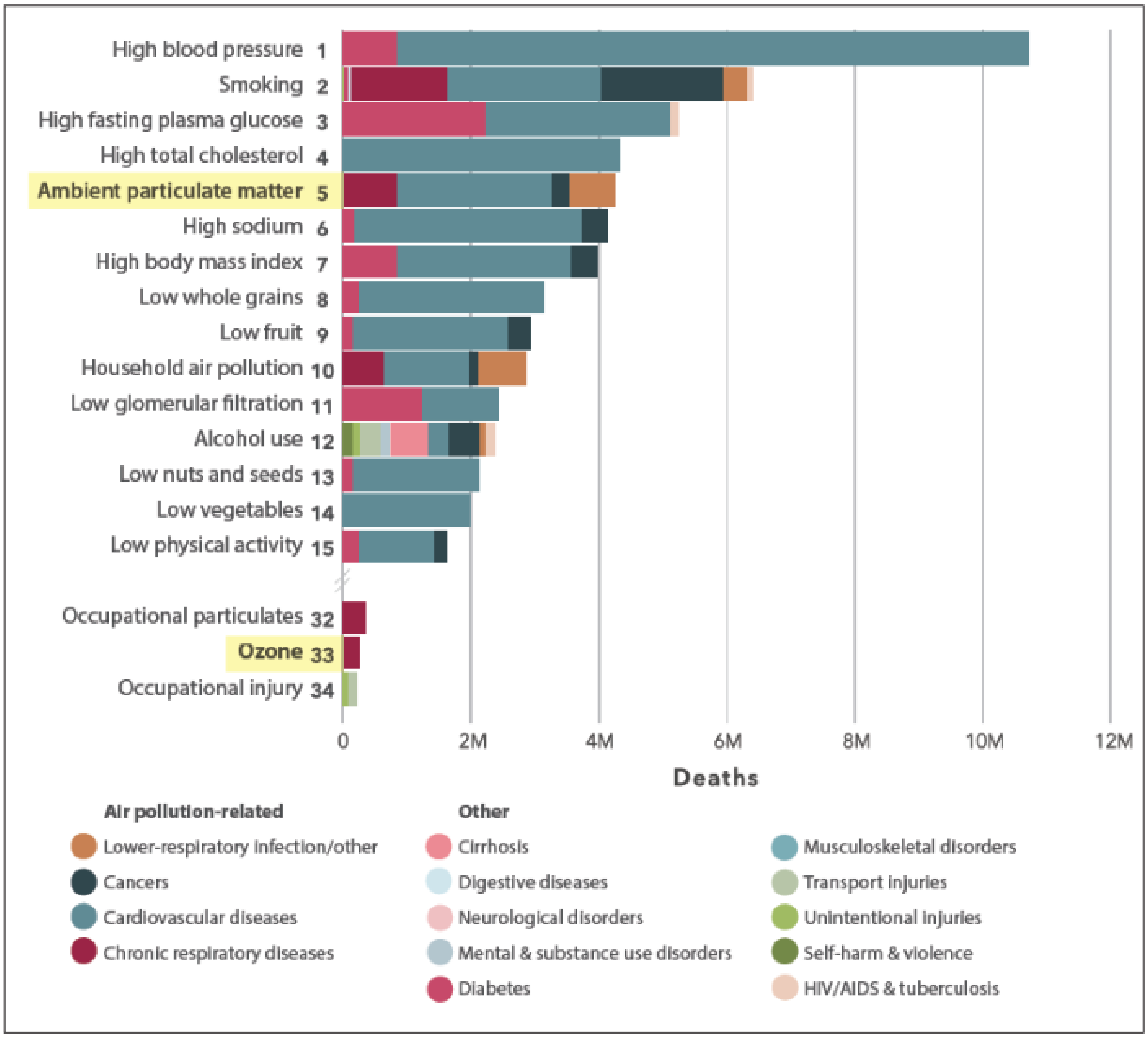




[1] Personal communication

Emission reduction after switching from 50 ppm to 10 ppm sulfur fuels

Figure 2. Ranking of Risk Factors Globally for Total Deaths from All Causes for All Ages and Sexes in 2015 (Source: Health Effect Institute and Institute for Health Metrics and Evaluation, 2017)

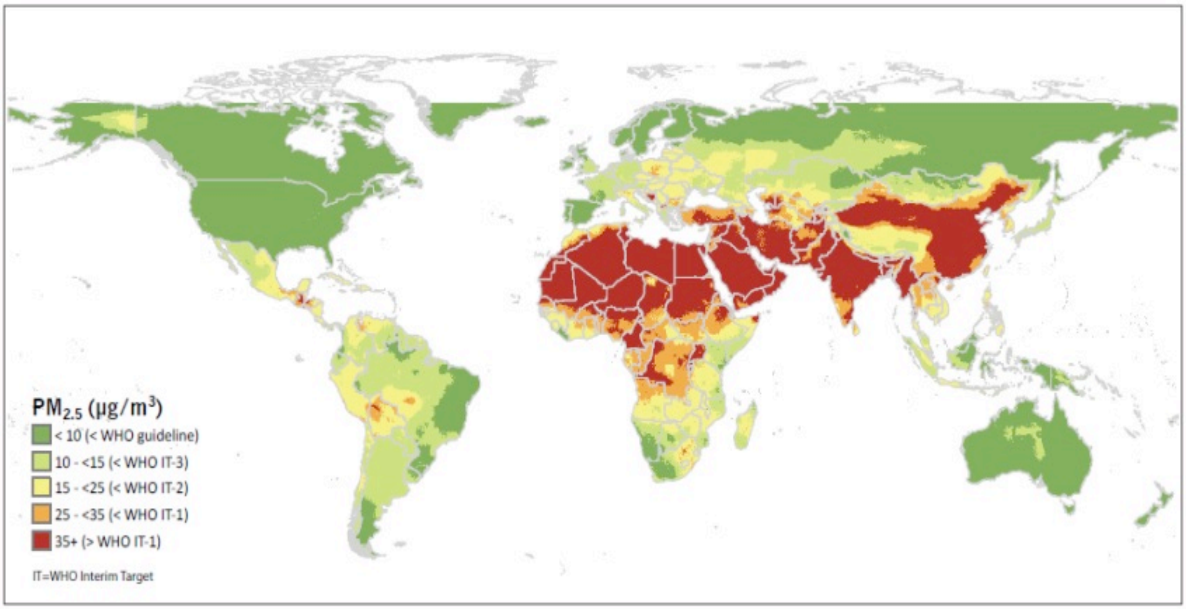


The global burden of disease and death from $PM_{2.5}$ is concentrated in developing and transitional economies, as shown in Figure 3. Motor vehicle exhaust is the primary source of fine and ultrafine particles in urban areas, and diesel vehicles are the largest contributors.

Matching vehicle emission standards to cleaner fuels would equal to a reduction in annual $PM_{2.5}$ and black carbon emissions from on-road vehicles by over 85 percent, resulting in 100,000/year fewer premature deaths in 2020, and 470,000/year fewer in 2050. In addition, implementing the Global Strategy would reduce cumulative black carbon emissions by 7.1 million tons by 2050.[5]

[5] http://www.ccacoalition.org/en/activity/global-sulfur-strategy

Figure 3. Global Map of Population-Weighted Annual Average Ambient Concentrations of $PM_{2.5}$ in 2015 comparing to WHO Air Quality Guidelines (Source: Health Effect Institute and Institute for Health Metrics and Evaluation, 2017)



2. Issues Specific to Importing Markets

This document addresses the implementation of cleaner fuels and vehicle emission standards in fuel importing markets. As such, it covers the challenges specific to these markets as they strive to make low and ultralow-sulfur fuels and advanced vehicle emission standards a reality. The main challenges faced by importing markets are:

- Costs to consumers
- Regulatory issues
- Matching advanced vehicle emission standards to cleaner fuels (including vehicle imports and second-hand vehicles)
- Inspection and maintenance for existing fleets
- Lubricity

This paper explores these topics, as well as case studies that illustrate how markets have coped with these challenges.

Commodity trading companies play an important role in ensuring adequate fuel quality in countries without refining capacity. Because these countries do not produce enough gasoline (petrol) and diesel for domestic consumption, they are reliant on imports for the majority of fuels consumed. Trading companies play an important role in the import and distribution of fuels, including fuel quality. These companies often control important downstream assets such as storage facilities and petrol stations in developing countries. In addition, trading companies rely on a common industry practice called blending, or mixing, intermediate petroleum products from refiners to cater to local fuel standards (or lack thereof). These intermediate products can contain high levels of sulfur as well as other toxic substances such as benzene and aromatics. This is a common occurrence in West Africa, for example, where “African Quality” imported fuels from Swiss trading companies leaving ports in Amsterdam, Rotterdam and Antwerp were found to contain sulfur levels hundreds of times above European norms (Public Eye, 2016).

Blending can occur at tank terminals, onboard ships, or at the interface between the two while still in port. For example, gasoline is always a blended product according to vehicle engine requirements and may consist of between six and ten blendstocks. Diesel fuel does not need to be blended but it is often blended to increase volume and may contain between four and six blendstocks. Weak national standards create an incentive to sell blendstocks with high levels of sulfur, aromatics and benzene that cannot be sold in markets with high fuel quality standards (e.g. Europe or the U.S.). Therefore, national fuel quality standards, harmonized regional standards and monitoring are necessary to stem such practices, and to ensure that fuels and vehicle emission standards can meet to deliver the air quality and emissions benefits possible with the best available technology.

2.1 Costs to Consumers

Although import-dependent markets do not need to make considerable capital investments for refinery upgrades, there can be premium costs imposed on imported low and ultralow-sulfur fuels. These costs are usually passed on directly to consumers resulting in higher fuel prices at the pump. Rising fuel costs are not only unpopular politically, but the transport and logistics industry will face higher operating costs resulting in even higher consumer goods and services costs. As a result, governments are often reluctant to impose better fuel quality standards for fear of rising fuel costs. And without a government mandate, importers will not import low-sulfur fuels. However, the historical reality on the global fuels market is that the incremental prices of low-sulfur fuels are generally small depending on the starting and ending sulfur levels.

For example, a study by the International Council on Clean Transportation found that additional costs could be 0.6 to 2.1 US cents and 1.1 to 3.2 US cents for a liter of diesel and 0.4 to 1.7 US cents and 0.8 to 2.4 US cents per liter of gasoline when going down to 50 ppm and 10 ppm, respectively, depending on the baseline fuel quality and sulfur levels (ICCT, 2012). These additional costs could be even lower with fiscal and policy intervention from governments during the transition phase.

Hong Kong is dependent on liquid fuel imports and has no refinery. When low-sulfur diesel with 50 ppm sulfur was first introduced in Hong Kong in 2000, the retail price before duty was 5.24 HK$ per liter which was 0.8 HK$ per liter higher than regular diesel with 350 ppm sulfur (4.44 HK$ per liter) (Legislative Council Panel on Economic Services, 2000). The government of Hong Kong lowered the tax for low-sulfur diesel from 2.00 HK$ per liter to 1.11 HK$ per liter resulting in a pump price with duty of low-sulfur diesel of 6.35 HK$ per liter which was slightly lower than that of regular diesel at 6.44 HK$ per liter. As a result of a tax concession provided for cleaner, low-sulfur diesel, there was no additional cost to fuel consumers. When ultralow-sulfur diesel (10 ppm sulfur) was introduced in Hong Kong in 2007, its import price was higher than low-sulfur diesel (50 ppm) by up to about 0.1 HK$ per liter (Legislative Council Panel on Environmental Affairs, 2007). To encourage the use of the cleaner fuel, its duty was halved (0.56 HK$ per liter) to that of low-sulfur (50 ppm) diesel to make it more price-competitive (Legislative Council Panel on Economic Development, 2008).

When fuel sulfur was reduced in Thailand from 150 ppm in gasoline and 350 ppm in diesel to 50 ppm in both gasoline and diesel in 2012, the estimated incremental cost was around 1.6 US cents per liter. However, the pump price actually increased only around 0.7 US cents per liter. This actual increase was equal to the price increase of fuels if imported from the Singapore market since fuel prices in Singapore are used as reference fuel prices in Thailand.

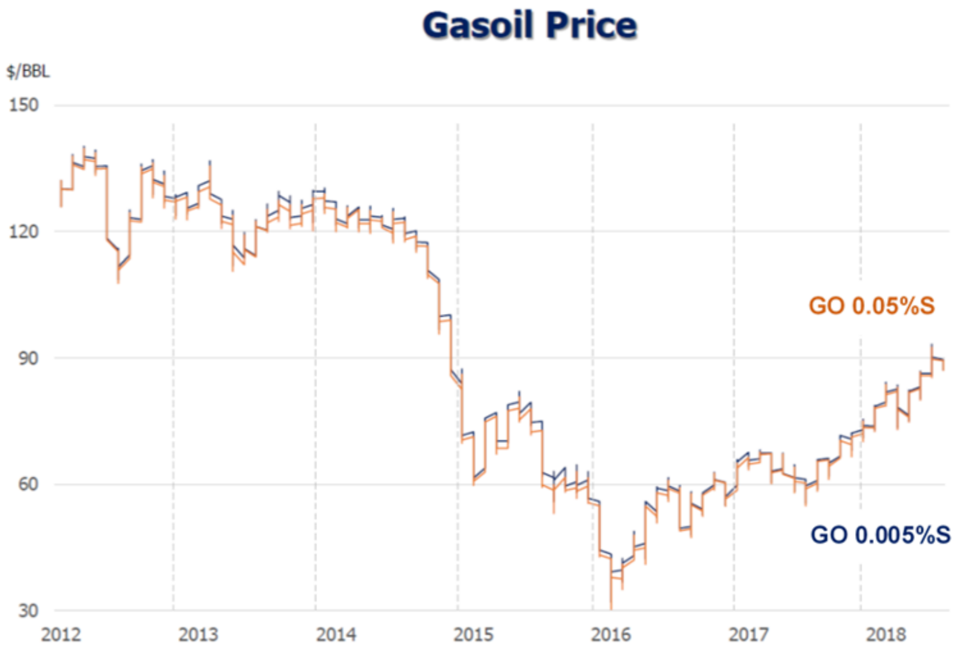
In fact, prices of low-sulfur fuels in various international oil markets have been only slightly higher than high-sulfur fuels, as shown in Table 1 which summarizes free on board (FOB) diesel prices on 1 October 2015 obtained from Asia-Pacific and Arab-Gulf market scan (data is extracted from www.platts.com marketscan). The FOB prices of 50 ppm sulfur diesel in Singapore and Arab-Gulf markets were only 0.69 US cent per liter and 0.79 US cent per liter higher than 500 ppm sulfur diesel, or 1.85 to 2.21% respectively. The price difference increase of 10 ppm sulfur diesel from 50 ppm sulfur diesel was even lower: 0.11 to 0.31 US cent per liter or 0.29 to 0.85%. In reality, the actual price increases in international oil markets for both 50 ppm and 10 ppm sulfur fuels have been much less than projected. Moreover, the price difference between high-sulfur and low-sulfur fuels has decreased in recent years.

Table 1. FOB Prices of Diesel with Difference Sulfur Levels (10, 50, 500 and 2,500 ppm) in Asia-Pacific (Singapore) and Arab-Gulf (Middle East) Markets on 1 October 2015 (Source: data is extracted from www.platts.com marketscan)

Diesel with difference sulfur levels	Asia-Pacific Market FOB Singapore (US$ per barrel)				Arab-Gulf Market FOB Arab Gulf (US$ per barrel)			
	Range	Mid	Diff.	Diff. (US cent per liter)	Range	Mid	Diff.	Diff. (US cent per liter)
Diesel 10 ppm S	60.39-60.43	60.41	0.17	0.11	58.11-58.15	58.13	0.05	0.31
Diesel 50 ppm S	60.22-60.26	60.24	1.09	0.69	58.06-58.10	58.08	1.25	0.79
Diesel 500 ppm S	59.13-59.17	59.15	0.51	0.32	56.81-56.85	56.83	0.85	0.53
Diesel 2,500 ppm S	58.62-58.66	58.64	-	-	55.96-56.00	55.98	-	-

The actual price increase associated with low-sulfur fuel is always smaller than the normal fluctuation of market fuel prices. Figure 4 shows the fluctuation of daily prices of gasoil with 50 ppm sulfur and 500 ppm sulfur from 2012 to 11 June 2018 (Petroleum Authority of Thailand, 2018). It is obvious that gasoil prices fluctuated significantly, from a minimum yearly average price of 52 US$ per barrel in 2016 to a maximum yearly average price of 129 US$ per barrel in 2012. The yearly average incremental prices of 50 ppm sulfur gasoil were from a minimum of 0.54 US$ per barrel (0.34 US cent per liter) in 2018 (up to 11 June 2018) to a maximum of 1.62 US$ per barrel (1.02 US cents per liter) in 2015. The incremental premium price of about 1 US$ cent or less is significantly less than normal market fuel price fluctuations. Several countries have taken the opportunity to introduce low-sulfur fuels while fuel prices were decreasing in order to avoid perceived price increases due to fuel quality change.

Figure 4. Daily prices of gasoil with 50 ppm sulfur and 500 ppm sulfur from 2012 to 11 June 2018 (Source: Petroleum Authority of Thailand, 2018).



2012	2013	2014	2015	2016	2017	2018	
128.10	123.27	112.69	64.74	52.07	65.60	82.29	Avg.
128.79	124.57	113.76	66.36	52.93	66.20	82.84	Avg.
0.69	1.29	1.07	1.62	0.86	0.60	0.54	Diff.

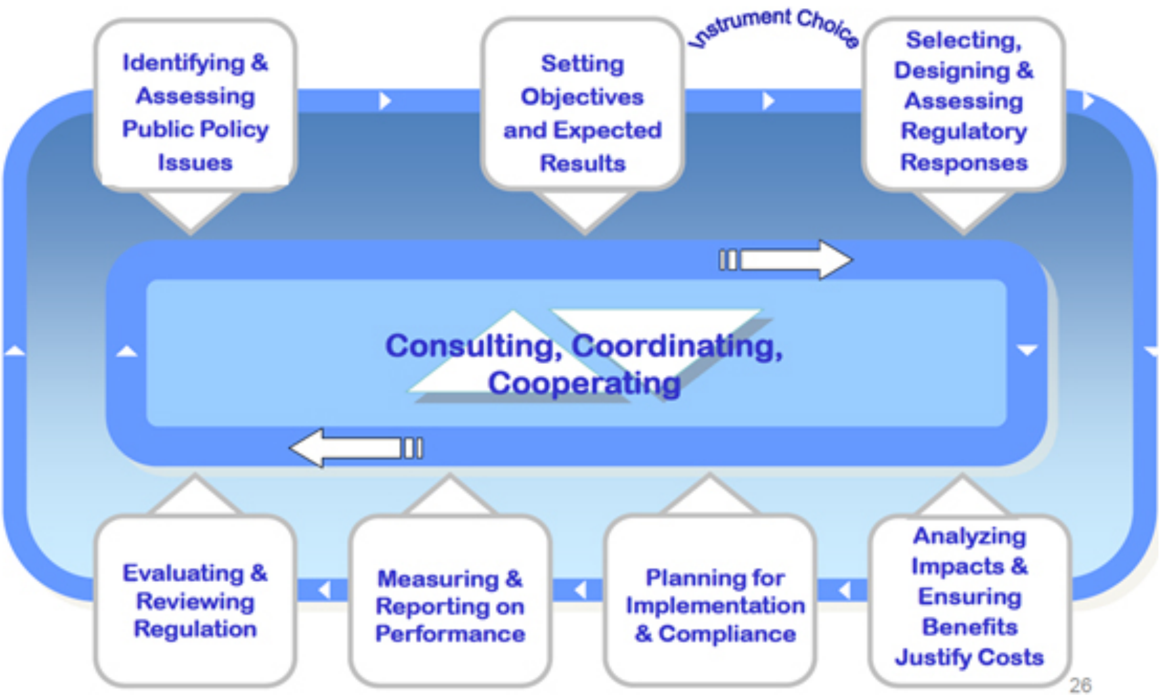
Since the incremental price of fuel when decreasing from 50 ppm to 10 ppm sulfur is less than one US$ cent (i.e. 0.11 to 0.31 US$ cent per liter), the immediate jump to ultralow-sulfur fuel without intermediate steps makes more sense in importing markets. Ultralow-sulfur fuels enable advanced aftertreament technology, including soot-free Euro 6/VI (U.S. 2010) standards. If it is necessary to equalize the incremental price of low-sulfur fuel, a mix of economic instruments, such as financing, subsidy, and taxation policies can be used to reduce economic and social impacts, as in the case of Hong Kong. These instruments can also encourage early and rapid introduction of low-sulfur fuels.

2.2 Regulatory Process and Governance

Regulatory governance connects the essential pillars of environmental change, which include: impact awareness of the environmental issue, actions to address the environmental issue and the instruments to enable the action to address the environmental issue. Regulatory governance is generally enabled by a central government-led agency that writes the laws and regulations, and administers and enforces the regulatory requirements (UNEP, 2014).

Each country or jurisdiction will have different ways of gathering resources to support an initiative such as a regulation. The lead agency will need to submit to the appropriate authorities the requirements for the new initiative. In this case, the initiative would be the introduction of clean fuels to the market. Budgets will be needed for each phase of the regulatory process; these include regulatory development, implementation and administration. Once the regulations are implemented, there would be the on-going regulatory administration, compliance promotion and enforcement. These units may be separate, but in all cases they should work closely together as illustrated below.

Figure 5. on-going regulatory administration, compliance promotion and enforcement (Source: UNEP, 2014)



The policy process, tools and examples for transitioning to low sulfur fuels are covered in detail in the Partnership for Clean Fuels and Vehicles Regulatory Toolkit available online (UNEP, 2014).

For the introduction and implementation of low-sulfur fuels in any country, the first step that should be taken is to develop policy for how to address sulfur in fuels in relation to air pollution (See Box 2 below summarizing Canada's experience). Subsequently, the necessary regulations with legal basis should be designed, developed, implemented, enforced and evaluated. Basic background and all relevant scientific information should be collected and analyzed for the development of a science- based policy to address sulfur levels in fuels.

At the very least, the supporting information should include:

- status of air pollution problems and associated impacts;
- emissions inventory and emission contributions from road transportation;
- fuel consumption;
- characteristics of existing fuels and distribution system;
- characteristics of existing vehicle fleets; and
- characteristics of fuel and automotive industries.

Box 2: Case Study for the Regulatory Process in Canada

Although Canada is a fuel-refining country, the Sulfur in Diesel Fuel Regulations in Canada are a good example to demonstrate how regulation is developed, designed, implemented and then enforced in Canada. The full development of these regulations took place incrementally over 20 years.

The first step was to develop the policy for how to address sulfur in diesel fuel. In the mid-1990s, the Canadian government set up a multi-stakeholder process called the Task Force on Cleaner Vehicles and Fuels, which brought together provincial/territorial governments, vehicle and engine manufacturers, fuel producers and importers, fuel users, and environment and health non-governmental organizations. This inclusive process identified issues and advised the Federal government on priorities for action. The inclusion of all relevant stakeholders ensured broad acceptance of the final recommendations of the Task Force. It also ensured that all relevant information was gathered and analyzed. With regards to sulfur in diesel fuel, the Federal government accepted the Task Force recommendation that the level in sulfur in diesel fuel should be lowered through regulation by the Federal government.

Once the policy was approved by the Cabinet, regulations were developed. These regulations were legally authorized by the Canadian Environmental Protection Act. The first step was to design how the regulations would work. This was done primarily by engineers with the assistance of lawyers. At the same time and building upon the analysis of the task force, the costs and benefits of the regulation were determined primarily by economists with the assistance of engineers and scientists. Stakeholders, especially fuel producers and importers, were consulted upon the details of the regulatory text and on the costs and benefits of the regulations. This process took several years, but ended in a regulation that met the policy requirements to reduce sulfur in diesel fuel and yet was understood and achievable by the affected fuel producers.

Sufficient time was given before the regulations came into force to allow for the design, construction approval, purchasing, installing and testing of the necessary equipment at the refineries (i.e. about 3 to 4 years). Once the regulations were in force, it was essential to the environment, to the engines/auto and to the fuel industry itself that the regulated requirements were complied with. Parties seeking financial advantage by supplying non-complying, less-expensive, high-sulfur diesel fuel have to be identified and prosecuted to ensure environmental goals are met, the engines are not damaged and other fuel suppliers are not undercut in the market.

The first step was to ensure that the regulatees (the fuel producers and importers) understand the regulations and their obligations. Various types of guidance documents were developed, including a very detailed and technical question and answer document, and all inquiries from regulatees were responded to. In addition, the regulation required fuel producers and importers to provide information on the sulfur level in their diesel fuel on a quarterly and then later an annual basis.

Government staff (engineers and administrative staff who administered the regulations) examined this data and compared it to other information to identify if there were issues and flag any issues to those responsible for enforcing the regulations. This data also formed the basis for annual reports to the public on the level of sulfur in diesel fuel. Fuel producers, vehicle manufactures, fuel users, environment and health groups and provincial governments all find this data to be of considerable use.

It was also necessary to train the enforcement officers who will be enforcing the regulations to ensure that they understood the significance and effect of the regulations and how the regulations worked. To this end, relevant guidance and training materials were developed by the engineers that designed the regulations, and an internal working group of staff from policy, compliance promotion, regions and enforcement was set up and it continues to ensure that any developing issues regarding the regulations are identified and addressed.

Source: Adapted from UNEP, 2014

Based on the collected information, an assessment of the feasibility of importing low-sulfur fuels to address air pollution problems from road transportation should then be conducted. The assessment may also include locally-specific cost-benefit analysis. Fuel quality and vehicle emissions issues involve many cross-cutting issues and sectors including economic development, environment, health, industry, transport, energy, land stakeholders and others.

Policy, strategies and planning should be developed in cooperation with relevant government agencies (national, regional, and local), private sector and civil society which ensures that different perspectives are discussed, priorities are identified, and consensus is achieved. It also provides a sense of ownership among stakeholders and helps to ensure the successful implementation of policy, strategies and plans. A multi-stakeholder task force on cleaner fuels and vehicles should be established at the earliest stage to ensure that all relevant information is gathered and properly analyzed for identifying issues and developing policy recommendations to the government for adopting and implementing low-sulfur fuels and tightening vehicle emission standards. The task force should consist of representatives from all relevant stakeholders including

- government agencies responsible for environment, energy, transport, health, industry, economic development, finance and communication;
- fuel producers, importers and distributors;
- vehicle manufactures, importers and distributors;
- consumers and civil society groups; and
- non-governmental organizations.

During the process, public stakeholder consultations, hearings, seminars, workshops, and meetings should be held to ensure adequate participation and involvement of all relevant stakeholders throughout the process of policy and regulatory formulation, implementation, enforcement and evaluation.

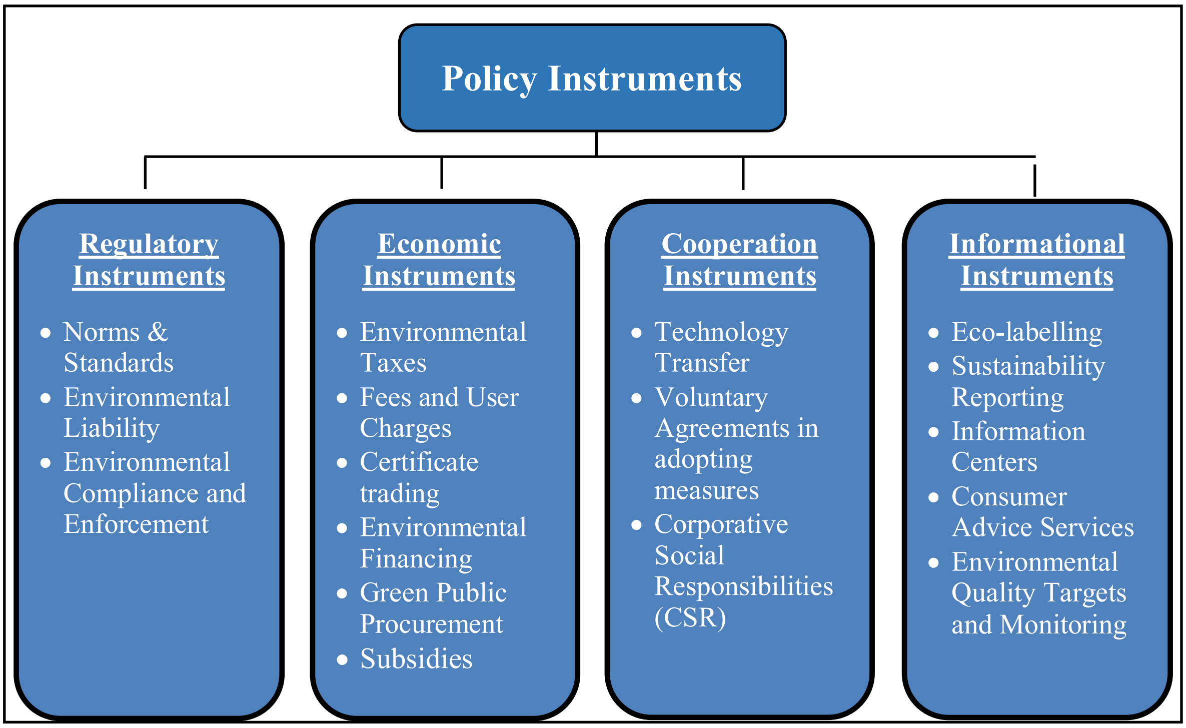
Once the policy is adopted by the government, the task force should continue to develop an action/implementation plan for the implementation of the adopted policy. The plan should establish:

- what steps/actions/activities to be undertaken;
- what regulations to be developed;
- how to enforce, monitor/verify compliance and audit;
- by when (timeframe);
- by whom; and
- required resources including human and financial resources.

Various types of policy instruments can be used to support the effective implementation of policy and planning including regulatory instruments (command and control), economic instruments (use of pricing, subsidies, taxes, and charges to alter production and consumption patterns), informational instruments and cooperation instruments (Figure 6). Capacity building activities such as trainings and development of relevant guidance and training materials should be included.

Differential fuel taxation and pricing were employed in Hong Kong between 2000 and 2010 to effectively equalize the incremental price of low-sulfur and ultralow-sulfur fuels (See Section 3, page 7 and page 9) which enabled Hong Kong to switch to low-sulfur and ultralow-sulfur fuels successfully.

Figure 6. Policy instrument options available for the effective implementation of policy.



Institutional mechanism should be identified for the implementation of the plan. The plan and its implementation should be periodically reviewed and evaluated to confirm its effectiveness and updated as appropriate.

2.3 Matching Advanced Vehicle Emission standards to Cleaner Fuels

Sulfur in fuels inhibits the effectiveness of modern emission control devices used in vehicles to reduce air pollutants as well as climate forcers, including black carbon. Sulfur in fuels above threshold values is a barrier to the adoption of tighter vehicle emission standards which require advanced emission control devices; high-performance catalysts and diesel particulate filters require ultralow-sulfur fuels (see Table 2).

The majority of developing countries reliant on fuel imports normally import higher-sulfur fuels because of lower market prices. These markets also tend to not have vehicle emission standards in place, or have lenient emission standards. Without vehicle emission standards in place, including emission limits placed on imports of new and used vehicles, these countries do not capitalize on the cleaner and more efficient technology enabled by cleaner fuels.

In addition to the immediate near-term emission reduction benefits obtained from existing in-use vehicles (See Box 1), a switch to importing low-sulfur fuels will make it possible for countries to adopt tighter emission standards for both new and used vehicles. It is this systems approach to both fuels and vehicles that allows for maximum air quality and climate benefits.

2.3.1 Matching Vehicle Emission Standards with Low-sulfur and Ultralow-sulfur Fuels

Vehicles and fuels must be treated as a system in order to achieve the optimum benefits from emissions control policy, which means that it is essential to match the right vehicle emission standards to improving fuel quality standards. For fuel importing countries, matching the corresponding vehicle emission standards to low- and ultralow-sulfur fuels is crucial for emission reductions.

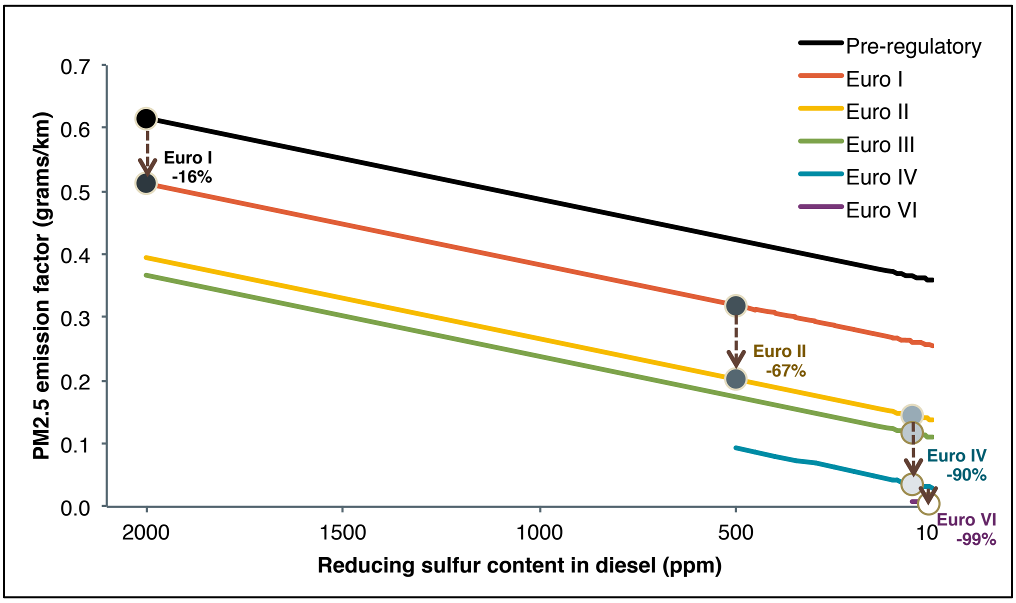
Table 2. Matching vehicle emission standards with low-sulfur and ultralow-sulfur fuels

Fuel Sulfur Contents	Matching Vehicle Emission Standards
Low-sulfur fuels ($S \leq 50$ ppm)	Euro 4-equivalent for light duty vehicles and earlier standards
	Euro IV-equivalent for heavy duty vehicles and earlier standards
Ultralow-sulfur fuels ($S \leq 10$ ppm)	Euro 5 and 6-equivalent, U.S. Tier 2 and 3 for light duty vehicles and earlier standards.
	Euro V and VI-equivalent, U.S. 2010 emission standards for heavy duty vehicles and earlier standards

By importing low-sulfur fuels with sulfur content of not more than 50 ppm, countries can adopt Euro 4/IV[6] emission standards for light-duty and heavy-duty vehicles. However, if countries jump to importing ultralow-sulfur fuels with sulfur content of not more than 10 ppm, Euro 5/V and 6/VI or U.S. Tier 2 and 3/U.S. 2010 standards can be adopted. A summary of European vehicle emission standards for new vehicles is contained in Appendix A.

Figure 7 demonstrates the reduction of $PM_{2.5}$ emissions from heavy duty diesel vehicles associated with fuel sulfur levels and vehicle emission standards. **The Euro VI emission standard employing diesel particulate filters combined with 10 ppm sulfur diesel will result in a 99% reduction in $PM_{2.5}$ as compared to combustion of 2,000 ppm sulfur diesel with no emission control device.**

Figure 7. Impact of fuel sulfur levels and vehicle emission standards on $PM_{2.5}$ emissions from heavy-duty diesel vehicles (grams/km) (Source: CCAC, 2016)



Functioning diesel particulate filters are very effective in controlling not only black carbon, but also ultrafine particles. A diesel particulate filter can reduce particle mass from a model year 2004 engine by 90% and ultrafine particles by at least a factor of 100 (Health Effects Institute, 2013).[7]

[6] Arabic numerals used in the context of the Euro standards refer to light duty vehicles, Roman numerals to heavy-duty vehicles.

[7] During regeneration events, whose duration and frequency will vary by engine design and duty cycle, ultrafine particulate emissions can temporarily increase but still remain lower overall.

2.3.2 Enforcement of Vehicle Emission Standards

When a country adopts vehicle emission standards, it becomes essential to ensure that all vehicles - including new and used imported vehicles - follow the vehicle emission standards in force before they are registered and used on roads. Traditionally, this meant subjecting certain vehicles to emission tests on a chassis or an engine dynamometer in a laboratory setting for emission verification, as shown in Figure 8. However, this system is costly, both in terms of the time required to set up and the skilled personnel needed for operations. Most vehicle importing markets do not have vehicle chassis dynamometer systems in place for emissions testing and verifications.

Figure 8. Laboratory for vehicle emissions testing on a vehicle chassis dynamometer and an engine dynamometer

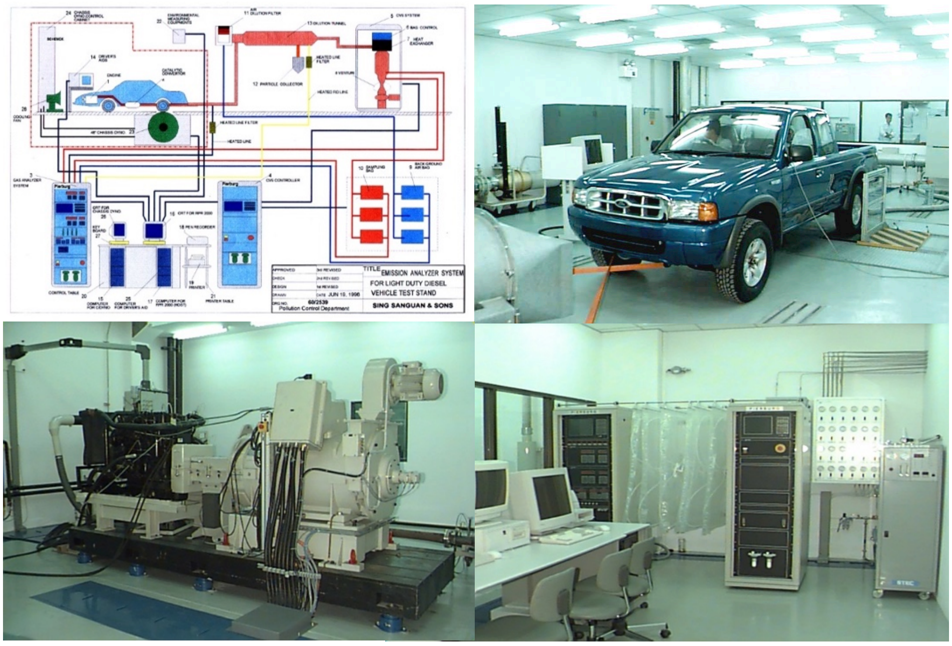


Photo credit: Pollution Control Department of Thailand

Alternatively, it is possible for a country to accept emission testing certificates for compliance with the set vehicle emission standards issued by international certified vehicle emissions testing laboratories. It is the responsibility of local vehicle manufacturers and importers to provide such certificates, either as a “Type Approval Certificate” or a “Certificate of Conformity,” to the relevant authorities. National officials may also be sent to witness the emissions tests at the certifying laboratory. All vehicles – either manufactured locally or imported, new or used - must be treated the same way as new vehicles when registered for the first time in a country from an emissions perspective.

If a certified vehicle emissions testing laboratory is established locally, it must now also support the new Worldwide Harmonized Light Vehicle Test Procedure (WLTP) which replaced the New European Driving Cycle (NEDC) from September 2017. The WLTP test cycle better represents real-world driving profiles on roads since it was developed using real driving data gathered from around the world with the aim of being used as a global test cycle across different regions. The previous NEDC test cycle, by comparison, was developed based on a theoretical driving profile.

Portable Emissions Measurement System (PEMS), as shown in Figure 9, can provide lower-cost on-road testing. This system can be a complement to laboratory testing. However, PEMS still requires investment and local calibration. Emissions from a vehicle are measured on a real-time basis while the vehicle is driven on local roads. This system is much more affordable as compared to laboratory. The PEMS can also support the adoption of Real Driving Emission standards in the future.

There are a number of efforts worldwide focused on real-world, on-road emissions following 'Dieselgate' scandal. The Real Urban Emissions (TRUE) initiative aims to independently monitor and report real-world vehicle emissions in cities. The TRUE project's emissions data is based on test results supplied by third parties, such as independent testing facilities or government laboratories, and vehicle tests commissioned by or carried out by the TRUE initiative itself. Emission measurements are made using PEMS testing and remote sensing. Vehicles are rated and information on ratings is provided in a publicly searchable online database available from https://www.trueinitiative.org/true-rating.

Figure 9. Portable Emissions Measurement System (PEMS)

Photo credit: AVL/ERMES Group

3. Inspection and Maintenance of Vehicle Imports and On-Road Vehicles

Enforced emission standards for all vehicles (new, used and existing on-road vehicles) will help to deliver air quality benefits from cleaner fuels and advanced vehicle emission standards. Enforcement requires vehicle engines to function properly and emission control devices to be performing efficiently and in the same way as when they were type-approved as new vehicles.

In order to maintain the emissions standards of in-use vehicles, they must be properly maintained on a regular basis. However, after the warranty is expired vehicle owners tend not to have their vehicles regularly maintained in accordance with the recommendations of vehicle manufacturers due to service costs. As a result, the performance of vehicle engines and emission control devices will deteriorate with time. Vehicles that are properly tuned and adjusted will be cleaner than vehicles out of tune.

Modern vehicles equipped with advanced emission control devices are even more dependent on properly functioning components to keep pollution levels low. Minor malfunctions in the air/fuel or spark management systems or problems with diesel fuel injectors can increase emissions significantly. Major malfunctions can cause emissions to skyrocket. A relatively small number of vehicles with serious malfunctions frequently cause the majority of the vehicle-related pollution problems. Unfortunately, it is rarely obvious which vehicles fall into this category, as the emissions themselves may not be noticeable and emission control malfunctions do not necessarily affect vehicle driveability.

An effective in-use vehicle inspection and maintenance program has to be put in place to ensure that the engines and emission control devices of in-use vehicles are durable, and that emissions are effectively controlled throughout the vehicle useful life. An effective vehicle inspection and maintenance program based on periodic short tests can identify these problem vehicles and, by requiring a retest after necessary maintenance, assures their repair (See Box 3). The combination of inspection (I) and remedial maintenance (M) has become known as I/M. Targeted I/M programs can contribute substantially to reducing the pollution caused by such vehicles.

Box 3: Periodical Emission Inspection and Maintenance Program for In-use Vehicles in Hong Kong

An effective I/M program is a core part of a comprehensive vehicle emission control strategy implemented in Hong Kong. It ensures that the expected emissions reduction of any implemented vehicle emission reduction program is actually realised once vehicles are used on roadways. A centralized system with both test-only centres and test-and-repair centres is employed in Hong Kong. There are both Government Vehicle Examination Centres and privately-owned Designated Car Testing Centres designated by the Transport Department. For gasoline vehicles, idle and fast idle are used to measure CO, whereas a free acceleration test is used to measure smoke emission opacity from diesel vehicles. Ten percent of the diesel vehicles presented for roadworthiness inspection are randomly selected to undergo loaded lug-down tests on a chassis dynamometer.

According to Hong Kong government transport regulations, all private cars and light goods vehicles (with Gross Vehicle Weight not exceeding 1.9 tonnes) over 6 years old are required to receive an annual vehicle examination including emission examination at a Designated Car Testing Centre. If the vehicle passes the examination, a Certificate of Roadworthiness with “PASS” will be issued for the annual renewal of vehicle license. If the vehicle does not pass the exam, a Vehicle Repair Order will be issued. Vehicles will have to be repaired and return to the same testing center for re-examination within 14 days. Only vehicles passing the examination will be allowed to renew a vehicle license. Commercial, goods and heavy-duty vehicles are also required to pass mandatory Certificate of Roadworthiness Examination annually including emission examination for the renewal of vehicle license.

Governments contemplating the establishment of an I/M system or expanding the scope of an I/M system need to consider: i) whether they have adopted the appropriate in-use vehicle emission standards and test procedures on which to base I/M, ii) whether there is the institutional capacity and willingness to enforce an I/M program, and iii) whether the repair sector has been trained sufficiently to be able to carry out the repairs on cars which fail the tests.

The aim of any I/M program should be the identification of gross polluters within each technology category and on having the failed vehicles repaired and retested to reach required emission levels. Key principles and key determinants of the overall success or failure of an I/M program include:

- **In-use vehicle emission standards and test procedures**
  - Pollutants of concern will differ between diesel-fuelled vehicles (PM, smoke and NO_x) and gasoline-fuelled vehicles (CO, HC and NO_x).
  - In-use vehicle emission standards and test procedures must appropriately reflect the differences between each classification of vehicles, and the differences in emission control technologies employed (See Box 4). On-road vehicles will then be controlled for the required emissions.
  - Tightening of new vehicle emission standards should be followed by a corresponding tightening of in-use vehicle emission standards (See Box 4).
  - As vehicle technologies advance, more sophisticated test procedures are necessary - including loaded mode tests that use a chassis dynamometer to simulate engine performance and emissions in actual driving. For example, a European short loaded mode test cycle or the US derived IM240 test cycle (the first 240 seconds of the hot-start FTP cycle, see Box 5). Alternatively, a PEMS, as described in Section 5.2 and shown in Figure 9, can be employed for real-time on-road testing under actual driving condition at a much lower cost.

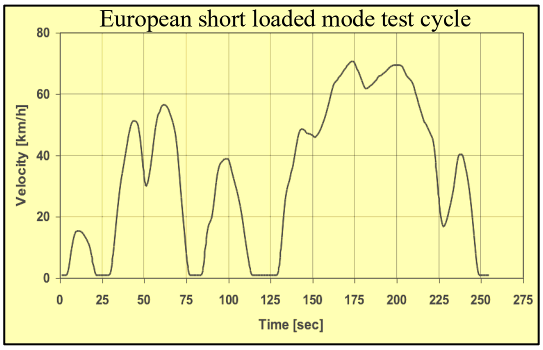
Box 4: Emission Standards for In-use Vehicles in Thailand

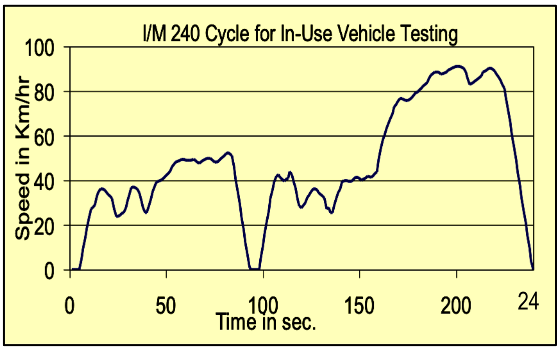
Since 1990 in-use vehicle emission standards have been periodically tightened following the new vehicle emission standards, in particular for light duty gasoline vehicles and motorcycles as shown in the table below.

Vehicle Types	In-use Vehicle Emission Standards		New Vehicle Emission Standards	Date of Vehicle's First Registration	Measuring Devices	Test Procedures
Light Duty Gasoline Vehicles	CO	4.5 %	ECE 15-04	Before 1st Nov. 1993	Non-Dispersive Infrared (NDIR)	Idle Test
		1.5%	Euro 1	From 1st Nov. 1993		
		0.5%	Euro 3	From 1st Jan. 2007		
	HC	600 ppm	ECE 15-04	Before 1st Nov. 1993		
		200 ppm	Euro 1	From 1st Nov. 1993		
		100 ppm	Euro 3	From 1st Jan. 2007		
Heavy Duty Gasoline/ Gasohol Vehicles	CO	4.5 %	Euro 3	-		
	HC	2.0 %				
Heavy Duty Natural Gas Vehicles	CO	600 ppm	Euro 3	-		
	HC	600 ppm				
Light and Heavy-Duty Diesel Vehicles	Black Smoke	50 %	Euro 3	-	Filter-Type Smoke Meter	Snap Acceleratio n Test
		45 %			Opacimeter	
		40 %	Euro 3	-	Filter-Type Smoke Meter	Full Load Test
		35 %			Opacimeter	
Motorcycles	CO	4.5 %	CO $\leq$ 13 gm/km	Before Jul 1, 2006	Non-Dispersive Infrared (NDIR)	Idle Test
		3.5 %	CO $\leq$ 3.5 gm/km	From Jul 1, 2006		
		2.5 %	Euro 3: CO $\leq$ 2 gm/km	From Jul 1, 2009		
	HC	10,000 ppm	HC $\leq$ 5 gm/km	Before Jul 1, 2006		
		2,000 ppm	HC+NOx $\leq$ 2 gm/km	From Jul 1, 2006		
		1,000 ppm	Euro 3: HC $\leq$ 0.8 gm/km	From Jul 1, 2009		

Box 5: Loaded Mode Test Cycles Used for Emission Inspection of In-use Vehicles

The shift towards more stringent emission standards for new vehicles should be followed by tighter in-use standards for the newer models. The test procedure should also be shifted to a "loaded test" rather than "idle test" or "free acceleration test" when new vehicle standards result in the introduction of advanced emission technologies on vehicles. For countries which have adopted EU or US vehicle emission standards for new vehicles, a European short loaded mode test cycle and the US derived IM240 test cycle (the first 240 seconds of the hot-start FTP cycle) are shown in figures below.





- **I/M Program Structure and Institutional–Administrative Set up**
  - In-use vehicles should be subject to I/M programs when the manufacturer warranty is expired, or even earlier. Frequency of inspections should vary for vehicles with differing mileage accumulation rates and with more, or less, durable emission control systems. Public and commercial vehicles, e.g. taxicabs and buses, typically accumulate far more mileage in a given period than private cars and should be subject to more frequent inspections.
  - The actual implementation of I/M programs can be carried out by the private sector, together with government regulation. A well-functioning audit and quality assurance system is necessary to maintaining credibility. Regular audits can be implemented by a special unit in the responsible government department or can be outsourced to a private sector firm provided it is not operating a part of the I/M program.
  - Test-only systems where the inspection function is separated from the maintenance function have produced the best results. Combined inspection and repair systems are very difficult to supervise and audit and have been found to be subject to poor quality control and corruption.
  - A centralized inspection system with a limited number of large inspection centres will produce much better results than a decentralized system with a large number of small independent inspection workshops. The latter will have lower numbers of customers which might make them uneconomical to operate and may provide poor quality inspection. A decentralized system is also subject to poor quality control. Additionally, if the test procedure is shifted to a "loaded test" with the use of a chassis dynamometer then costs of new, additional test equipment including a chassis dynamometer will make it difficult for small-scale inspection workshops to take part in I/M programs.

- An appropriate fee structure should be developed in which the affected vehicle owners pays the full costs of the I/M program, including the costs of auditing and overseeing the program by government or private auditors.
- Poor coordination between the agencies involved in the implementation of an I/M program will hamper its effectiveness. Dialogue at the early stages of I/M program design should be undertaken and specific roles and responsibilities agreed.
- I/M programs should be linked to the registration of vehicles, i.e. failure to present proof of passing an inspection leads to denial/repeal of registration. The registration-based enforcement system will ensure that all vehicles subject to the I/M program are actually inspected and repaired.
- A data management system is needed to ensure that all emission test data are transmitted to a central database at the vehicle registrar office. It will be more effective if I/M inspection centres are linked by computers through which vehicle information together with emissions test data are automatically transmitted on a real-time basis to the vehicle registrar office to prevent data tampering. Increased reliance on data management centres will make it necessary to strengthen the quality of the overall database on vehicles in actual use.

- **Technical Issues and Capacity Building**
  - For the inspection sector of the I/M program, a capacity building program must be put in place to ensure that the staff of all inspection centres are trained to have adequate capability to do proper emission tests, including calibration of equipment and maintenance of all hardware. The staff of inspection centres performing emission tests should be trained and certified to carry out emission tests and inspections.
  - For the maintenance or repair sector of the I/M program, vehicle manufacturers can play an important role in providing training to mechanics for repairs on vehicles which fail tests. This is particularly important for vehicles equipped with modern, advanced emission control technologies. Mechanics should be involved in the development of an overall strategy to upgrade the repair sector.

- **Roadside Inspection Programs**
  - The practice of “Clean for a Day” occurs when vehicles equipped with simple carburetor technology with/without simple catalytic converters are tuned or catalytic converters are installed simply in order to pass tests. Subsequently, these vehicles are readjusted, or catalytic converters removed, in order for vehicles to gain more power while also returning to the status of super-emitters.
  - To avoid this practice, a roadside inspection can be carried out to complement periodical inspections for in-use vehicle. However, roadside inspections are not an alternative or replacement for periodic inspections. On-road vehicles will be spotted and checked for emissions by police or official inspectors. Vehicles failing the tests will be subject to fines and prohibited from roads until they are repaired and pass the retest (See Box 6).

– Remote sensing technologies can also be used to complement roadside inspections as a screening. Real-time exhaust emissions are measured remotely by a spectrophotometer in real time (See Box 7). Vehicles that are identified as high-emitting vehicles will then be called in for official inspections.

- **Public Participation in I/M**

  – Public perceptions of the effectiveness and transparency of I/M systems will heavily influence the willingness of the general public to cooperate with I/M systems. To ensure a positive public perception, it is important that such a program is perceived as fair and effective.

  – I/M programs should have an on-going public awareness and participation component that routinely informs the public of the need for the program, the benefits accrued and the overall performance of the program.

  – Performance standards, such as waiting times and pass/fail rates, should be developed for I/M centres to ensure fast and reliable testing. Poorly performing centres should be penalized.

  – Complementary tax incentives, lower registration fees, less frequent inspection for cleaner vehicles, and/or linkages to vehicle insurance rates may also be considered.

Box 6: Roadside Inspection of In-use Vehicles in Hong Kong

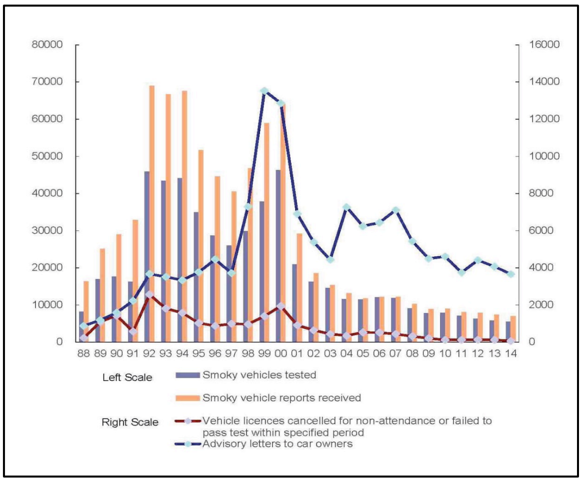
Since 1988 the Environmental Protection Department (EPD) of Hong Kong has implemented a Smoky Vehicle Control Programme in parallel with the periodical emission inspection and maintenance program for in-use vehicles. On-road smoky vehicles reported by volunteer spotters who are trained and accredited to identify smoky vehicles are required to report to one of the Designated Car Testing Centres for a smoke emission test within 12 working days. If a vehicle fails to pass the test, it needs to be repaired and retested, otherwise the vehicle's registration will be revoked. More than 21,000 vehicle license cancellations have been recommended since the implementation of the programme in 1988.[8]

A smoke emission opacity test with free acceleration was used when the Smoky Vehicle Control Programme started in 1988. To enhance the effectiveness of the programme, a more advanced smoke emission opacity test by loaded lug-down testing on a chassis dynamometer, as shown below, was introduced in September 1999 for diesel vehicles up to 5.5 tonnes and extended to all diesel vehicles in December 2000.

[8] https://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/cleaning_air_atroad.html

A lug-down test is considered a steady state loaded smoke emission test on a chassis dynamometer at three loading conditions: 100 percent, 90 percent and 80 percent maximum engine power. The lug-down test gives much better results than an unloaded free acceleration test.

Additionally, EPD together with the Police Department regularly set up roadside smoky vehicle inspection stations. A suspected smoky diesel vehicle is pulled over to undergo a Free Acceleration Smoke test on the spot using a portable smokemeter. If the vehicle fails to pass the test, the vehicle owner will be fined HK$1,000 and the vehicle is required to be repaired and retested at one of the Designated Vehicle Test Centres using a lug-down test within 12 working days.

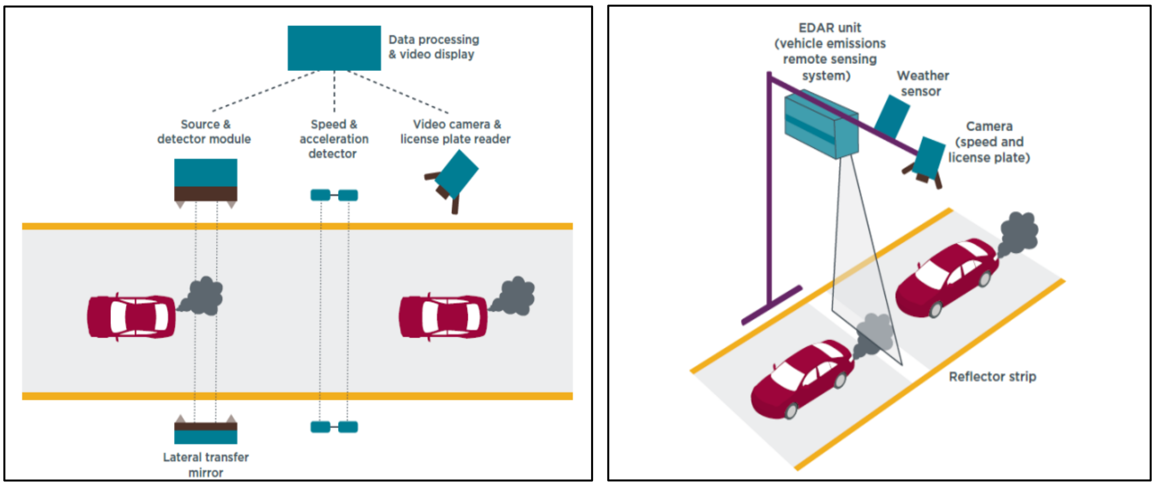


Since the start of the the Smoky Vehicle Control Programme in 1988, smoky vehicle reports started to decline from 2000 onward.

Source: Information retrieved from https://www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/cleaning_air_atroad.html

Box 7: Remote Sensing Measuring Emissions of Vehicles Driven on Actual Roadways

Exhaust emissions of on-road vehicles in real driving conditions are measured remotely by a spectrophotometer on a real-time basis. A light source and a detector placed either at the sides of or above the roadway measure exhaust emissions of vehicles as they are passing by the measurement location, as illustrated below (Borken-Kleefeld and Dallman, 2018). Speed and acceleration of the vehicle can be measured, and an image of the vehicle's number plate can be captured along with the emissions measurement. A large number of vehicles can be measured in a short period of time. Remote sensing technology can be used to complement roadside inspection programs for in-use vehicles as a screening step.



- **Quality Assurance & Audit**
  - It is crucial to ensure that quality assurance and auditing functions are fully built in to the overall I/M program design. This means that the less the test and audit systems rely on human judgment or manual actions, the more reliable the results (See Box 8).
  - A fully-automated test and data transmission to minimise the chance of data manipulation can greatly improve the reliability of the test results, deter fraud and enable easier and more effective audits of test center and individual performance.
  - Test fees should be set at a reasonable level that will allow private I/M centres to make a sufficient profit to maintain, replace and upgrade equipment as required for good quality testing.
  - Calibration audits of test equipment, audits of test centres using the data reported, and covert audits of test centres should be made on a regular basis. The audit functions could be outsourced to independent third parties provided they are not operating a part of the I/M program.

Box 8: The Mexico I/M Program's Oversight and Quality Assurance System

The quality assurance and audit measures built into the I/M program in Mexico are viewed best practices that have effectively deterred fraud and corruption.

- Tests are controlled by computers and inspectors on the test lanes are not allowed to see emission test results which can only be seen in a control room. This discourages any tampering with the test equipment or vehicle and deters manipulation of the test.
- All data, including emission test data, access data and calibration data are transmitted in real time as generated to a central authority automatically and electronically. In this way, data tampering is eliminated. The data are audited remotely at the central authority as follows:
  - Second-by-second emission test data pattern of tests of similar cars of a given model and year that have passed the test in different test centres are compared. If the vehicle's traces have a different shape, a 'flag' is raised for the test lane of that centre. If a test lane or centre gets an unusually high number of flags, the test lane or centre will be subject to further investigation.
  - Test results calculated from the second-by-second emissions data are compared to the test results reported by the centre; different results suggest possible tampering.
  - To ensure that one car is not being used to generate multiple certificates, the computer server compares the second-by-second emissions data pattern of one car with those of other cars being tested on the same test lane, and other test lanes in the same test centres.
  - All access data and calibration data are also analysed for anomalies.
- Video cameras are installed at all test centres and transmit live video feeds 24 hours every day to enable remote surveillance. Live videos are broadcast online on a real time basis. The cameras can be controlled remotely from the central authority to zoom in and see the letters and numbers on the registration documents and license plate which are used for data entry. A hotline is also set up for the public to report any suspicious acts.
- The test equipment is audited once a month by an independent ISO-certified materials standards laboratory to ensure that test equipment is properly maintained and that consistent test results are generated across all test lanes and centres.
- A vehicle counting system is set up at each centre which is totally independent of the test equipment. The count checks the number of vehicles that enter and leave the test centre and each test lane. The timing from the vehicle count is cross-checked against the verification process by the central server.
- All test personnel are required to be certified, and a system is in place so that a tester dismissed in one test centre due to fraudulent inspection cannot be hired by a different centre.

- **Maintenance - the "M" in I/M**
  - I/M programs need to include a particular focus on the repair sector, in particular where the repair sector is very informal in terms of training and equipment. This is necessary to ensure the quality of repairs and the sustainability of emission reductions.

- Vehicle manufacturers can play an important role in providing training for mechanics, in particular for those vehicles equipped with modern advanced emission control technologies.
- The repair centres must have sufficient equipment to properly repair vehicles. In addition, adequate training must be made available so that the mechanics and technicians are sufficiently skilled to repair the failed vehicles.
- In tightening I/M requirements, careful attention should be paid to ensuring that the repair sector has sufficient lead-time, e.g. up to one year, to equip itself to repair failing vehicles.

4. Lubricity

One important concern which has to be taken into consideration in the introduction of low or ultralow-sulfur fuels, in particular diesel fuel, is the impact of fuel desulfurization on the lubricity of the fuel. Fuel lubricity is the ability of the fuel to reduce friction between solid surfaces of engine components in relative motion. Diesel fuel refined from the distillation of petroleum crude has inherent lubricity-enhancing compounds which include heavy hydrocarbons and organo-sulfur. The lubrication mechanism is hydrodynamic lubrication in which a layer of diesel fuel is in between the opposing surfaces in the diesel fuel pump and injector preventing contact between them.

Viscosity is the key fuel property with regard to lubrication. Fuel with higher viscosity will provide better hydrodynamic lubrication. Diesel fuels with lubricity in accordance with the ASTM D975 standards for lubricity can provide adequate hydrodynamic lubrication. The ASTM D975 standards define the lubricating specification for the minimum lubricating characteristics of all diesel fuels by setting the maximum amount of wear on materials when tested with specific fuels or blends of fuels.

Without an external lubricating system, the moving parts of some engine components of diesel vehicles, i.e. rotary fuel injection pump and fuel injector, must rely on natural lubricating properties of the fuel to operate properly and for protection against excessive wear and failure. Engines using poor lubricity fuel will encounter deterioration in the fuel injection system, i.e. increasing fuel pump and injector wear, which could also affect the combustion process and lead to higher emissions, or even perhaps even engine failure.

Hydrodesulfurization by hydrotreating, the process used to reduce sulfur and aromatics in fuel refining, can also reduce the components that provide natural lubricity. However, lubricating additives are readily available which can effectively increase the lubricity of low and ultralow-sulfur fuels and do not have any negative impact on exhaust emissions.

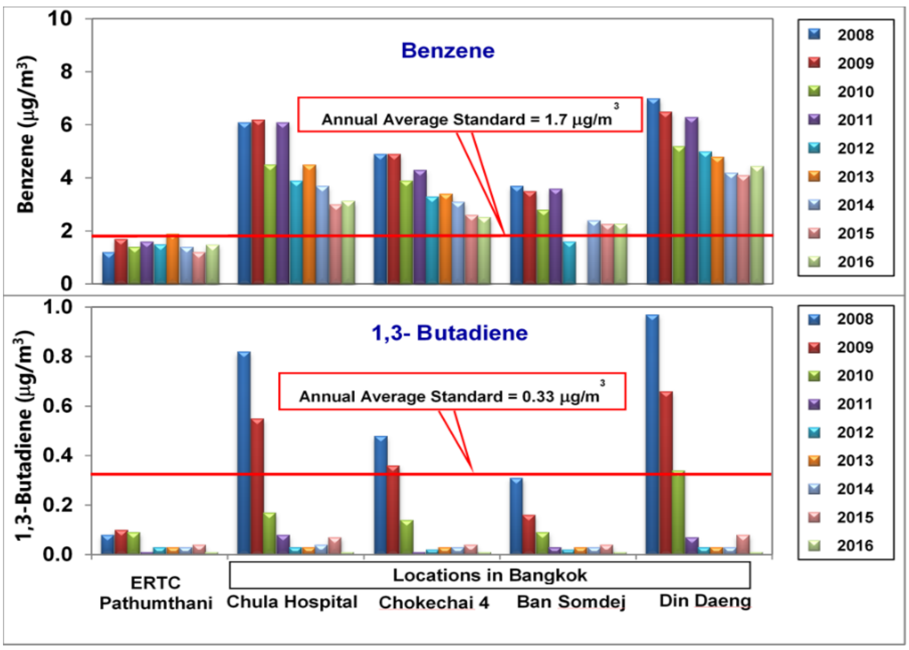
Biodiesel, with its higher viscosity, has excellent lubricating characteristics and can be used as a lubricating additive to increase the lubricity of petroleum-based diesel. It has been demonstrated that blending 2% biodiesel can increase the lubricity of petroleum-based diesel fuel to the acceptable levels (EPA 2000). In general, lubricating additives should be blended with any fuels with 50 ppm sulfur or below. However, blending can also be made on a batch-by-batch basis for any batch of petroleum-based low-sulfur and ultralow-sulfur fuels with low lubricity.

5. Other Emission Reduction Benefits Associated with Low and Ultralow-sulfur Fuels

The European Union has mandated ultralow-sulfur fuels with sulfur content of not more than 10 ppm in both gasoline (EN 228) and diesel (EN 590) fuels since 2009; the preceding fuel sulfur content was 50 ppm. In addition to limits on sulfur there are also limits on other fuel parameters whose revision will also lead to emission reductions – namely, benzene and aromatics. Both low-sulfur and ultralow-sulfur gasoline fuels have limits on benzene and aromatics content of not more than 1% and 35%, respectively. Low-sulfur and ultralow-sulfur diesel fuels have limits on polycyclic aromatic hydrocarbons (PAHs) of 11% and 8%, respectively. Therefore, enforcing low-sulfur and ultralow-sulfur fuels will also result in the immediate reduction of benzene and 1,3-butadiene emissions from gasoline vehicles and the reduction of PAHs from diesel vehicles. Benzene, 1,3-butadiene and PAHs have been classified by World Health Organization as carcinogenic to humans. A summary of key specifications of European fuel quality standards may be found in Appendix B.

Figure 10 shows the declining ambient benzene and 1,3-butadiene concentrations in four congested areas in Bangkok, Thailand (Chulalongkorn Hospital, Chokchai 4, Ban Somdej and Din Dang) after benzene content in gasoline was reduced from 5% to not more than 3.5% and Euro 3 emission standards for new light duty vehicle were enforced in 2005. Further to that, low-sulfur gasoline fuel with benzene content of not more than 1% and Euro 4 light duty vehicle emission standards for new vehicles were enforced in 2012. Much lower concentrations were found at a monitoring station at the Environmental Research and Training Center located in a rural area in Pathumthani - about 50 kilometers north of Bangkok.

Figure 10. Declining annual average concentrations of Benzene and 1,3- Butadiene at four congested areas in Bangkok and at a rural area in Pathumthani



6. Conclusions

Reducing sulfur in transportation fuels provides immediate near-term emission reductions to improve air quality and mitigate climate change by reducing emissions from the existing, on-road fleet. Longer-term benefits are obtained with the implementation of complementary emission standards for all new and in-use vehicles. Black carbon and $PM_{2.5}$ associated with diesel combustion can be controlled using diesel particulate filters required by soot-free emission standards like Euro 6/VI or U.S. 2010, but these devices are only effective with low, or ideally ultralow, sulfur fuels.

Fuel-importing countries can shift relatively quickly to low-sulfur or ultralow-sulfur fuels and should aim for an immediate jump to ultralow-sulfur fuels without intermediate steps. Although the premium costs imposed on low or ultralow-sulfur fuels are of concern to both policymakers and consumers, historical data has shown that the prices of low-sulfur fuels in various international oil markets have been only slightly higher than high-sulfur fuels. Moreover, the price difference between high-sulfur and low-sulfur fuels has decreased in recent years. The actual price increase associated with low-sulfur fuel is always smaller than the normal fluctuation of market fuel prices. Several countries have taken the opportunity to introduce low-sulfur fuels while fuel prices were decreasing in order to avoid perceived price increases due to fuel quality change.

In order to maximize the benefits of low and ultralow-sulfur fuels, vehicle emission standards for new and in-use vehicles should be put in place or improved – from Euro 4/Euro IV (with 50 ppm fuels) to Euro 6/VI (U.S. 2010) with 10 ppm fuels. Fine particle and black carbon emissions from diesel vehicles can be reduced by 99 percent with a transition to soot-free diesel technology. A soot-free vehicle (Euro 6/VI or U.S. 2010) – be it diesel, natural gas or electric – will emit 99% less tailpipe $PM_{2.5}$ and black carbon compared to a diesel vehicle without any emission controls. Attaining these reductions requires a combination of ultra-low sulfur diesel fuels (between 10-15 parts per million sulfur), tailpipe emission controls (such as Euro VI or U.S. 2010 standards), adequate compliance and enforcement systems, and inspection and maintenance practices.

Used vehicle import restrictions (including emission standards) should be combined with emission controls for vehicles. The emissions verification system may include international certified vehicle emission testing laboratories and/or Portable Emissions Measurement System (PEMS). Vehicle manufacturers and importers should be required to provide a valid "Type Approval Certificate" or "Certificate of Conformity" for both new and used vehicles entering the market. An effective in-use vehicle inspection and maintenance (I/M) program is essential to ensuring engines and emission control devices are durable and emissions are effectively controlled throughout the vehicle useful life. A centralized test-only I/M program where the inspection function is separated from the maintenance function has produced the best results. A roadside inspection program can complement periodical inspection programs for in-use vehicle but is not a replacement.

Nine out of every ten people breathe unhealthy air, according to the BreatheLife Campaign. In 2016 an estimated 4.2 million premature deaths resulted from chronic exposure to ambient fine particulate matter and ambient ozone, reducing global average life expectancy at birth by about 1 year (Apte et al. 2018). The benefits always outweigh the costs of desulfurization in countries that have analyzed the impact of low-sulfur fuels on air quality and public health. All cost-benefit analyses in the US, Europe and Asia consistently found that the public health and economic benefits associated with phasing down sulfur in fuels greatly outweigh the costs, especially in combination with tightened vehicle emission standards.

Appendix A: European Emission Standards for Vehicles

European Emission Standards for Passenger Cars (Category M(1))

Diesel (g/km)								
Tier	**Date**	**CO**	**THC**	**NMHC**	**NOx**	**HC+NOx**	**PM**	**PN(#/km)**
Euro 1(2)	July 1992	2.72 (3.16)	-	-	-	0.97 (1.13)	0.14 (0.18)	-
Euro 2	January 1996	1.0	-	-	-	0.70	0.08	-
Euro 3	January 2000	0.66	-	-	0.50	0.56	0.05	-
Euro 4	January 2005	0.50	-	-	0.25	0.30	0.025	-
Euro 5a	September 2009	0.50	-	-	0.18	0.23	0.005	-
Euro 5b	September 2011	0.50	-	-	0.18	0.23	0.005	$6x10^{11}$
Euro 6	September 2014	0.50	-	-	0.08	0.17	0.005	$6x10^{11}$
Petrol (Gasoline), g/km								
Tier	**Date**	**CO**	**THC**	**NMHC**	**NOx**	**HC+NOx**	**PM**	**PN(#/km)**
Euro 1(1)	July 1992	2.72 (3.16)	-	-	-	0.97 (1.13)	-	-
Euro 2	January 1996	2.2	-	-	-	0.50	-	-
Euro 3	January 2000	2.3	0.20	-	0.15	-	-	-
Euro 4	January 2005	1.0	0.10	-	0.08	-	-	-
Euro 5	September 2009	1.0	0.10	0.068	0.06	-	0.005(3)	-
Euro 6	September 2014	1.0	0.10	0.068	0.06	-	0.005(3)	6×10^{11} (4)

(1) Before Euro 5, passenger vehicles > 2500 kg were type approved as light commercial vehicles N_1-I
(3) Applies only to vehicles with direct injection engines
(4) 6×10^{12}/km within first three years from Euro 6 effective dates
(2) Values in parentheses are conformity of production (COP) limits

European Emission Standards for Heavy Duty Engines

Heavy Duty Engines, gm/kWh							
Tier	**Date**	**Test Cycle**	**CO**	**HC**	**NOx**	**PM**	**Smoke m^{-1}**
Euro I	1992, < 85 kW	ECE R-49	4.5	1.1	8.0	0.612	-
	1992, > 85 kW		4.5	1.1	8.0	0.36	
Euro II	October 1996		4.0	1.1	7.0	0.25	
	October 1998		4.0	1.1	7.0	0.15	
Euro III	October 1999, EEV(1) only	ESC(2) & ELR(3)	1.0	0.25	2.0	0.02	0.15
	October 2000		2.1	0.66	5.0	0.10 0.13(4)	0.8
Euro IV	October 2005		1.5	0.46	3.5	0.2	0.5
Euro V	October 2008		1.5	0.46	2.0	0.2	0.5
Euro VI	December 2013	WHSC(5)	1.5	0.13	0.4	0.1	-

(1) EEV is "Enhanced environmentally friendly vehicle".
(4) For engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3,000 per minute.
(2) ESC is European Stationary Cycle
(3) ELR is European Load Response
(5) WHSC is World Harmonized Stationary Cycle

Appendix B: Summary of Key Specifications of European Fuel Quality Standards with Matching Vehicle Emission Standards

Gasoline (EN 228)				
Parameters	**Concomitant Emission Standards for New Vehicles**			
	Euro 2/II	**Euro 3/III**	**Euro 4/IV**	**Euro 5/V/VI**
Aromatics, vol% max	-	42	35	35
Olefins, vol%, max	-	18	18	18
Benzene, vol%, max	5.0	1.0	1.0	1.0
Oxygen, wt%, max	-	2.7	2.7	2.7/3.7
Sulfur, ppm, max	500	150	50	10
RVP, kPa	35-100	60.0/70.0	60.0/70.0	60.0/70.0
Lead, g/l, max	0.013	0.005	0.005	0.005

Diesel (EN 590)				
Parameters	**Concomitant Emission Standards for New Vehicles**			
	Euro 2/II	**Euro 3/III**	**Euro 4/IV**	**Euro 5/V/VI**
Polycyclic Aromatic Hydrocarbons, vol% max	-	11	11	8
Sulfur, ppm, max	500	350	50	10
Cetane number, min	46-49	51	51	51
Density @ 15 °C, kg/m^3	820-860	845	845	845
Distillation, T95 °C, Max	360	360	360	360

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