Safe and Clean Vehicles for Healthier and More Productive Societies

GRSF
Global Road Safety Facility

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About GRSF

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Foreword

The expansion of motorized road transport has been a powerful driver of economic and social development, offering people greater access to jobs, markets, education, and essential services. Yet its rapid growth, especially in emerging and developing economies, has come with mounting costs for public health, safety, and the environment. As vehicles fill roads across the globe, so too do the risks: increased traffic crashes, worsening air pollution, and their severe impacts on human capital—that is, the aggregate health, skills, and productivity of people in a society.

This study is the first of its kind to examine the twin crises of vehicle safety and emissions in an integrated and holistic manner. It brings together a robust, cross-sectoral evidence base to demonstrate that the management of motorized transport is not merely a public health, transport or environmental concern—it is closely linked to the level of human capital in emerging and developing economies and therefore has far-reaching downstream effects.

The scale of the problem is staggering. Road crashes claim roughly 1.2 million lives each year, while pollution from road transport—including $PM_{2.5}$ and NO_2 emissions—caused an estimated 550,000 premature deaths in 2021. These losses are not evenly distributed. Over 90% of road traffic fatalities and a vast majority of pollution-related illnesses occur in emerging and developing economies. These injuries, illnesses, and deaths are more than health outcomes—they represent lost productivity, missed educational opportunities, and barriers to inclusive growth.

What makes this pioneering study so critical—and timely—is its focus on how countries can better manage the quality and quantity of their motorized vehicle fleets across the full life cycle: from vehicle entry; to in-use maintenance; to end-of-life scrappage. The report provides new modeling and evidence, as well as clear policy recommendations, for strengthening safety and emissions standards, managing used-vehicle imports, improving fuel quality, and retiring old, non-compliant vehicles. Importantly, the report highlights the underestimated threat of NO_2 emissions, especially in middle-income countries, and calls for expanded attention to this pollutant.

This study moves beyond technological fixes. While strict standards for vehicle safety and emissions are the cornerstone of the solution, they are not enough. A comprehensive motorization management strategy—combining regulations, enforcement, consumer awareness, periodic vehicle inspections, and real-time data systems—is essential to achieving safer, cleaner, and more equitable motorized transport networks.

We hope this report will serve as both a wake-up call and a roadmap. By addressing the safety and environmental performance of vehicles simultaneously, policymakers can protect lives, reduce economic losses, and build healthier, more productive societies. The World Bank Group is ready to support countries in making this transition—not only as a matter of transport policy, but as a pillar of growth and productivity.

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Abbreviations

ABS	Anti-lock braking system
AEBS	Advanced emergency braking systems
AQG	Air quality guideline
ASEAN	Association of South-East Asian Nations
BAU	Business-as-usual
CNG	Compressed Natural Gas
CVD	Cardiovascular disease
COPD	Chronic obstructive pulmonary disease
DPF	Diesel particulate filter
EAP	East Asia and Pacific
ECA	Europe and Central Asia
ELV	End-of-life vehicle
ESC	Electronic stability control
EV	Electric vehicle
FRUPD	Front- and Rear-Underrun Protective Devices
FSI	Fatalities and serious injuries
GBD	Global burden of disease
GNI	Gross national income
GTR	Global technical regulation
HDV	Heavy duty vehicle
IHD	Ischemic heart disease
LAC	Latin America and the Caribbean
LDV	Light duty vehicle
LEZ	Low emission zone
LPG	Liquefied Petroleum Gas
MAPS	Major air pollution sources
MENA	Middle East and North Africa
MTW	Motorized two wheelers
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
SAR	South Asia Region
SCR	Selective catalytic reduction
SSA	Sub-Saharan Africa
ULEZ	Ultra-low emission zone
UNEP	United Nations Environment Programme
VSF	Vehicle stability function
VSL	Value of statistical life
WHO	World Health Organization
YLD	Years lived with disability

Executive Summary

Message 1: Motorization management is a critical health issue.

Road crashes and air pollution from motorized road transport impose a substantial health burden in emerging and developing economies, causing hundreds of thousands of deaths and disabilities annually. Road traffic crashes lead to an estimated 1.19 million fatalities every year and countless more injuries, amounting to $2.9 trillion in costs (author's calculation based on Wijnen, Dahdah and Pkhikidze, 2025).

Pollutants emitted from vehicles also cause significant health effects. This report finds that emissions of particulate matter 2.5 microns or smaller in diameter (commonly referred to as $PM_{2.5}$) from road transport caused an estimated 311,000 premature deaths globally in 2021, resulting in an economic welfare cost of $385 billion. Vehicle emissions of nitrogen dioxide (NO_2)—another noxious air pollutant—caused an estimated 240,000 premature deaths, representing a welfare cost of $420 billion.

Exposure to fine particles also impairs children's cognitive development. In 2021, $PM_{2.5}$ emissions from motorized vehicles caused the loss of 64 million intelligence quotient (IQ) points globally, resulting in productivity losses estimated at $157 billion. In addition to claiming lives, these impacts reduce workers' productivity, impair children's ability to learn, and increase the proportion of scarce resources spent on health expenses, negatively affecting the ability of emerging and developing economies to achieve their development goals.

Message 2: Priority should be given to applying standards to the existing fleet—including retirement of non-roadworthy vehicles—rather than just focusing on stricter standards for brand-new vehicles entering the fleet.

Only regulating new vehicles entering the fleet has a limited impact if no requirements are adopted related to used vehicles entering the fleet, maintenance of the existing fleet, and fleet retirement. The largest gains—particularly pertaining to emissions reduction—tend to be achieved when old (over twenty-year old), non-roadworthy vehicles are removed from the fleet. In practice, this involves mandating vehicle standards but also setting in place a) periodic vehicle inspection and maintenance procedures—especially for high-usage diesel vehicles; b) incentives for scrapping; c) relevant technologies like diesel particle filters for $PM_{2.5}$ and selective catalytic reduction systems for nitrogen oxides. The most impactful approach for improving road safety is through simultaneously improving the standards of old vehicles in the existing fleet as well as used vehicle imports entering the fleet. For instance, in Kazakhstan, Ghana and Lao PDR, the safety benefits were 6, 15 and 35 times higher, respectively, if standards are mandated for imports and also for old vehicles in the existing fleet. For health benefits linked to air pollution, the most impactful policy is vehicle retirement—reductions of $PM_{2.5}$ and NO_x emissions can increase by an order of magnitude when retirement is added to vehicle standards.

Message 3: Trade policies that aim to lower vehicle users' costs by allowing lightly regulated used vehicle imports tend to backfire when considering the adverse health and productivity implications.

Perhaps the key motivation to allow the importation of used vehicles is to increase the supply of affordable vehicles and, with that, increase mobility and access to opportunities for populations in need. However, this report demonstrates that, unless carefully crafted, a trade policy allowing used vehicle importation can backfire, leading to non-complaint vehicles and outdated safety and emissions standards, as well as undermining technology diffusion.

In a broader context, it can also promote overconsumption of private vehicles, creating congestion for already over-stretched infrastructure, as well as lead to incentives for high-income countries to export rather than scrap their non-roadworthy vehicles.

Countries that rely on used vehicle imports would benefit from enforcing stricter mandates at entry and revamping inspection procedures. By implementing these measures across the fleet mix of light duty vehicles (LDVs), heavy duty vehicles (HDVs) and motorized two wheelers (MTWs), countries can reduce crash-related fatalities by up to nine percent. Including imported used vehicles in mandates also results in significant emissions reductions: up to 20 percent for $PM_{2.5}$ and up to 30 percent for NO_x. In Ghana, emissions reductions almost doubled for mandates covering both new and imported used vehicles relative to enforcement only applied to new vehicles.

Emerging and developing economies would benefit from the shift from age-based vehicle import restrictions to performance-based criteria that directly assess roadworthiness, safety features, and environmental compliance. Relying solely on vehicle age as a proxy for quality is an imprecise and often ineffective strategy (World Bank 2022). Implementation of harmonized standards would ideally be enforced by conducting inspections in both export and importing countries. New Zealand's two-stage import certification process, a potential model for emerging and developing economies, ensures that vehicle imports meet national safety and emissions standards before entering the fleet.

Message 4: Adoption of electric vehicles, while effective in achieving zero tailpipe emissions, only lead to modest health and air quality gains when no other reforms are implemented.

In countries with mandates for "Euro 4" (the European vehicle emissions standard that sets legal limits on the amount of pollutants that vehicles can emit, the fourth version of which was introduced in phases around 2005) and lower, the largest emissions savings come from leapfrogging to Euro 6—the standard introduced around 2015. Vehicle electrification leads to emission reduction gains significantly greater than mandating an incremental standard improvement to Euro 5 (the standard introduced around 2010), but not as high as moving to Euro 6. This is the case of Egypt, Ghana, Kazakhstan and Mexico. In countries with fleets of older, used vehicles, especially those without diesel particulate filters (DPFs) or selective catalytic reduction (SCR) systems, the impact of electric vehicle (EV) adoption alone is modest since air pollution remains high from the existing fleet. Older vehicles, particularly those using diesel, emit very high levels of $PM_{2.5}$, nitrogen oxides, sulfur oxide, and other pollutants. Without emission control technologies like DPFs or SCRs, their per-vehicle pollution is many times higher than newer vehicles.

The key challenge is that EVs typically enter the fleet as an addition to—rather than as a substitute of—non-roadworthy and non-compliant vehicles. Enforcing emissions standards through inspection and maintenance can quickly identify non-roadworthy vehicles and reduce emissions through the engine tuning, replacing worn-out components, retrofitting, and increasing the use of DPFs and SCRs.

Message 5: Vehicle electrification may contribute significantly to non-exhaust emissions and add to environmental challenges.

When focusing on tailpipe emissions—and particularly on greenhouse gas emissions—the cleanest vehicle technology is electrification. But even vehicle electrification as a tailpipe zero-emission technology has limited effects in addressing some critical air quality challenges. First, while beneficial in terms of reducing emissions of $PM_{2.5}$ and nitrogen oxides, EV uptake showed less impact in the short term compared to adoption of Euro 6 standards if not paired with the retirement of old vehicles and if vans and trucks were not included in the transition. Second, EVs are heavier than equivalent-sized internal combustion engine vehicles and therefore tend to emit more non-exhaust emissions. The heavier mass of EVs also makes these vehicles more dangerous for pedestrians and other non-motorized road users in traffic crashes.

In the analysis, these two factors resulted in significant reduction of nitrogen oxide emissions from increased vehicle electrification, yet relatively minor reductions in $PM_{2.5}$ emissions. Moreover, non-exhaust emissions from EVs include $PM_{2.5}$ and toxic heavy metals such as cadmium and lead from tire, brake, and road wear. Increased power plant electricity production for EVs also adds to $PM_{2.5}$, NO_x (incl. NO_2) and other emissions. Converting existing diesel-fueled vehicles to run on Compressed Natural Gas (CNG) or Liquefied Petroleum Gas (LPG), supported by investments in refueling infrastructure, could offer immediate air quality benefits, so decision makers could emphasize the roll-out of training programs for mechanics and technicians to ensure proper repair and maintenance.

Other environmental impacts of vehicle electrification could be addressed as part of, or at least in tandem with, motorization policies; for instance, by adding regulations for batteries and tire reuse and disposal. This is particularly pertinent for electrification of two- and three-wheelers with lead acid batteries (LABs). Informal recycling and inadequate disposal of used lead acid batteries (ULABs) are among the most significant sources of lead pollution globally. Exposure to lead is estimated to cause 5.5 million cardiovascular deaths and a loss of 765 million IQ points annually (Larsen and Sánchez-Triana 2023).

Message 6: The health and economic impacts from vehicle-related nitrogen dioxide emissions are particularly high in middle-income countries due to their motorization levels and rates.

Globally, deaths from road transport-generated NO_2—about 240,000 annually—are equivalent to 77 percent of the total premature deaths from road transport-generated $PM_{2.5}$, estimated at 311,000 per year, which makes NO_2 a health concern of roughly similar magnitude. But the level of ambient NO_2 relative to ambient $PM_{2.5}$ rises with country income level. Notably, deaths from road transport-generated NO_2 are increasingly salient in higher income economies. Road transport-related premature deaths from NO_2 are about 30-36 percent of road transport deaths from $PM_{2.5}$ in low- and lower-middle income countries, 84 percent in upper-middle income countries and close to 158 percent in high-income countries.

Regionally, premature deaths from transport NO_2 are particularly problematic in East Asia, equivalent to 80-90 percent of $PM_{2.5}$ related deaths. In Latin America and the Caribbean—in countries such as Argentina, Brazil and Mexico, for example—annual deaths from road transport-generated NO_2 are substantially higher than from road transport-generated $PM_{2.5}$, or equivalent to 136 percent. The global welfare cost of mortality from road transport-generated NO_2 was equivalent to 0.44 percent of global GDP in 2021. Combating NO_2 emissions is particularly important in countries with relatively moderate ambient $PM_{2.5}$ levels but rapid motorization rates.

Message 7: Incremental adoption of newer standards might not be cost effective. Countries should attempt to leapfrog as much as possible.

Early adoption of safety technology and emissions standards is the key to achieving greater air quality and health benefits over the coming decades. For every new safety standard, the beneficial returns are proportionally higher when the new standard is introduced globally and immediately mandated in a specific country. The additional benefit of a standard then tends to decrease over time with the inflow of imported used vehicles and a slower adoption of the new standard to the existing fleet when there is no mandate to do so. Similar patterns have been observed for passive safety crashworthiness features—as fleet renewal occurs over time, the average quality of vehicle safety performance typically improves to a certain degree without the influence of mandatory adoption of safety technology. For example, and per the study, Ghana, which does not mandate electronic stability control (ESC) technology for LDVs, may see increased ESC benefits through early adoption up to about year 2038, after which time the benefits are expected to be proportionally smaller as the overall fleet renews over time.

With respect to emissions, adopting Euro 6 offers significantly greater reductions in harmful emissions, particularly NO_2—compared to Euro 5. This leapfrogging strategy presents a powerful opportunity to maximize public health benefits, including reductions in premature mortality, morbidity, and cognitive impairments linked to vehicle-related air pollution. The benefits stemming from adopting Euro 6 as the emissions mandate, rather than investing in enforcing Euro 5, are many times higher. $PM_{2.5}$ reductions with Euro 6 are from 30 percent higher to 8 times higher than with Euro 5 adoption. Euro 6 gains for NO_2 reduction comes in even higher ratios vis-à-vis Euro 5; for example, spanning 3 times more beneficial in Kazakhstan and Lao PDR to 16 and 18 times more beneficial in Egypt and Ghana respectively.

If vehicle electrification is the path decided by a country, evidence supports that more aggressive strategies lead to greater health benefits. A scenario of 30 percent of new cars, buses, and minibuses, and 70 percent of new motorcycles, going electric by 2030 ("30X30") results in higher emissions reductions than an electrification scenario of 50 percent of new cars, buses, minibuses, motorcycles, and vans going electric by 2050 and 50 percent of new trucks going electric by 2055 (50x50). This observation holds across all countries analyzed under the study. Emissions control in the power sector is, however, important for vehicle electrification to yield maximum emissions reduction benefits.

Concluding Remarks: Reaping the health and productivity benefits of improved safety and emissions mandates requires comprehensive motorization management and multi-sectoral policies.

Addressing road transport's significant impacts on human capital calls for the adoption of comprehensive motorization management strategies. The modeling results show that policies focused on the entry of new and imported used vehicles to a country's vehicle stock can result in significant safety and emissions benefits. However, the benefits are significantly enhanced in most countries when older vehicles that do not comply with safety and air quality standards are retired from the fleet.

Motorization management is a structured, policy-driven approach designed to guide the growth and governance of a country's motor vehicle stock across its full life cycle—from vehicle entry to active use to end-of-life scrappage. This approach is accompanied by the adoption and enforcement of standards as well as periodic vehicle inspections as part of the vehicle life cycle process. Motorization management seeks to improve safety, environmental, and fuel efficiency outcomes by applying targeted regulations and institutional measures at each stage of a vehicle's life.

In emerging and developing economies with older vehicles and high importation rates of used vehicles, it is particularly important to focus on the existing fleet, regulation of imports, and scrapping policies, even though policy makers might be inclined to limit their focus to ambitious targets for new technology adoption at vehicle entry. A comprehensive motorization management approach would also prioritize the uptake of safety technology for commercial-use vehicles, which are often overlooked. Further, to raise the public demand in countries which lack robust regulatory framework, consumer awareness programs can be extremely effective.

Motorization management is also increasingly understood as a multi-sectoral agenda. Linkages with trade policies are evident from the analysis of this report. Coordinating with energy policies is critical given the role that vehicle fuel quality plays in emissions and vehicle well-functioning. Lowering the sulfur content in diesel from 2000 parts per million to 500 parts per million alone can reduce $PM_{2.5}$ emissions by at least 20 percent. Designing fuel standards in tandem with vehicle emissions standards is essential to achieve the desired reductions in pollutant emissions.

Many emerging and developing economies have already implemented diesel sulfur standards based on international frameworks, and these countries could be supported to limit sulfur content to 10 parts per million required for achieving Euro 5 and Euro 6 emission standards.

Policies developed using an avoid, shift, improve (ASI) framework can lead to significant reductions of vehicle emissions and risks of traffic crashes, as well as incentivize consumers to avoid purchasing private vehicles altogether. Similarly, the introduction of bus rapid transit systems has shifted many former private vehicle users to public transport, thereby reducing emissions and contributing positively to the urban environment. Air quality can be improved through urban planning policies that establish low emission zones (LEZs) or ultra-low emission zones (ULEZs) in urban areas where the entry of older and diesel-driven vehicles is restricted or prohibited. This encourages vehicle owners to upgrade to cleaner alternatives to access these areas.

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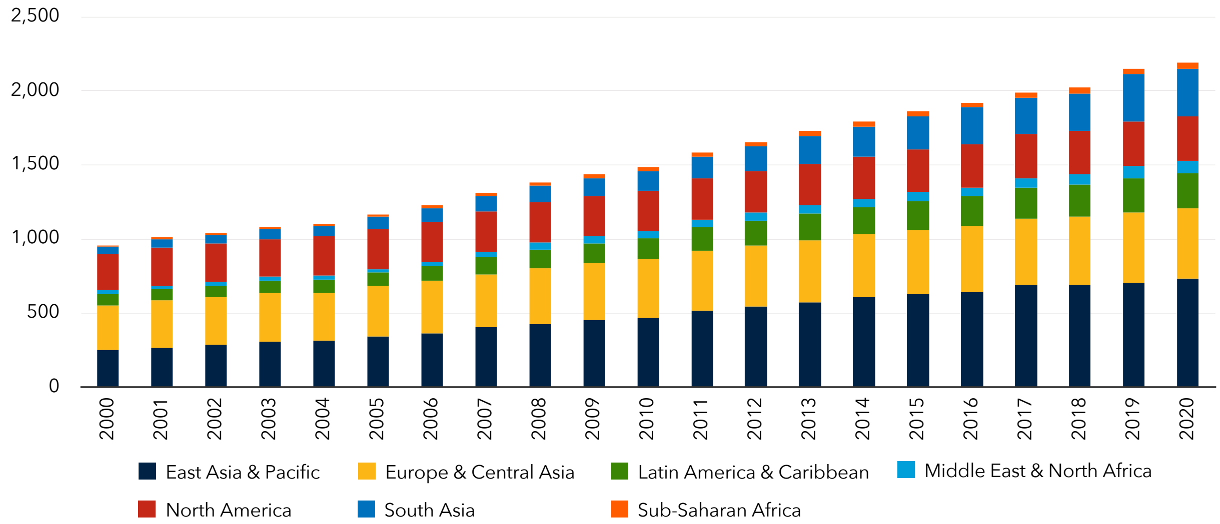
Introduction

Background

Motorization in road transport links closely to economic and population growth, particularly in emerging and developing economies. Vehicle growth rates in emerging and developing economies could reach up to 10 percent annually in certain regions, potentially doubling the global vehicle fleet by 2050 (EIA 2021) currently estimated at between 1.6 and 2.2 billion vehicles. The increase in motorized road transport offers significant opportunities, including greater access to economic opportunities, services, and social activities. However, it also brings significant health-related challenges. Road crashes and air pollution from road motor vehicles result in millions of premature deaths, injuries, and illnesses. Addressing these issues is essential to harness the growth of motor road vehicles and ensure that their benefits significantly outweigh their costs.

The adoption and use of motor vehicles worldwide have grown substantially over the last two decades. The World Road Statistics estimates that the global population of 960 million vehicles in use in the year 2000 increased steadily to 2.2 billion in 2020 at an average growth rate of 4.2 percent per year. In 2020, North America had a median motorization rate of 623 motor vehicles per 1,000 persons, compared with just over 40 in Sub-Saharan Africa. East Asia and the Pacific experienced the largest increase in vehicles during this period, from 254 million in 2000 to 730 million in 2020. Vehicle numbers increased at a rate of 9.8 percent per year in South Asia, the highest rate globally, leading to an increase of 271 million vehicles (6.5 times) within the same period (World Road Statistics 2022). This growth has regional disparities (figure I.1) but is spurred by high motorization rate in emerging and developing economies. Globally, passenger cars, vans, and pickups account for about 73 percent of all in-use vehicles, while motorcycles and other two-wheelers account for an additional 23 percent. Only about four percent of the worldwide vehicle stock are trucks (World Bank 2022).

Figure I.1 Number of four wheelers and motorcycles in use by region, 2000-2020 (millions)



Source: Author's rendition using data from World Road Statistics.

Most emerging and developing economies have limited domestic vehicle manufacturing capabilities and rely on imports to address demand for vehicle stock. For many emerging and developing economies, these imports are primarily used vehicles that have been previously used in other geographic jurisdictions. In fewer emerging and developing economies, imported used vehicles are banned and demand is met through locally manufactured or assembled vehicles or importation of new vehicles. Estimates indicate that by 2022, approximately 70 percent of emerging and developing economies imported more used vehicles than new ones in 2018, and 58 percent imported more than three times as many used vehicles as new ones (World Bank 2022).

New and imported used vehicles in developing countries are of lower quality than those manufactured in high-income countries, members of the Organisation for Economic Co-operation and Development (OECD). In most emerging and developing economies, most vehicles are imported used vehicles that have been previously used in other geographic jurisdictions. A large share of the used vehicles traded does not meet globally accepted road safety and air quality standards and is a major contributor to crashes and air pollution. Imported used vehicles into emerging and developing economies are also likely to be equipped with outdated safety and emissions technology relative to the most stringent levels in high income OECD countries (UNEP 2020).

Importance of vehicle safety standards in emerging and developing economies

Road traffic injuries are a leading cause of death and disability worldwide, disproportionately affecting emerging and developing economies. According to the World Health Organization (2023), approximately 1.19 million people died in 2021 from road crashes, with more than 90 percent of these fatalities occurring in emerging and developing economies, despite these countries owning only about 60 percent of the world's motor vehicles. A major contributing factor is the lack of effective vehicle safety standards and regulatory enforcement in these regions (WHO 2023).

Vehicle safety standards are crucial for reducing crash risks and minimizing injury severity. These standards include crashworthiness—ensuring vehicle design protects occupants—and crash avoidance technologies like antilock braking systems (ABS), electronic stability control (ESC), and seatbelt reminders. In high income countries, such standards are mandated by law and strictly enforced, accompanied by strong consumer awareness programs. However, in emerging and developing economies, many vehicles lack these vital safety features, creating a safety disparity.

Despite global recognition of vehicle safety, progress in emerging and developing economies has been inconsistent. The UN Decade of Action for Road Safety 2021–2030 prioritizes safer vehicles, and initiatives like the Safer Cars for India campaign have driven some policy and awareness improvements. For example, India mandated driver airbags in all new vehicles in 2019, followed by requirements for ABS and front passenger airbags. Similar advances have occurred in Latin America, with countries like Brazil and Argentina mandating ESC in new models, following the Latin New Car Assessment Program (NCAP) recommendations.

Nevertheless, these advancements are isolated and insufficient. Many emerging and developing economies still do not mandate minimum crashworthiness standards or advanced safety technologies. Outdated regulatory frameworks, weak enforcement, and financial constraints hinder progress. In some cases, political and commercial interests further delay stricter regulations.

However, vehicle safety improvements have occurred due to global advancements in original equipment manufacturer (OEM) technology. Over the past two decades, OEMs have made significant strides in enhancing vehicle safety, driven by innovation, competitive pressures, and regulatory requirements in high income countries. These advances include stronger vehicle structures, crumple zones, advanced airbag systems, ESC, and collision avoidance technologies. As global production platforms become more harmonized and manufacturing costs decrease, many safety technologies have been incorporated into vehicle models sold across diverse markets, including emerging and developing economies. However, without formal regulatory frameworks, the adoption of such features remains inconsistent and market dependent, rather than a guaranteed baseline of protection for all vehicles.

A complicating factor is the widespread importation of used vehicles into emerging and developing economies, many of which do not meet modern safety standards. The United Nations Environment Programme (UNEP) reported that between 2015 and 2018, more than 14 million used vehicles were exported from Europe, Japan, and the United States to emerging and developing economies, particularly in Africa and Southeast Asia. Many of these vehicles lack essential safety features and are not subject to adequate pre-export inspection (UNEP 2020). Without comprehensive national regulations or import controls, these vehicles exacerbate existing safety challenges.

The absence of effective vehicle safety regulations is costly from a public health and economic perspective. Road traffic injuries can result in welfare costs equivalent to between three and five percent of countries' annual GDP due to lost productivity, healthcare costs, and social impacts (WHO 2023). A United Nations Economic Commission for Europe (UNECE) case study analysis found that effective regulations significantly reduced road fatalities and injuries, particularly in emerging and developing economies (UNECE 2021). These findings underscore that vehicle safety is a technical issue and a strategic investment in sustainable development.

A critical barrier to policy adoption in many emerging and developing economies is the limited availability of localized data quantifying the economic benefits of adopting vehicle safety technologies. While global studies have demonstrated the cost effectiveness of interventions such as ESC, airbags, and seatbelt reminders, a lack of disaggregated data remains at the national or regional level in many developing countries. This evidence gap makes it difficult for policy makers to conduct comprehensive cost-benefit analyses or justify safety regulations against competing development priorities. Moreover, the indirect societal and economic costs of road trauma—such as long-term disability, loss of family income, and strain on public health systems—are often underreported or excluded from national planning tools. Developing robust methodologies to estimate these impacts, supported by real-world data from health, insurance, and transport sectors, are essential to strengthen policy case for vehicle safety standards and investments in safer technologies.

Air pollution emissions from road vehicles in emerging and developing economies

The transport sector is a major source of air pollution, contributing significantly to particulate matter ($PM_{2.5}$) and nitrogen oxides—including nitrogen dioxide and nitric oxide—in the atmosphere. These pollutants are harmful to human health and the environment.

Air pollution caused an estimated 8.1 million premature deaths in 2021, 95 percent in emerging and developing economies (IHME 2024). While several air pollutants are harmful, fine particulate matter or $PM_{2.5}$ is responsible for the majority of these impacts. $PM_{2.5}$ can penetrate deep into the respiratory system and cause multiple diseases, including ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, pneumonia, type 2 diabetes, and neonatal disorders (World Bank 2025). In 2021, The burden of morbidity from $PM_{2.5}$ exposure was equivalent to 105 billion days lived with disease (IHME 2024). Scientific evidence has also found that exposure to $PM_{2.5}$ during pregnancy and early childhood can lead to impaired cognitive development (Alter et al. 2024)

$PM_{2.5}$ in the atmosphere originates from various sources, notably fossil fuel combustion processes (e.g., vehicles, coal and oil-powered power plants and industry, and the burning of biomass). Trace constituents from $PM_{2.5}$ and $PM_{2.5}$ mass from fossil fuel combustion are among the greatest contributors to PM toxicity. Of the fossil fuel combustion particles, the health risks associated with $PM_{2.5}$ from road transport traffic are particularly significant. Long- and short-term exposures to particles from both sources are most consistently associated with cardiovascular mortality, especially ischemic heart disease. Several epidemiological and toxicological studies indicate that sulfate or particulate sulfur is among the most, if not the most, important constituents of $PM_{2.5}$ associated with adverse health effects such as additional hospital admissions and mortality. With respect to traffic-related sources, chemical species in the $PM_{2.5}$ emissions from diesel-fueled vehicles are particularly associated with adverse human health impacts (The World Bank 2021; Thurston et al. 2021; Thurston et al. 2024). Nitrogen dioxide (NO_2) is another harmful air pollutant. Exposure to NO_2) causes premature deaths and illnesses such as asthma in children and adults, and lower respiratory infections in children. Nitrogen emissions also contribute to secondary particles that is particulate matter formed from gaseous pollutants through chemical reactions in the atmosphere. They form from nitrogen oxides and ammonia (Anenberg 2022; Chakraborty 2020; Cooper 2022; Gu 2023).

Air pollution has broad social and economic consequences. The WHO estimates that 99 percent of the global population breathes harmful concentrations of air pollutants. Increased illnesses and hampered cognitive development increase health expenditures, affect human capital, and reduce workers' productivity, resulting in lost earnings. These effects thwart economic growth in individual emerging and developing economies and globally (Dechezleprêtre et.al. 2020; Dong et al. 2021; Mujtaba and Shahzad 2020).

Motorized road transport is a major source of ambient air pollution globally. Urban areas are particularly affected by transport-related air pollution due to high vehicle density and traffic congestion. Fossil fuel-powered vehicles release $PM_{2.5}$, nitrogen oxides, and many other harmful pollutants through exhaust emissions (World Bank 2025). Additionally, vehicles emit non-exhaust emissions from tires, brakes, and road dust suspension (HEI 2022). Motorized road vehicles account for approximately 6.7 percent of population-weighted ambient $PM_{2.5}$ globally, ranging from about three percent in low income countries to 6.9 percent in upper middle income countries (McDuffie et al. 2021a,b). NO_2emissions from road transport are estimated to account for 26 percent of global NO_2 emissions. Road transport contributes about 34 percent of total nitrogen dioxide emissions in upper middle income countries and low income countries, compared with 12 percent in low income countries (Duffie et al. 2020 a,b).

Policy makers have used several tools to limit road motor vehicles' pollutant emissions. These include emission standards that set quantitative limits on the permissible amount of specific air pollutants that may be released, including $PM_{2.5}$ and nitrogen oxides. Mandatory vehicle inspection and maintenance programs help monitor vehicles' emissions and the condition of emission control systems, ensuring that vehicles meet existing emission standards. The design and implementation of air quality management policies in the transport sector contributed to reducing air pollution in high income OECD countries and many middle income countries such as China, Chile, Mexico, and Peru (World Bank 2025).

Objective

This report aims to strengthen the evidence base for tackling the health effects of road transport as a key element of the human capital agenda, particularly across emerging and developing economies. It presents the findings of analytical work conducted to assess the health and economic effects of increased road transport motorization. It also provides evidence-based recommendations to inform the design and implementation of policies that emerging and developing economies can adopt to enhance the safety and environmental performance of road vehicles.

Approach

The report presents findings of innovative research and modeling conducted to estimate the benefits of adopting alternative policies to improve safety and environmental performance of road transport. Drawing from economics, epidemiology, engineering, and other disciplines, the report estimates the number and societal costs of fatalities and injuries caused by crashes, and of increased mortality, morbidity and impairment of children's cognitive development caused by road vehicles' pollutant emissions.

The approach includes state-of-the-art economic analyses to estimate the costs of increased mortality and serious injuries from crashes, increased mortality and morbidity from air pollution, and innovative modeling to estimate the impacts of $PM_{2.5}$ pollution from road vehicles on children's cognitive development. The cost of health effects from road traffic crashes and vehicle air pollution is estimated by a welfare measure of mortality and serious injuries, productivity cost of morbidity, and lifetime income losses from IQ impairments. The welfare measure of mortality is country-specific values of statistical life (VSL) that reflect people's willingness-to-pay (WTP) to reduce the risk of death. The welfare cost of serious injuries is estimated as a fraction, or 25 percent, of VSL. The productivity cost of morbidity is estimated as a fraction of daily wages per day lived with illness of varying degrees of disability. The cost of IQ impairments is estimated based on a loss of lifetime income or economic productivity per IQ point.

The analytical work also developed a spreadsheet-based model designed to assess simultaneously the effects of key socioeconomic trends on the composition of a country's vehicle fleet and the associated safety and air pollution implications. The model forecasted the effects of alternative policy scenarios in eight countries: Argentina, Brazil, Egypt, Ghana, India, Kazakhstan, Lao PDR and Mexico. These countries were selected for their geographic diversity, varying income levels and motorization characteristics, and the availability of quality data on motorization management. These criteria ensured that the model could be effectively used to generate insights relevant across diverse contexts.

This report assesses road safety and air quality impacts from different vehicle classes—that is, MTWs, LDVs, and HDVs—and analyzes vehicle crash and air pollution effects for these eight countries Additionally, estimates of the effects of $PM_{2.5}$ exposure on young children's cognitive development and the health burden caused by nitrogen dioxide exposure are presented in this report for the first time, incorporating recent scientific evidence.

Structure of the report

The report has four chapters in addition to this overview. Chapter 1 discusses the global cost of road transport crashes and air pollution. It estimates the number of people that die and suffer non-fatal injuries every year due to road traffic crashes. It quantifies the premature mortality and morbidity caused by exposure to two harmful air pollutants emitted by road motorized vehicles: $PM_{2.5}$ and NO_2. Chapter 1 also estimates the monetary value of the health effects of road transport. The evidence presented in the chapter builds a strong case for the need to address the safety and environmental risks associated with road transport as part of the human capital agenda in emerging and developing economies.

Chapter 2 provides an overview of the adoption of vehicle standards impacting safety and air pollution outcomes globally and in emerging and developing economies. It also highlights the need for an improved understanding of the contributions of internationally recognized standards to reduce fatalities and serious injuries and air pollution from road motor vehicles. It also introduces a simple and stylized model to estimate the impact of adopting alternative motorization management policies that simultaneously address vehicle crash safety and air pollution in eight selected emerging and developing economies. The model has been developed to assess the contribution of alternative standards to prevent and mitigate the significant number of preventable deaths, injuries, illnesses, and IQ losses, and the associated costs, caused by road motor transport.

Chapter 3 assesses the safety and emissions-related impacts of motorized road transport in the eight select countries to set the stage to apply the proposed model at the country level. The assessment's findings underscore the need to identify evidence-based policies to mitigate these risks, designed to address country specific conditions, such as the vehicle fleet's composition by age and types of vehicles, existing policies influencing the fleet's composition, and existing requirements for safety and emissions control technologies. The proof-of-concept of the model uses data from the eight selected emerging and developing economies to illustrate how the effects of alternative policies lead to different results, depending on factors such as fleet composition, the existing safety and emission standards, and policies related to the import of used vehicles. The findings presented in the chapter identify policies that result in improved outcomes across the eight countries, as well as the varying impacts of different technologies that are influenced by the characteristics of each country's vehicle fleet. The findings highlight how policies must be developed based on a life-of-vehicle approach, including specific interventions when vehicles enter the fleet, while they are in use and when they exit the fleet.

Chapter 4 provides policy recommendations to improve road vehicle safety and air quality performance in emerging and developing economies. Building on the analysis of the model's results, it provides evidence-based recommendations to realize the social and economic benefits of adopting available technologies and standards for road vehicles, based on a life-of-vehicle approach. The recommendations highlight opportunities to build synergies by designing and implementing policies aimed at simultaneously reducing fatalities and serious injuries, and those designed to reduce air pollution. The recommendations prioritize the policy options that would result in the most significant benefits in the medium to long term. While the analysis focused on eight countries, the recommendations present policy options that other emerging and developing economies might assess to reduce the significant costs caused by motorized road transport, including negative health effects and the associated impacts on human capital, productivity, and well-being.

Notes

1. For the purpose of this document, emerging and developing economies include, from the World Bank country income classifications of countries LI = low income, LMI=lower middle income, UMI=upper middle income. In other contexts, it is also referred as the Global South.

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Chapter 1. Health Impacts of Motorized Road Transport

Motorization in road transport is commonly correlated with increased economic and population growth and its rate of growth can only be expected to increase as emerging and developing economies advance. Vehicle growth rates in emerging and developing economies could reach up to 10 percent annually in certain regions, potentially doubling the global vehicle fleet (EIA 2021) from the prevailing 1.6–2.0 billion by 2050. The increase in motorized road transport offers significant opportunities, including greater access to economic opportunities, services, and social activities, However, the quality and quantity of a country's motor vehicle stock fundamentally influence the unintended risks posed by road transport, including road crashes and air pollution.

This chapter addresses questions about the depth of the human capital problem of poor vehicle standards and the opportunity cost of not assuming motorization management as a centerpiece of a health agenda.

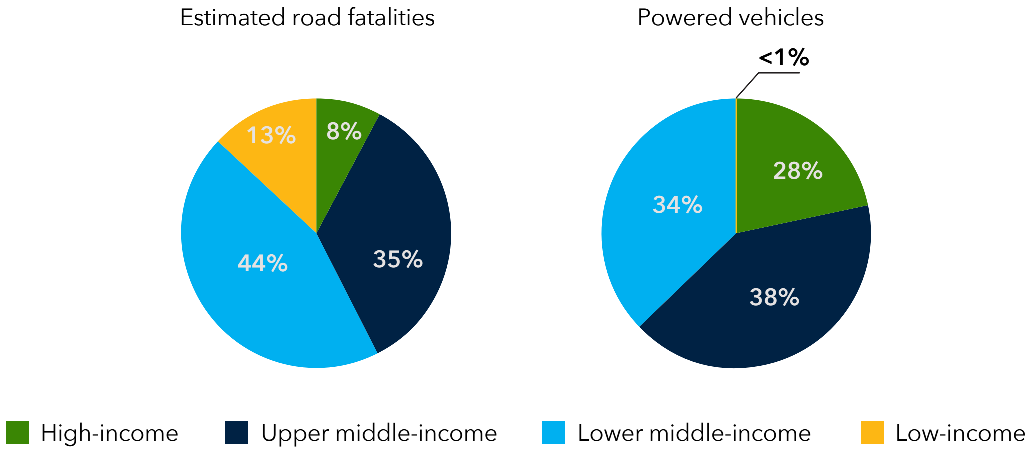
1.1 Health impact of key risks from motorized road transport

Deaths from road transport exceed those from HIV, tuberculosis, or malaria. Injuries and pollution from road vehicles contribute to six of the top 10 causes of death globally. Annually, approximately 1.19 million lives are lost in road traffic crashes (WHO 2023). Additionally, around 50 million more people suffer non-fatal injuries, with many incurring a disability because of their injury. Global air pollution—to which road transport is a key contributor — was responsible for 8.1 million premature deaths in 2021 (IHME 2024) equivalent to approximately 14 percent of all non-COVID19 deaths that year. An estimated 311,0000 premature deaths can be attributed to $PM_{2.5}$ air pollution linked to road transport and 240,000 premature deaths to NO_2 air pollution from road vehicles.

Fatalities and serious injuries because of vehicle crashes

The burden of road traffic deaths is also disproportionately high in countries with lower incomes, relative to the number of vehicles in circulation. Low income, lower middle income and upper middle income countries together account for 73 percent of the global vehicle population but suffer close to 92 percent of road traffic deaths (figure 1.1). Low-income countries have one percent of the world's motor vehicles but comprise 13 percent of global road deaths. On the other hand, high income countries account for 28 percent of the global fleet and not even eight percent of global fatalities.

Figure 1.1 Road traffic deaths in emerging and developing economies by income, in shares of totals



Source: WHO Global Status Report 2023.

Air pollution from road transport

Motorized transport is a principal source of harmful air pollutants such as primary and secondary fine particulate matter($PM_{2.5}$), nitrogen dioxide (NO_2), and precursors of ground level ozone. The mechanism through which these pollutants impact health and enter the environment varies greatly.

Fine particles smaller than 2.5 microns, best known as $PM_{2.5}$, can penetrate deep into the respiratory system, causing diseases such as stroke, ischemic heart disease (IHD), and chronic obstructive pulmonary disease (COPD). Exposure to $PM_{2.5}$ also causes a large burden of morbidity, measured by the global burden of disease (GBD) as years lived with disability (YLDs). Days lived with type 2 diabetes, COPD, stroke, cataract, and IHD account for nearly 4 billion or 99 percent of the days lived with illness from exposure to road transport $PM_{2.5}$.

Recent research documents that, besides increases in morbidity, exposure to $PM_{2.5}$ during prenatal development and early childhood impairs children's cognitive development, which can be measured by declines in their IQ. This impact is particularly concerning given the long-term consequences of reduced cognitive ability on individual productivity and societal well-being (box 1.1).

Ambient $PM_{2.5}$ originates from all types of combustion, including motor vehicles, household use of solid fuels for cooking and other purposes, solid waste burning, burning of agricultural residues, use of nitrogen-based fertilizers power plants, road and construction dust, forest fires, and some industrial processes. Motorized road transport is a significant source of ambient $PM_{2.5}$ via tailpipe emissions, evaporative emissions, resuspension of road dust, particles from brake and tire wear.

Globally, motorized road vehicles account for approximately seven percent of population-weighted ambient $PM_{2.5}$ –or the equivalent of 2.75 µg/m3 of annual $PM_{2.5}$. They are estimated to cause about 311,000 premature deaths per year and a loss of 64 million IQ points. HDVs are responsible for more than half of $PM_{2.5}$ emissions from road transport.

While correlated with traffic density and activity levels, ambient $PM_{2.5}$ from road transport is influenced by structural factors such as fuel quality, fuel type, vehicle and engine types, and emission control technologies. Fuel quality standards play a critical role, as sulfur concentrations in fuels exceeding 10 parts per million degrade the performance of Euro 5/V and Euro 6/VI compliant technologies. This impairs the effectiveness of DPFs and SCRs, which control

Box 1.1 Cognitive impacts of ambient $PM_{2.5}$

A recent meta-analysis shows a linear relationship between ambient $PM_{2.5}$ exposure and IQ decline, with higher exposure levels associated with greater IQ loss. IQ declines linearly by 0.27 points per $\mu g/m^3$ increase in prenatal or early childhood exposure to ambient $PM_{2.5}$ (Alter et al. 2024). Further analysis and inclusion of additional outcomes from studies of $PM_{2.5}$ exposure and IQ may suggest that the decline in IQ is as large as 0.69 IQ points per µg/m3 increase in $PM_{2.5}$ for $PM_{2.5}$ exposures below 11 $\mu g/m^3$ and 0.31 IQ points for exposures above 11 $\mu g/m^3$. This implies an IQ loss of 10 points at an exposure of 30 $\mu g/m^3$ of $PM_{2.5}$. To be conservative, one may assume there is no additional IQ loss above this exposure level.

Applying these $PM_{2.5}$ – IQ loss relationships to ambient $PM_{2.5}$ globally suggests an average loss of 8.4 IQ points per child from ambient $PM_{2.5}$ exposure. This amounts to a global loss of 1.1 billion IQ points among children in 2021. The estimate is nearly 50 percent greater than the estimated losses of 765 million IQ points from lead exposure in 2019 (Larsen and Sanchez-Triana 2023).

As many as 96 percent of the IQ losses from $PM_{2.5}$ exposure occurred in emerging and developing economies, including 62 percent of losses in South Asia and Sub-Saharan Africa. Average IQ losses ranged from 3.3 points in high income OECD countries to 9.2 points in lower middle income countries. Regionally, the average IQ loss per child ranges from 5.4 points in LAC to 10 points in South Asia region. These losses result from multiyear exposure to ambient $PM_{2.5}$

For technical details on the analysis see Appendix D.

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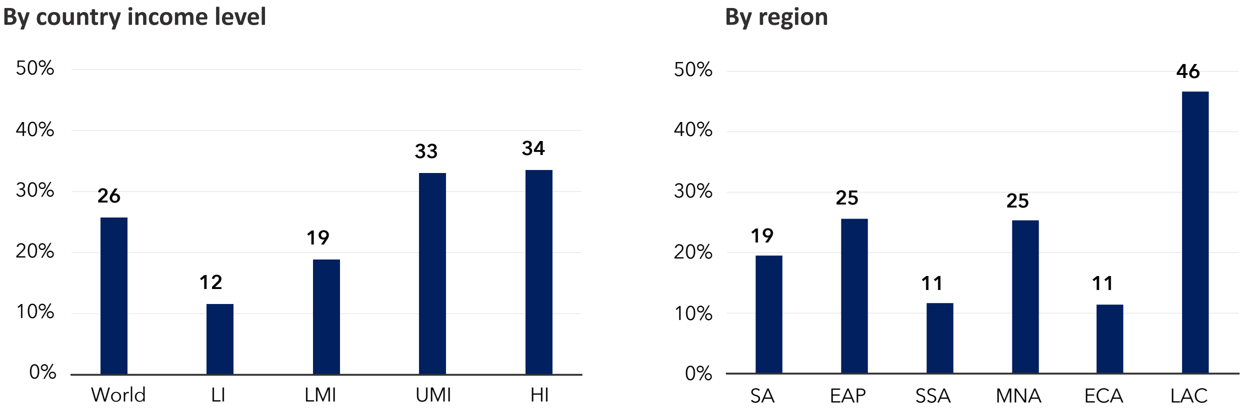
$PM_{2.5}$ and nitrogen oxides emissions. Sulfur oxides and nitrogen oxide emissions from vehicles contribute to the formation of secondary $PM_{2.5}$. When sulfur in fuel combusts, it forms sulfur dioxide and small amounts of sulfur trioxide. The incomplete combustion of fuels at high temperatures inside engines contributes to the reaction of nitrogen and oxygen from the air to form nitrogen oxides and nitrogen dioxide, collectively called nitrogen oxides.

Long-term exposure to ambient NO_2 has significant mortality effects. Additional health effects of nitrogen dioxide include asthma in children and adults, and lower respiratory infections in children. In 2019, the global population-weighted concentration of NO_2 was 14.6 micrograms per cubic meter, which is 46 percent higher than the WHO annual air quality guideline (AQG) of 10 micrograms per cubic meter. In 2021, global premature deaths attributable to ambient NO_2 exposure exceeding the WHO annual AQG are estimated at 943,000. Of these, 77 percent, or 726,000 deaths, are from cardiovascular disease (CVD), 14 percent from respiratory disease, and nine percent from lung cancer.

In 2017, about 26 percent of global NO_2 emissions come from road transport (Duffie et al. 2020 a,b).[1] These emissions rise steeply from 12 percent of total NO_2 emissions in low-income countries to about 34 percent in upper-middle income and high-income countries (figure 1.2). Per capita NO_2 emissions from road transport rose from 0.4 kilograms in low income countries to 7.1 kilograms in high income countries. Regionally, in emerging and developing economies, NO_2 emissions from road transport as a share of total NO_2 emissions are by far highest in LAC and lowest in SSA and ECA (figure 1.2). However, per capita NO_2 emissions from road transport are highest in ECA at 11.5 kilograms, followed by EAP, MNA and LAC from five to 6.8 kilograms.

Figure 1.2 Proportion of total NO_2 emissions generated by road transport



Notes: LI=Low income; LMI=Lower middle income; UMI=upper middle income; HI=high income. SA=South Asia; EAP=East Asia and Pacific; SSA=Sub-Saharan Africa; MNA=Middle East and North Africa; ECA=Europe and Central Asia; LAC=Latin America and Caribbean.

Source: Authors' derivation with data from McDuffie et al. 2020b.

Annual premature deaths from road transport NO_2 emissions are estimated at 240,000 in 2021.[2] Seventy-seven percent of the deaths are in emerging and developing economies, and 60 percent of these deaths are in EAP. As a percent of GDP, the cost of road transport NO_2 increased markedly with country income level, ranging from 0.01 percent in low income countries to 0.54 percent in upper middle income countries, and then declined to 0.43 percent in high income countries. This pattern is observed because ambient NO_2 relative to ambient $PM_{2.5}$ from road transport rises with income. In LAC, such as in Argentina, Brazil and Mexico, annual deaths from road transport NO_2 are substantially higher than from road transport $PM_{2.5}$. Thus, combating NO_2 emissions is particularly important in countries with relatively moderate ambient $PM_{2.5}$ but rapid motorization of road transport.

The health impacts and cost of nitrogen-based emissions from road transport go beyond the impacts of NO_2. Nitrogen oxides emissions form into secondary $PM_{2.5}$ in the atmosphere. A large study of 40 countries in Europe estimated that nitrogen oxide emissions from road transport contributed 10 percent of all $PM_{2.5}$ deaths to as much as 66 percent of transport-related $PM_{2.5}$ deaths (Gu et al. 2023).

In summary, road crashes and pollution-related illnesses and mortality are silent pandemics (table 1.1). Road crashes seem to disproportionately affect low income countries and vulnerable populations. $PM_{2.5}$ and NO_2 from road transport disproportionately affect middle income countries, and NO_2 especially a upper middle income countries. As a way of example, the death toll of ambient $PM_{2.5}$ and NO_2 from motorized road transport is, respectively, eight and eighteen times higher in middle income countries than in low income countries, being as well the third leading risk factor for death among children under five in year 2021 after malnutrition and low birthweight or short gestation (IHME 2024). Meanwhile, the average crash fatality rate in low income countries is 27.5 deaths per 100,000 population, more than three times higher than the 8.3 deaths per 100,000 population in middle income countries (table 1.1). Based on the age distribution of all-cause mortality, crashes are the leading cause of death for children and young people aged 5–29 years (WHO, 2023).

Table 1.1 Lives lost due to road traffic crashes and air pollution from motorized road transport, 2019 (deaths/100,000 pop.)

	Low Income Countries	Middle Income Countries
Road Crashes (*)	27.5	8.3
Ambient $PM_{2.5}$ (**)	0.55	4.60
Ambient NO_2 (***)	0.17	3.10

Sources: (*) WHO (2023), (**) Authors estimates based on Global Burden of Disease (GBD) data(HEI 2024) and McDuffie et al. 2021a,b. (***) Authors estimates based on GBD data and McDuffie et al. 2020a,b.

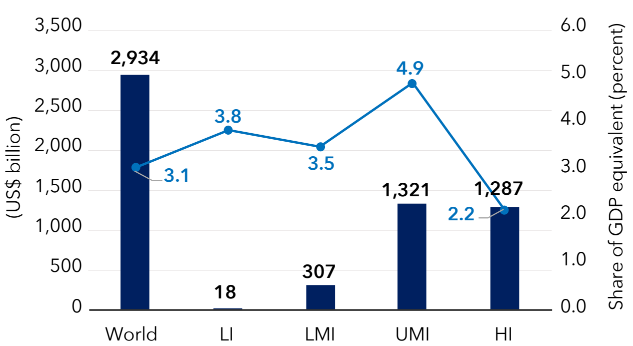
Comparing NO_2 and $PM_{2.5}$, the ratio of road transport deaths from NO_2 to road transport deaths from $PM_{2.5}$ rises from 0.3 to 0.36 in low income and lower middle income countries to 0.84 in upper middle income countries and 1.58 in high income countries. Regionally, in emerging and developing economies, the ratio is 0.39-0.42 in SA and MNA; 0.77-0.89 in EAP and ECA; and as high as 1.36 in LAC. This pattern is observed because ambient NO_2 relative to ambient $PM_{2.5}$ from road transport rises with income. In LAC, such as in Argentina, Brazil and Mexico, annual deaths from road transport nitrogen dioxide are substantially higher than from road transport $PM_{2.5}$. Thus, combating NO_2 emissions is particularly important in countries with relatively moderate ambient $PM_{2.5}$ but rapid motorization of road transport.

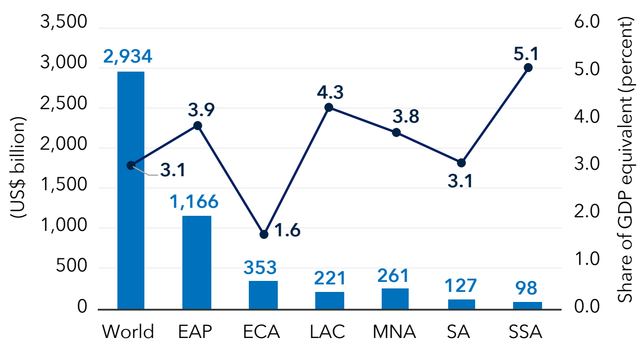
1.2 The economic cost of motorized road transport

This report estimates that the annual cost of deaths and serious injuries caused by road traffic crashes amounts to about $2.9 trillion while mortality and morbidity from $PM_{2.5}$ from road transport is estimated at $385 billion per year. Productivity losses due to cognitive impairment from $PM_{2.5}$ emissions from road transport is $157 billion. The cost from road transport is 7.7 percent of the cost of total ambient $PM_{2.5}$. The global welfare cost of mortality from NO_2 from road transport is estimated at $420 billion.[3] In 2021, the global cost of annual IQ losses totaled $2 trillion, which represents the present value of the associated lifetime income losses and is equivalent to 2.1 percent of global GDP (box 1.2).

Aggregates mask significant income and regional disparities. Emerging and developing economies altogether account for $1.6 trillion or 55 percent of the aggregate economic cost for road crashes. By region, these costs range from $98 billion in Sub-Saharan Africa to $1.16 trillion in East Asia and the Pacific (figure 1.3). The economic toll of road transport fatalities and injuries translates to 3.0 percent of the global GDP, with upper middle income countries amounting to a staggering 4.9 percent of their GDP (figure 1.3).

Figure 1.3 Annual cost of road traffic crashes including fatalities and serious injuries as 2021





Notes: LI=Low income; LMI=Lower middle income; UMI=upper middle income; HI=high income. SA=South Asia; EAP=East Asia and Pacific; SSA=Sub-Saharan Africa; MNA=Middle East and North Africa; ECA=Europe and Central Asia; LAC=Latin America and Caribbean.

Source: Authors' estimates, based on GBD 2021 data.

Box 1.2. Estimating the economic cost of car crashes and air pollution (or the economic benefits of preventing mortality and morbidity)

The economic cost of premature deaths, injuries, days of illness, and impaired cognitive development in children caused by road traffic crashes and air pollution is estimated using a value of statistical life (VSL) approach for mortality; cost of illness approach for morbidity; and a lost productivity approach for cognitive losses.

The VSL is a welfare metric that reflects people's willingness to pay for a reduction in risk of death. VSL is used to quantify the cost of mortality, or benefit of reducing the risk of death, primarily in cost–benefit analyses of public policies related to health, environment, and transport safety. This approach allows policy makers to evaluate the economic justification for safety and pollution control interventions by comparing the cost of the intervention with the value of the mortality risk reduction it achieves.

The avoidable cost for each fatality for traffic crashes is assumed to be equivalent to the VSL estimated for each year of analysis from 2025 to 2050 based on the emerging and developing economies model described in Wijnen et al., 2025. VSL for each study country was calculated with 2020 prices. The cost of serious injury avoided is assumed to be a quarter of the VSL value for that year based on McMahon and Dahdah, 2008. The cumulative economic benefit of FSI saved over 2025 to 2050 is calculated in its present value (PV).

Country specific VSLs are also applied to estimate the cost of mortality from air pollution (Sanchez-Triana et al, 2021; World Bank 2022). The cost of IQ impairments is estimated based on a loss of two percent of lifetime income per IQ point (Appendix D, Larsen and Sanchez-Triana 2023).

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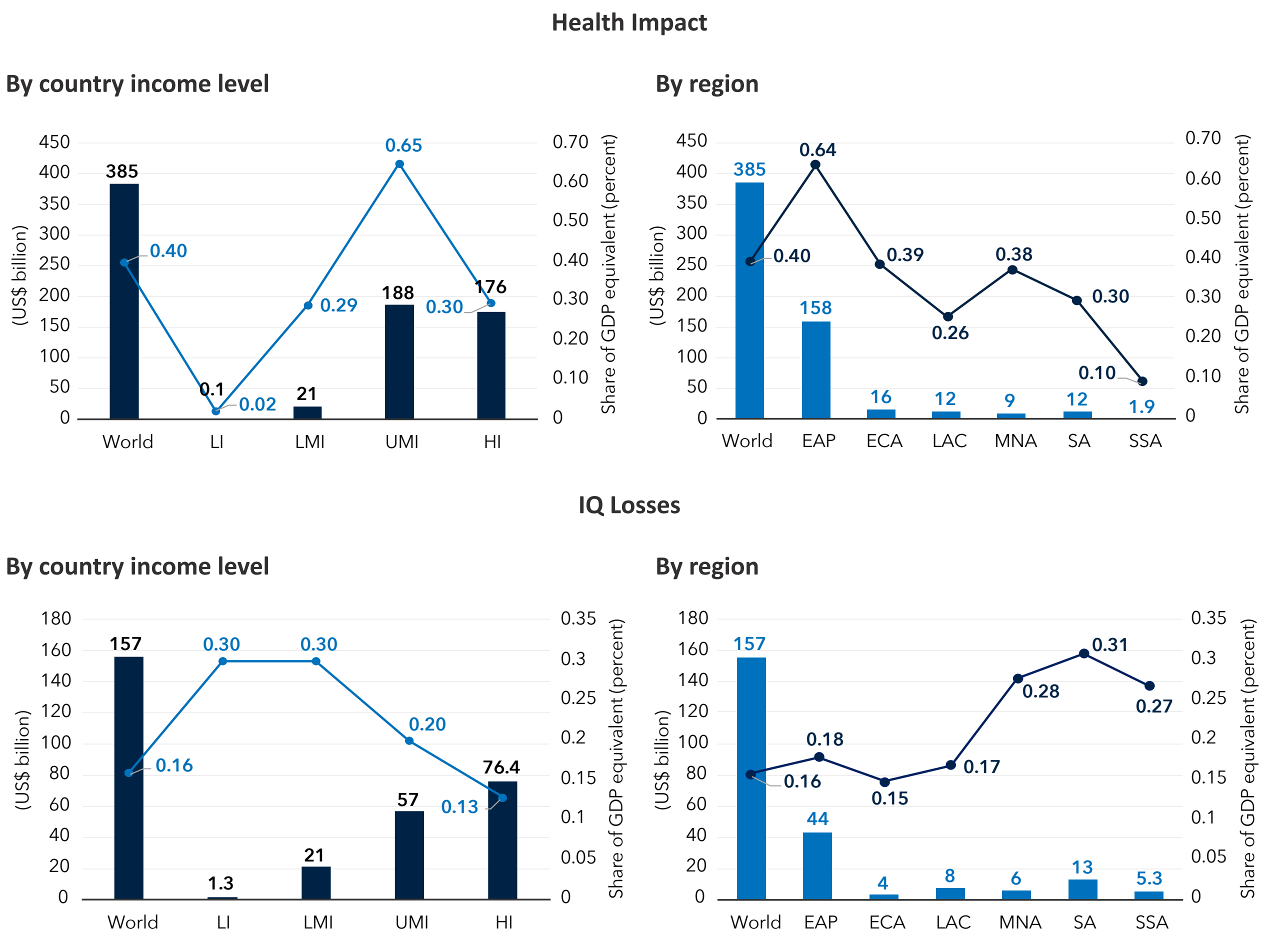
The economic cost of IQ losses from road transport $PM_{2.5}$ in comparison to GDP is greatest in low income and lower middle income countries and declines with income level. For emerging and developing countries by region, the cost of IQ losses in comparison to GDP is highest in MNA and lowest in ECA.

The cost of health impacts (mortality and morbidity) of road transport $PM_{2.5}$ in comparison to GDP dominates in upper middle income countries and is by far the lowest in low income countries. In emerging and developing countries by region, the cost of $PM_{2.5}$ from road transport is greatest in EAP and lowest in SSA (figure 1.4). The high cost of IQ losses compared to the cost of mortality and morbidity in the low income countries and SSA is primarily due to the population age structure with larger child populations vulnerable to cognitive impairment.

Figure 1.4 Annual cost of $PM_{2.5}$ attributable to road transport as of 2021

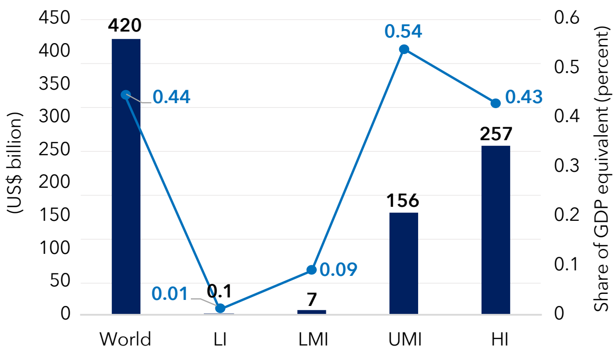


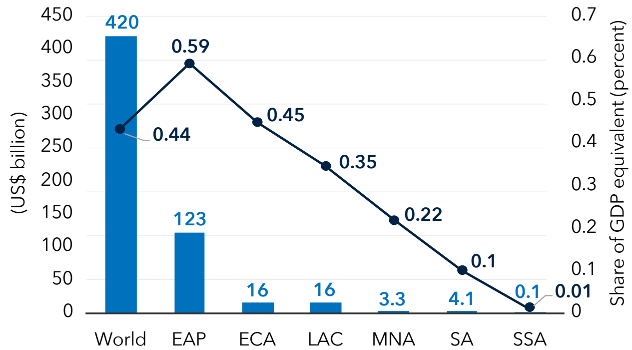
Notes: Only low and middle income countries are included within the regions, whereas all countries are included in the "World" columns. LI=Low income; LMI=Lower middle income; UMI=upper middle income; HI=high income. SA=South Asia; EAP=East Asia and Pacific; SSA=Sub-Saharan Africa; MNA=Middle East and North Africa; ECA=Europe and Central Asia; LAC=Latin America and Caribbean.

Source: Authors' calculations 2025.

The global welfare cost of mortality from road transport NO_2 emissions was $420 billion in 2021. The cost in emerging and developing countries are estimated at $163 billion per year, somewhat less than in high income countries (figure 1.5).[4] Regionally in emerging and developing countries, the dominant share of the cost rests in the upper middle income countries of EAP. The cost of transport NO_2 was equivalent in magnitude to 0.44 percent of global GDP in 2021, with a clear ascending pattern from 0.01 percent in low income countries to 0.54 percent in upper middle income countries, and then declining to 0.43 percent in high income countries. (figure 1.5).

Figure 1.5 Annual cost of NO_2 from road transport as of 2021





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Source: Authors' calculations, 2025.

Notes

1. Based on an anthropogenic emission inventory of atmospheric pollutants for more than 200 countries.
2. The estimate is based on the share of total nitrogen dioxide emissions from road transport and not ambient share of nitrogen dioxide. The estimate should therefore be considered a rough approximation only.
3. The cost from road transport in each country is calculated as the cost of ambient nitrogen dioxide multiplied by the share of nitrogen dioxide that originates from road transport, and should therefore be considered a rough approximation of cost.
4. The cost from road transport in each country is calculated as the cost of ambient nitrogen dioxide multiplied by the share of nitrogen dioxide that originates from road transport.

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Chapter 2. Vehicle Safety and Emission Standards

In the absence of motorization management policies, emerging and developing economies—with the highest growth of motor vehicle fleets—tend to be disproportionately at risk of the health costs linked to crashes and air pollution for, at least two reasons:

- Reliance on used vehicles and sub-standard vehicle technologies: In 2018, 70 percent of emerging and developing economies imported more used vehicles than new ones, with 58 percent importing more than three times as many used vehicles. Many of these used vehicles do not meet globally accepted road safety and air quality standards. (Ministry of Infrastructure and Water Management of the Netherlands 2020).
- Weak systems and policies: Emerging and developing economies often lack comprehensive policies based on a life-of-vehicle approach, with guidelines and operational protocols designed for different phases of the vehicle lifecycle, including entry, active use, and exit. Fragmented policies, uncoordinated systems, and ad hoc protocols result in gaps in regulatory and operational oversight of vehicle stocks (World Bank 2022).

This chapter addresses issues of vehicle standards, how internationally accepted principles for vehicle safety and emission standards influence, patterns and behaviors of the fleet and impact the potential health burden of traffic crashes and air pollution.

2.1 Vehicle standards impacting health outcomes

Most emerging and developing economies have limited domestic vehicle manufacturing capabilities and rely on imports to address demand for vehicle stock. A significant portion of these imports are used vehicles, accounting for an estimated 30 percent of newly registered vehicles and totaling 360 million vehicles annually (World Bank 2022). These imported used vehicles often come with outdated safety and emissions technology relative to the most stringent standards in high income OECD countries (Ministry of Infrastructure and Water Management of the Netherlands 2019).

The situation is exacerbated by the lack of regulations or inadequate regulations governing the quality of imported used vehicles in emerging and developing economies. Even where regulations exist, they are poorly enforced or lack the governance structures to ensure compliance. Consequently, a high likelihood prevails that imported used vehicles do not meet minimum roadworthiness or emissions standards.

This observation is underpinned by a governmental study carried out in the Netherlands in 2019. The ministry tested 160 vehicles in the port of Amsterdam destined for export to Africa and found that more than 80 percent of the vehicles were below the Euro 4 standard. Most of these vehicles did not have valid roadworthy certificates and many had key emissions and safety equipment either removed or not working (Ministry of Infrastructure and Water Management of the Netherlands 2020).

Most vehicles imported by emerging and developing economies are not required to meet internationally accepted vehicle safety standards, and often, local crashworthiness and safety standards are non-existent. Imported used vehicles face significant challenges in meeting crashworthiness and road fitness requirements (World Bank 2022).

Safe vehicles encompass both vehicle crashworthiness and fitness features. Crashworthiness refers to the design aspects of the vehicle, such as seat belt anchorages, front and side airbags, adequate child-restraint systems, adequate front crumple zones, structural design to avoid rollovers, pedestrian contact height, and advanced crash avoidance features like ESC. Fitness refers to the maintenance of the vehicle, ensuring that key features such as brakes, lights, and turn signals are functional, tire treads are not substantially worn, sight lines are not obstructed, and no other hazardous conditions that could compromise passenger safety in the event of a crash.

The legislative landscape for vehicle safety varied widely across emerging and developing economies in 2022. They related to with requirements and standards of five core vehicle safety equipment: seat belts and seat belt anchorages, front and side impact protection, pedestrian protection, ESC, and braking systems (WHO 2023). Thirty-five countries had legislation mandating all five core areas of safety equipment; ten countries had legislation for four core areas, nine countries had legislation for three core areas; eight countries had legislation for two core areas, and twenty-nine countries had legislation for only one of the five core areas. Seventy-nine countries reported no legislation on vehicle safety at all (box 2.1).

Box 2.1 Global evolution of vehicle safety features

Vehicle safety features have evolved significantly over the past several decades, focusing on avoiding crashes and reducing injuries in the event of a crash. In OECD countries, modern vehicles are equipped with sophisticated restraint systems, air bags, traction control, antilock brakes (ABS), electronic stability control (ESC), and crumple zones. These safety features are required and enforced in OECD countries by regulatory agencies. The National Highway Traffic Safety Administration (NHTSA) in the U.S. oversees a 5-star safety rating system based on results from front, side, and rollover crash tests. The implementation of these safety features has had a measurable impact on reducing the number and severity of vehicle crashes, thereby reducing traffic-related injury and deaths. The next generation of safety features in the form of Advanced Driver Assistance Systems (ADAS) has emerged in the past decade. ADAS include technologies such as brake assist, forward collision warnings, pedestrian detection, and lane-crossing warning. The Global New Car Assessment Programme (Global NCAP) has identified a core set of safety features based on OECD standards to serve as a benchmark for developing countries. These include seat belts, impact protection, pedestrian safety measures, and the use of child seats.

The United Nation's World Forum for Harmonization of Vehicle Regulations (WP.29) continuously defines and updates technical safety standards for motor vehicles that can be applied worldwide. Many world regions have adopted at least some of these safety standards, laid down in about 170 UN Regulations, as a prerequisite for new vehicles to be allowed into the fleet. These standards have contributed to substantial vehicle safety improvements beginning in 1958. The Global Plan by the Decade of Action for Road Safety 2021–2030 highlights eight WP.29 safety standards for light duty vehicles as being most important for worldwide safety:

- Occupant Protection in Frontal Impact; UN Regulation No. 94
- Occupant Protection in Side Impact; UN Regulation No. 95
- Pedestrian Impact Protection; UN Regulation No. 127

Box 2.1 Global evolution of vehicle safety features *(contd.)*

- Safety Belts; UN Regulation No. 16
- Safety Belt Anchorages; UN Regulation No. 14
- Child Restraint Systems; UN Regulations No. 44 and 129
- Electronic Stability Control; UN Regulation No. 140
- Advanced Emergency Braking System; UN Regulation No. 152

The first six of these are passive safety standards, that is the design standards for vehicles and child seats to ensure that vehicle occupants and vulnerable road users—such as pedestrians and cyclists—are adequately protected from injury in case of a collision. The last two standards in the above list are active safety systems like the advanced driver assistance systems (ADAS) that use sensors to detect imminent collisions and avoid them if possible or at least mitigate their severity. Despite being technologically mature and well-established in some world regions, the adoption of these safety technologies remains low in emerging and developing economies, even among new vehicles entering their fleets.

The Global Plan by the Decade of Action for Road Safety 2021–2030 does not list specific priority safety standards for Heavy Duty Vehicles (HDVs), but collisions between Light Duty Vehicles (LDVs) and HDVs continue to lead to severe injury outcomes for LDVs occupants. Single vehicle collisions, particularly rollovers, present high injury risks for HDVs occupants.

Passenger car occupants are at particular risk of severe injuries when colliding against HDVs, which generally have a higher ground clearance. This allows cars to underrun the heavy vehicle, resulting in catastrophic damage to the occupant survival cell. In comparison, occupants of trucks, buses, and coaches are generally at lower risk of injury in vehicle-to-vehicle collisions compared to car occupants. This is because their vehicles are heavier, thereby absorbing less of the crash energy, and their seating positions are higher, reducing the risk of intrusion. However, rollovers and collisions with fixed objects or other heavy vehicles have a high potential for serious consequences, particularly when occupants are not wearing seat belts.

The Global Plan by the Decade of Action for Road Safety 2021–2030 prioritizes the implementation of active safety system to address collisions involving motorized two wheelers (MTWs). Motorcycle and moped riders are at high risk of losing control of their vehicle during heavy braking maneuvers or moderate braking on low-grip surfaces, which can cause the front or rear wheel to 'lock-up.' Such incidents often result in serious consequences.

Sources: WHO 2023; UNECE 2021.

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Used vehicles and new vehicles with obsolete technology are sources of comparatively high pollutant emissions. The UN Vehicle Agreements under WP.29 provide a framework that allows countries and vehicle manufacturers to ensure vehicles meet emission requirements. These requirements are achieved through emission standards that set quantitative limits on the permissible amount of specific air pollutants that vehicles can release. These limits are thresholds above which different types of vehicle emission control technologies might be needed. Emission performance standards dictate limits for conventional pollutants such as oxides of nitrogen, hydrocarbons, and fine particulate matter. The United Nations Environment Programme (UNEP) compiled emission standards in Emerging and developing economies in 2020, categorized by prevailing Euro standard level (box 2.2). This compilation revealed that many countries either have no emission standards or adhere to the first- generation Euro 3 standard or below.

Box 2.2 Adoption of emission standards in emerging and developing economies

Different regions and countries have varying standards for vehicle emission, but three main sets of standards dominate: United States, Japanese, and European. Various markets mostly use these as their base. For example, since 1993, the European Union has applied its Euro 1, 2, 3, 4, 5 and 6 standards to measure and control the environmental impact of new cars sold within its jurisdiction. These standards are defined in a series of European Union Directives and allow for staging the progressive introduction of increasingly stringent requirements. Emission standards, when supported by well-managed inspection and enforcement programs, can help drive the adoption of baseline vehicle technologies needed to produce cleaner vehicles.

Source: UNEP. 2020. Used Vehicles and the Environment. A Global Overview of Used Light Duty Vehicles: Flow, Scale and Regulation. United Nations Environment Programme.

Many emerging and developing economies lack the leverage and resources to manage the emissions performance of new vehicles manufactured in OECD countries. As a result, they often inherit performance standards set by other countries, which may be a generation behind prevailing technology. In addition, emerging and developing economies importing used vehicles inherit fleets that may no longer comply with original standards, may have environmental technology removed, or require significant oversight and repair to achieve intended levels. Different factors contribute to ineffective management of emissions performance in many emerging and developing economies. These inefficiencies are normally observed at vehicle entry or during the vehicle in-use life. For example, in some emerging and developing economies, black markets facilitate the removal and trade of catalytic convertors from vehicles, which are then sold as precious metals. In others, catalytic convertors and oxygen sensors are removed from vehicles because technicians are not trained in their functioning and maintenance, and believe they hamper vehicle performance (World Bank 2022).

In addition to vehicle technology, fuel specifications play a crucial role in motor vehicle pollution outcomes. As such, it is important to design and implement vehicle emission standards in conjunction with fuel quality standards. For example, studies have shown that sulfur concentrations in fuels greater than 50 parts per million progressively degrade the effectiveness of Euro IV/4 technology, with concentrations greater than 500 parts per million rendering them ineffective. Even more restricted levels of sulfur, generally less than 10 parts per million, are required for more stringent Euro emissions control technology. While lead has largely been removed from gasoline supply streams worldwide, other anti-knocking additives, such as methylcyclopentadienyl manganese tricarbonyl (MMT), continue to be used in many regions. Manganese, like lead, can inhibit the functioning of emissions control equipment and is a neurotoxin.

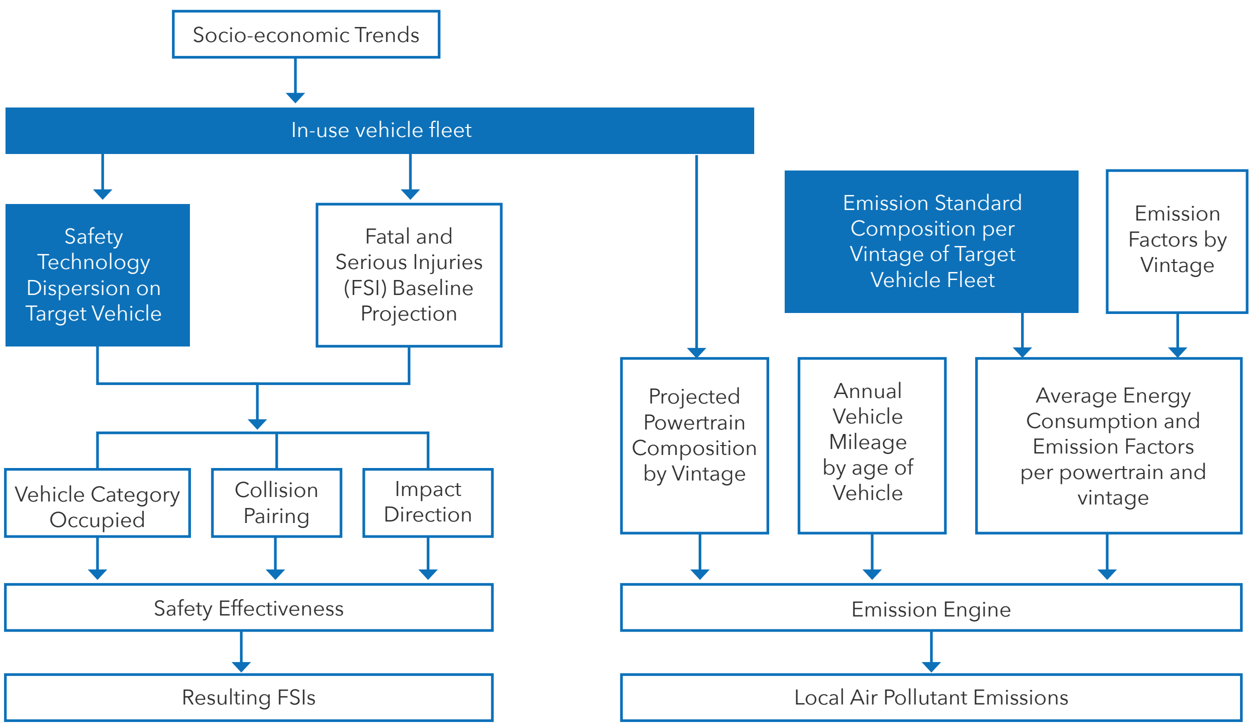
Similar to vehicle safety, internationally adopted standards exist for clean vehicles. The three main standards—United States, Japanese, and European—are widely used globally and have similar impacts on emissions control. The relevant vehicle age limit for a car to be considered roadworthy is another standard as older vehicles have higher emissions because of engine and vehicle degradation. Emission factors consider the type of vehicle and the powertrain per mode moving at low speed.

2.2 Modeling vehicle standards for health outcomes

Global experience shows that motorized vehicles contribute significantly to improving a country's safety and air quality outcomes when they meet internationally recognized safety and emissions standards. Literature highlights the positive effects of vehicle standards and technology on safety and air quality outcomes. For example, European Union countries registered a 55-percent reduction in car occupant fatalities between 2001 and 2012 because of the adoption of automotive safety technologies (UNECE 2021). Similarly, an analysis of vehicle-based crash rates in the Australian state of New South Wales estimates that occupant fatality risk for cars built in 2010 is 75 percent lower than for those built in 1995 (Anderson and Searson 2015). New passenger vehicles produced in the U.S. today are 98-99 percent cleaner for most tailpipe pollutants compared to those from the 1960s (EPA 2025).

This chapter introduces a simple and stylized model that links the quality and quantity of vehicle fleet with health outcomes and allows for understanding the potential impact of alternative sets of policy levers when performance is compared against the business-as-usual scenario, which responds to projections that retain the existing status quo (figure 2.1).

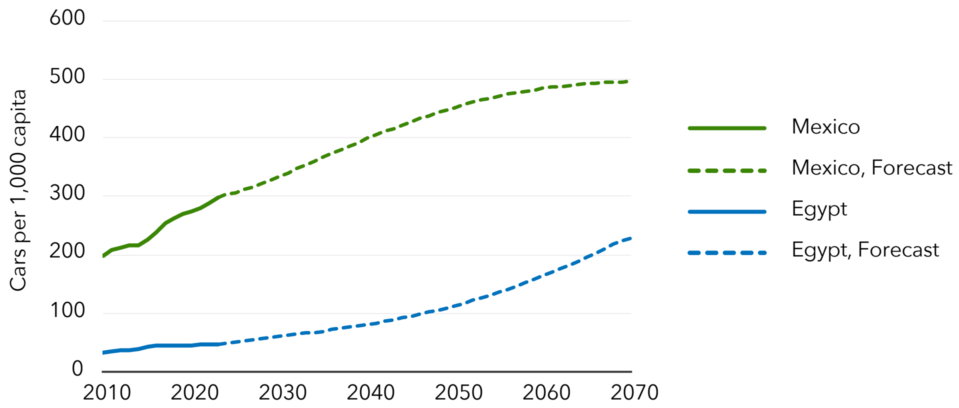
Figure 2.1. Model for estimating simultaneous vehicle safety and air quality impacts



Source: Original figure for this publication.

The model starts by using the socioeconomic trends to project the in-use vehicle fleet, including aspects pertaining to vehicle age profile and vehicle mileage. The projection of the level of motorization—or number of vehicles per population—follows the estimation of calibrated Gompertz (S) curves for each country. This traditional approach uses projected population and GDP growth rates to forecast motorization rates (figure 2.2 presents calibrated Gompertz curve for Egypt and Mexico).

Figure 2.2 Sample forecast motorization rates for Egypt and Mexico



Source: Original figure for this publication.

The alternative set of policy levers are classified in three categories (shaded areas in figure 2.1):

- In-use vehicles by mode considers changing composition of vehicle stocks owing to influx of new and imported used vehicles, and the growing electric vehicle (EV) fleets,
- Technology dispersion on target vehicle fleet captures the impact of safety measurement adoption; and
- Emission standard composition allows for modeling various emission pollutant scenarios based on given air quality standards.

Finally, the metrics of health performance are grouped in two categories:

- Road safety performance: the number of fatalities and serious injuries (FSIs) from road traffic crashes that could be prevented by mandating the fitment of six vehicle safety technologies starting in 2030. These technologies are linked to respective global safety standards and vary by vehicle category —LDVs, HDVs and MTWs.
- Air quality: the reduction in particle pollutant concentrations expected from adopting applicable emissions standards. The air pollutants analyzed include exhaust or tailpipe emissions and non-exhaust emissions from brake and tire wear.

The six vehicle safety technologies included covers the mandatory fitment of UN safety technologies (box 2.1):

(i) Active safety measures for LDVs:
  - Electronic stability control (ESC), a system to prevent loss of control and rollover by targeted brake interventions to pull the vehicle on course (UN Regulation 140).
  - Advanced emergency braking (AEB) for:
    - vehicles — a system to prevent frontal impacts against other motor vehicles or wide objects, by warning the driver and automated emergency brake interventions (UN Regulation 152);
    - pedestrians and cyclists — as AEB above but technologically more advanced and designed to prevent impacts with pedestrians and cyclists (UN Regulation 152).

(ii) Passive safety measures for HDVs to increase the geometric compatibility with cars:
  - Front- and rear underrun protective devices (FRUPD) — strong metal structures fitted to the front and rear of HDVs to engage the crash-absorbing structures of passenger cars in impacts (UN Regulations No. 58 and 93).
  - Vehicle stability function (VSF), a system similar to ESC, which prevents loss of control, rollover, and jack-knifing (UN Regulation No. 13).

(iii) Well-established technology for MTWs:

- Anti-lock brake system (ABS) — a system that detects locking wheels and automatically releases brake pressure helping the driver to maintain control (UN Regulation No. 78).

The model considers the adoption of European standards, namely Euro 4, Euro 5 and Euro 6 for air quality (table 2.2). Emissions standards for new vehicles joining the fleet in future years are held at the prevailing standard adopted by each country for the business-as-usual scenario. For example, if a country follows Euro 4, then no Euro 5 or Euro 6 vehicles would join the fleet in future years. The Euro standards differ based on the type of vehicle and monitor the environmental impact of exhaust pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter (table 2.1).

The emissions factors for both exhaust and non-exhaust emissions follow the tier 2 methodology presented in the European Environment Agency (2024). This methodology considers vehicle size, powertrain, Euro standard, and average speeds. The model uses emission factors for medium-sized vehicles in each Euro standard, assuming a low average speed of 40 kilometers per hour. The low average speed was chosen to better match driving conditions in a city environment, where emissions are a greater concern. A limitation of tier 2 is that this methodology has been developed for a European environment, where road roughness and vehicle maintenance conditions are likely to be better than in emerging and developing economies.

For the two pollutants of main concern in this report, the difference in PM and NO_x emissions between a compliant Euro 4 and Euro 6 diesel vehicle is substantial while the difference in emissions for petrol vehicles is minor. Moreover, old pre-Euro 1 and Euro 1 in-use heavy duty diesel vehicles may emit one hundred times more PM and 40 times more NO_x per vehicle km than a corresponding compliant Euro 4 diesel vehicle, indicating the importance of addressing emissions from in-use diesel vehicles.

Table 2.1. Standards for clean vehicles.

Emission standard	Description	Sulfur content in diesel
Euro 4	Euro 4 standard was introduced in 2006. • For petrol vehicles, the emission limits are set at 1.0 g/km for CO, 0.10 g/km for HC, and 0.08 g/km for NO_x. • Diesel vehicles have tougher restrictions of 0.50 g/km for CO, 0.30 g/km for a combination of HC and NO_x, 0.25 g/km for NO_x alone, and 0.025 g/km for PM.	50 ppm
Euro 5	Introduced in 2009, Euro 5 standard officially came into force in 2011. • For petrol vehicles, the emission limits were set at 1.0 g/km for CO, 0.10 g/km for HC, 0.06 g/km for NO_x, and 0.005 g/km for PM. • Diesel vehicles faced stricter demands, with limits of 0.50 g/km for CO, 0.23 g/km for HC and NO_x, 0.18 g/km for NO_x alone, and 0.005 g/km for PM, along with a particulate number limit of 6.0 × 10^11 particles per km.	10 ppm
Euro 6	• Euro 6 limits for petrol vehicles are set at 1.0 g/km for CO, 0.10 g/km for HC, and 0.06 g/km for NO_x. Direct injection petrol engines are also subject to a PM limit of 0.005 g/km and a particulate number limit of 6.0 × 10^11 particles per km. • Diesel vehicles have stricter requirements, with limits of 0.50 g/km for CO, 0.17 g/km for a combination of HC and NO_x, 0.08 g/km for NO_x alone, and 0.005 g/km for PM. A particulate number limit of 6.0 × 10^11 particles per km also applies to diesel engines.	10 ppm
Net Zero Vehicles	• These are vehicles that do not produce direct exhaust or tailpipe emissions locally. They comprise battery-electric vehicles, hydrogen fuel cell vehicles and plug-in vehicles. Electric vehicles are considered for this study.	Not applicable

Source: Michelin 2025.

The emissions estimations account for both direct—tank-to-wheel (TTW)—and indirect —wheel-to-tank (WTT) —emissions. They include passenger modes such as car, motorcycle, bus, minibus, and freight modes such as van, medium truck, and heavy truck. Different powertrain and fuel options are included as appropriate for each mode (table 2.2).

Table 2.2. Potential powertrains for each mode.

Car	Bus	Minibus	Motorcycle	Van	Medium Truck	Heavy Truck
Gasoline Diesel Plugin hybrid gasoline Plugin hybrid diesel Electric Hydrogen fuel cell LPG CNG	Gasoline Diesel Electric vehicle Hydrogen fuel cell electric LPG CNG Trolleybus	Gasoline Diesel Electric vehicle Hybrid electric diesel Hydrogen fuel cell LPG CNG	Gasoline Diesel Electric	Gasoline Diesel Plugin hybrid gasoline Plugin hybrid diesel Electric Hydrogen fuel cell LPG CNG	Diesel Plugin hybrid diesel Electric Hydrogen fuel cell LPG CNG	Diesel Plugin hybrid diesel Electric Hydrogen fuel cell CNG

Source: Original table for this publication.

The key metrics for air quality and clean vehicle performance are emissions at the national level, including exhaust emissions, nitrogen oxides, $PM_{2.5}$ and sulfur, and non-exhaust emissions from brake wear and tire wear, for example, $PM_{2.5}$). The model for these calculations,: (i) considers the trend for older vehicles to have a lower annual mileage than newer vehicles; (ii) assumes older vehicles have higher emissions owing to engine degradation through use, and (iii) considers the local sulfur content of fuel to calculate sulfur emissions.

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Chapter 3. Impact of Vehicle Standards on Safety and Air Quality

Motor vehicles are a salient common element from road transport that directly impact both vehicle crashes and transport emissions contributing to ambient pollution, among other things fatal and non-fatal injuries and air quality. The nature of a country's motor vehicle stock and how it grows affect crucial safety and air quality outcomes. First, the quality of the motor vehicle stock impinges road safety outcomes—that is, the number of people killed or seriously injured in motor vehicle crashes. The characteristics of vehicles and their fitness or roadworthiness can influence fatality and serious injury (FSI) outcomes. Second, the quality of the motor vehicle fleet alters air quality, particularly in cities. Motor vehicles are a key source of harmful air pollution, including fine particulates ($PM_{2.5}$), nitrogen oxides (NO_x, NO_2) sulfur oxides, various hydrocarbons, carbon monoxide and other pollutants. The amount of these pollutants they emit is directly related to how the vehicle was built and how well it is maintained. In addition to vehicle technology, fuel specification plays an important role in motor vehicle pollution outcomes. As such, it is important to design and implement vehicle emission standards in conjunction with fuel quality standards.

The estimates in this chapter are based on results that only account for the reduction of primary $PM_{2.5}$. In many contexts, secondary $PM_{2.5}$ formed in the atmosphere from precursor gases (sulfur dioxide, nitrogen oxides, and volatile organic compounds) constitutes the majority of total $PM_{2.5}$ levels. The model used in this study estimates the effect that the implementation of vehicle emission standards would have on emissions of NO_x, encompassing both NO_2 and NO. Consequently, the actual reductions in NO_2 emissions and the associated health benefits may be less pronounced.

This chapter addresses questions about how policy decisions pertaining to vehicles influence mortality and morbidity of road transport, the adoption of good vehicle safety and emission standards sparing deaths, serious injuries and disabilities, and whether it makes economic sense to invest in policies and institutions that improve motorization patterns.

3.1 Assessing the need for vehicle standards adoption at the country level

This study selected eight emerging and developing economies to assess the key health impacts caused by road motor vehicles through the lens of road crashes and air pollution. The countries— Argentina, Brazil, Egypt, Ghana, India, Kazakhstan, Lao PDR, and Mexico—were selected for their diverse levels of income, geographic spread, population, motorization levels, existing motorization management policies, and availability of data (table 3.1).

Table 3.1 General country statistics, 2023

	Region	Income category	GDP per capita (nominal US$)	Population (million)	Motorization rate (registered vehicles/1000 population)*	Imported vehicles (units)
Argentina	Latin America	Upper middle	14,187	45.5	583	178,567
Brazil	Latin America	Upper middle	10,295	211.1	520	201,626
Egypt	Middle East	Lower middle	3,457	114.5	100	225,000
Ghana	Sub-Saharan Africa	Lower middle	2,260	33.8	101	73,417
India	South Asia	Lower middle	2,481	1,438.1	232	14,583
Kazakhstan	Eastern Europe	Upper middle	12,919	20.3	226	32,985
Lao PDR	East Asia and Pacific	Lower middle	2,067	7.7	274 (**)	9,000
Mexico	Latin America	Upper middle	13,790	129.7	419	519,167

Notes: (*) including 2/3 wheelers; (**) 2016 data.

Sources: GDP per capita, Population – World Bank Open Data (latest data available: 2023) Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data). Used vehicles imports – World Road Statistics (Latest data available 2020: Argentina, Brazil), Trend Economy (estimated based the import values in 2020 for Egypt, Ghana, India, Lao PDR, and Mexico).

Health case for better vehicle standards at the country level

The selected countries have a combined population of nearly 2 billion or one-quarter of the world's population. These countries account for a total of 291,768 traffic crash fatalities—24.5 percent of the global traffic crash-related fatalities (table 3.2). Although serious injury estimates are not reliably reported in emerging and developing economies, it is estimated that for each fatality, approximately 10 seriously injured victims of traffic crashes can be added. Considering the country's population, the average fatality rate per 100,000 population is 14.9 for these eight countries. In comparison, the global average fatality rate per 100,000 population in 2021 was 15.

Table 3.2 Selected statistics on road crashes, 2021

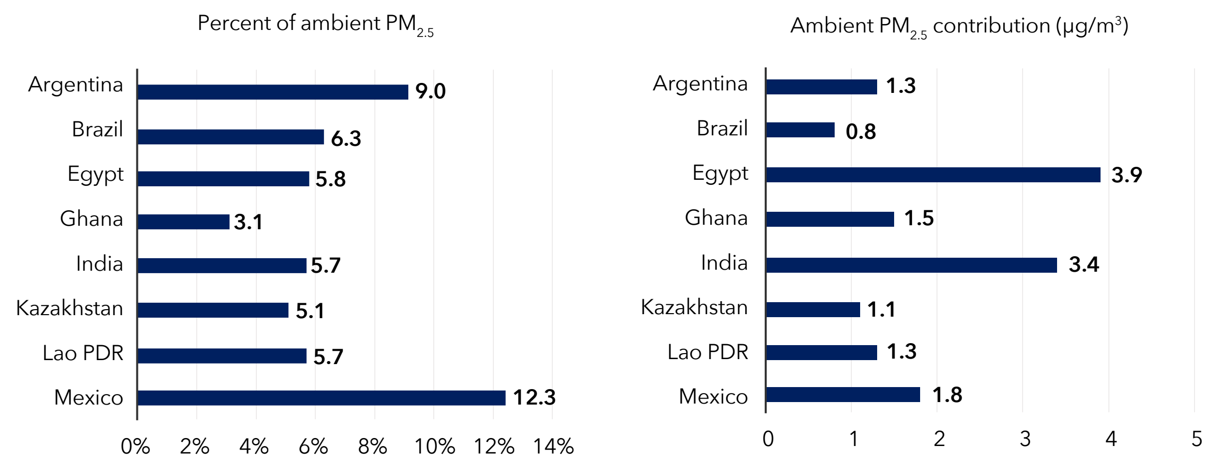
	Fatalities (annual deaths)	Fatality rate per 100,000 pop.
Argentina	3,983	8.8
Brazil	33,586	15.7
Egypt	10,263	9.4
Ghana	8,494	25.9
India	216,618	15.4
Kazakhstan	2,341	12.2
Lao PDR	1,217	16.4
Mexico	15,267	12

Source: WHO 2023.

The population-weighted annual ambient $PM_{2.5}$ in the eight countries in 2019 ranged from 12-15 micrograms per cubic meter in the three LAC countries to 50-68 micrograms per cubic meter in Ghana, India and Egypt. This pollution concentration is estimated to cause 1.2 million premature deaths from ambient $PM_{2.5}$ exposure in the eight countries in 2021. At the country level, deaths from road transport ranged from 2,361 in Lao PDR to nearly one million in India (GBD 2021).

Global averages mask significant country disparities in how road transport emissions contribute to aggregate ambient $PM_{2.5}$ pollution. According to GBD major air pollution sources (GBD MAPS) estimates for 2017 (McDuffie et al. 2021a,b), the contribution of motorized road transport to ambient $PM_{2.5}$ levels ranges from 3.1 percent in Ghana to 12.3 percent in Mexico. In absolute terms, the contribution ranges from 0.8 micrograms per cubic meter in Brazil to 3.4 micrograms per cubic meter in India and 3.9 micrograms per cubic meter in Egypt (figure 3.1).

Figure 3.1 Motorized road transport's contribution to population weighted ambient $PM_{2.5}$



Source: Original figure for this publication, based on estimates reported by McDuffie et al. 2021a,b.

Although the contribution from motorized road transport to $PM_{2.5}$ levels may seem small, it caused 71,685 premature deaths and the loss of 17.4 million IQ points in children in eight countries in 2021 (table 3.3).

Table 3.3 Deaths and IQ losses from $PM_{2.5}$ attributable to motorized road transport, 2021

	IQ point losses (million)	Premature deaths
Argentina	0.3	1,374
Brazil	0.74	3,339
Egypt	1.44	6,708
Ghana	0.27	342
India	13.18	54,012
Kazakhstan	0.15	647
Lao PDR	0.07	135
Mexico	1.23	5,128

Source: Original table for this publication.

NO_2 emissions from road transport accounted for 25 percent of total NO_2 emissions in emerging and developing economies in 2017. In the eight selected countries, the share from motorized road transport ranged from 13–15 percent in Kazakhstan and India to 44–60 percent in the three LAC countries and Lao PDR. The high share in the LAC countries is associated with a high degree of motorized transport. The high share in Lao PDR is due to low NO_2 emissions from other sectors, primarily because most of electricity in the country is generated from hydropower. Exposure to ambient NO_2 attributed to motorized road vehicles caused an estimated 40,600 premature deaths in the eight countries in 2021. The number of deaths from road transport NO_2 was significantly higher than from road transport $PM_{2.5}$ in the three LAC countries because of their relatively moderate ambient $PM_{2.5}$ levels.

Table 3.4 Ambient NO_2 and mortality in eight select countries

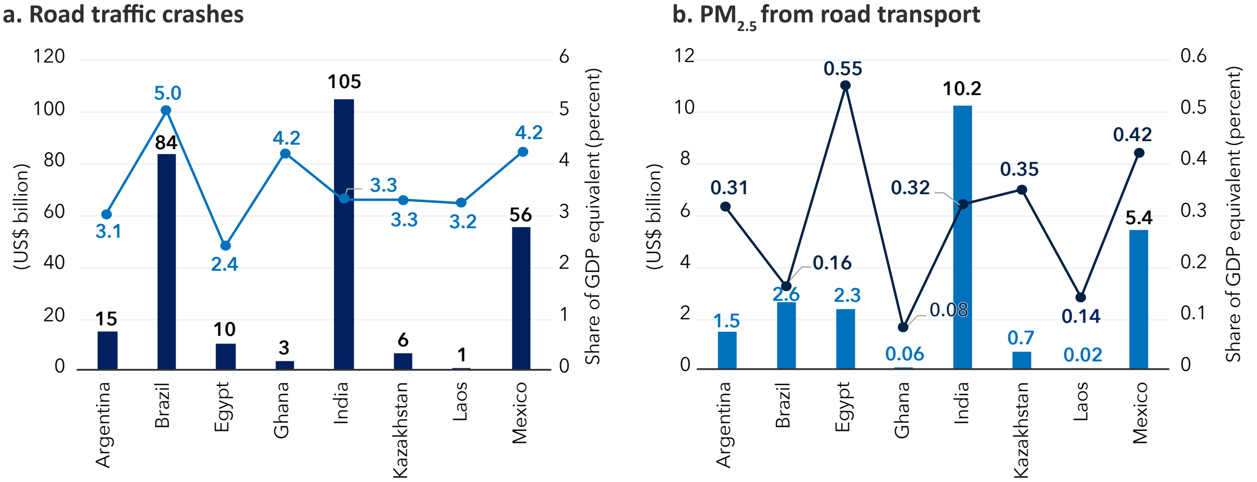
	Road transport NO_2 emissions (% of total NO_2 emissions), 2017	Premature deaths from road transport NO_2, 2021	Premature deaths from road transport NO_2 (% change relative to road transport deaths from $PM_{2.5}$)
Argentina	44	1,830	133
Brazil	48	6,772	203
Egypt	17	2,204	33
Ghana	26	N/A	N/A
India	15	20,771	38
Kazakhstan	13	144	22
Lao PDR	48	N/A	N/A
Mexico	60	8,877	173

Source: Original table for this publication based on NO_2 emissions estimates reported by McDuffie et al. 2020a,b.

Economic cost of suboptimal vehicle standards at the country level

The estimated annual cost of road traffic crashes in the selected countries ranged from $1 billion in Lao PDR to $105 billion in India. The estimated annual cost as a share of the country's GDP ranges from 2.4 percent in Egypt to 5.0 percent in Brazil (figure 3.2a).

Figure 3.2 Selected health cost associated to road transport by country as of 2021



Note: Including fatalities and serious injuries.

Source: Authors estimates, based on GBD 2021 data.

The cost of mortality and morbidity attributed to $PM_{2.5}$ from motorized road transport totaled $22.9 billion in 2021 in the sampled countries and went from 0.08 percent of GDP in Ghana to 0.55 percent in Egypt in 2021. The annual cost of IQ losses in children from $PM_{2.5}$ traceable to road transport totaled $15.5 billion and ranged from 0.11 percent of GDP in Brazil to 0.26-0.29 percent in Ghana, India and Egypt. On average, the cost of mortality and morbidity was equivalent to 0.3 percent of GDP (figure 3.2b) and the cost of IQ losses to 0.2 percent of GDP. Cost of mortality and morbidity attributed to NO_2 from road transport totaled $21.5 billion and ranged from 0.08 percent of GDP in Kazakhstan to 0.71 percent in Mexico (table 3.5).

Deaths and cost of mortality and morbidity from road transport NO_2 are far higher than from road transport $PM_{2.5}$ in the three LAC countries (table 3.5). These countries have relatively high ambient NO_2 from road transport while $PM_{2.5}$ from the sector is relatively moderate. In contrast, ambient $PM_{2.5}$ from road transport is particularly high in Egypt and India while ambient NO_2 from the sector is moderate, with cost of road transport $PM_{2.5}$ being substantially higher than the cost of road transport NO_2 . In Kazakhstan ambient NO_2 from road transport is moderate with a relatively small share of the population exposed to ambient NO_2 above the WHO annual AQG. Thus the low cost of road transport NO_2 relative to $PM_{2.5}$.

Table 3.5 Health impacts and costs associated to road transport by country as of 2021

	Deaths from ambient air pollution*		Cost of mortality and morbidity (US$ million)		Cost of mortality and morbidity (% of GDP)	
	Road transport $PM_{2.5}$	Road transport NO_2	Road transport $PM_{2.5}$	Road transport NO_2	Road transport $PM_{2.5}$	Road transport NO_2
Argentina	1,374	1,830	1,476	1,966	0.31	0.40
Brazil	3,339	6,772	2,619	5,312	0.16	0.32
Egypt	6,708	2,204	2,324	764	0.55	0.18
Ghana	342	N/A	67	N/A	0.08	N/A
India	54,012	20,771	10,248	3,941	0.32	0.12
Kazakhstan	647	144	679	151	0.35	0.08
Lao PDR	135	N/A	27	N/A	0.14	N/A
Mexico	5,128	8,877	5,417	9,378	0.42	0.71

* Estimates of deaths from ambient NO_2 and $PM_{2.5}$ should not be considered additive. It is plausible that estimates of deaths from $PM_{2.5}$ include deaths that are caused by NO_2 and vice versa. What the estimates of deaths from NO_2 does demonstrate, however, is that NO_x is a pollutant of public health concern and importance.

Note: Impacts of ambient NO_2 from road transport could not be estimated due to data constraints.

Source: Original table for this publication.

3.2 Evaluating the health impact of vehicle policies at the country level

This section uses the analytical model discussed in chapter 2 to estimate the health burden of traffic crash fatalities and serious injuries, and air pollutants mortality and morbidity over the period from 2025 to 2050. The analysis is at the country level and will represent the proof of concept of the model proposed to quantify the impact of vehicle standard adoption under alternative scenarios.

The mandate for a specific technology or standards is country specific and applies in cases where the technology is voluntary for vehicle types in that country. The model simulates the technology equipment levels of the in-use vehicle fleet, starting from the status quo in 2025 and projecting forward to the end of the assessment period.

The state of adoption of various motorization policies is diverse throughout the sample (table 3.6). Argentina, Brazil, Egypt, and India have national policies on complete or near-complete ban on the import of used vehicles, whereas motorization growth in Ghana, Lao PDR, Kazakhstan, and Mexico is influenced by import of used vehicles. In the adoption of UN vehicles safety mandates linked to active safety systems, India has adopted most except for the vehicle stability function for heavy vehicles (UNECE, 2025). Egypt, Ghana, Kazakhstan, and Lao PDR, on the other hand, lack all the advanced safety technologies analyzed in this study.

Table 3.6 State of analyzed motorization policies as of 2024

Adoption of vehicle safety technology									
		Argentina	Brazil	Egypt	Ghana	India	Kazakhstan	Lao PDR	Mexico
Electronic Stability Control	LDV	✓	✓	x	x	✓	x	x	✓
Advanced Emergency Breaking : Vehicles	LDV	x	x	x	x	✓	x	x	x
Advanced Emergency Breaking: pedestrians & cyclists	LDV	x	x	x	x	✓	x	x	x
Front and Rear Underrun Protective Devices	HDV	✓	x	x	x	✓	x	x	x
Vehicle Stability Function	HDV	✓	x	x	x	✓*	x	x	x
Anti-lock Brake System	MTW	✓	x	x	x	✓	x	x	x

* excluding trucks

Adoption of vehicle emission standards								
	Argentina	Brazil	Egypt	Ghana	India	Kazakhstan	Lao PDR	Mexico
Euro 4	x	x	✓	✓	x	✓	✓	✓
Euro 5	✓	✓	x	x	x	x	x	x
Euro 6	x	x	x	x	✓	x	x	x

Adoption of rules for imported vehicles								
	Argentina	Brazil	Egypt	Ghana	India	Kazakhstan	Lao PDR	Mexico
Used vehicles	x	x	x	✓	x	✓	✓	✓
New vehicles	✓	✓	✓	✓	✓	✓	✓	✓

Source: Original table for this publication.

The scenarios are defined to address the impact of motorization management policies with focus on vehicle standards becoming mandatory in the year 2030 for:

- New vehicles entering the fleet
- Used vehicles entering the fleet
- 20 years and older vehicles not meeting air quality and safe standards exiting the fleet.

Two additional scenarios showing the uptake of electric vehicles (EVs) as part of diversifying in-country vehicle fleet were modeled for all study countries

The modeling results were estimated for the following five scenarios summarized in table 3.7:

- Scenario 1: New vehicles—vehicles being registered for the first time as new—that are entering the fleet are mandated by 2030 to meet study-prescribed safety and air quality standards whereas used vehicle imports may or may not meet new standards.
- Scenario 2: All first-time registered vehicles—new, and used imports—are mandated by 2030 to meet study-prescribed safety and air quality standards.
- Scenario 3: All first-time registered vehicles—new, and used imports—are mandated to meet study-prescribed safety and air quality standards, and in addition, vehicles older than 20 years that do not meet prescribed standards are required to exit circulation, this latter is being referred to as "fleet retirement" in the report.
- Scenario 4: EV 30x30 scenario illustrates 30 percent of new cars, buses and minibuses and 70 percent of new motorcycles are electric by 2030. This scenario does not include higher EV uptake of vans or trucks. EV growth is held at a constant two percent for cars and buses, 10 percent for motorcycles and two percent for vans.
- Scenario 5: In this EV 50x50 scenario, 50 percent of new cars, buses, minibuses, motorcycles and vans are electric by 2050, and 50 percent of new trucks are EVs by 2055. EV growth is held at a constant two percent for cars and buses, 10 percent for motorcycles and two percent for vans.

Table 3.7 Motorization management scenarios

	New Vehicles	Used Vehicles	Vehicle Scrappage	EV 30x30	EV 50x50
Scenario 1	✓	x	x	x	x
Scenario 2	✓	✓	x	x	x
Scenario 3	✓	✓	✓	x	x
Scenario 4	✓	x	x	✓	x
Scenario 5	✓	x	x	x	✓

Note: Scenarios 1-3 include the adoption of Euro 6 and/or Euro 5 emission standards as applicable to the country.

Source: Original table for this publication.

The results are estimated at the national level and benefits quantified for crash safety and air quality outcomes by comparing fleet growth and composition under a business-as-usual (BAU) scenario against scenarios resulting from projecting fleet behavior under alternative motorization management policies. The estimates run from 2025 to 2050, with policies impacting emissions in five-year intervals. The estimates consider that newer vehicles are used more than older vehicles and hence have higher annual mileage than older vehicles. Motorization polices are broadly categorized for the three vehicle types: MTWs, LDVs, buses and HDVs. All projections were prepared for the period 2025–2050 based on five years of historic data, and cumulative results compared with the BAU scenario.

Additional key assumptions were made to transform a complex real-world situation with the best available data into a coherent model. The model considered incomplete data and ensured a consistent approach in each country. These assumptions are:

- The best exposure metric available for all countries was the vehicle fleet size. Calculations performed were based on the number of fatalities and serious injuries per vehicle circulating on the roads. Other metrics that were not available, such as miles driven, would have enabled the modelling of more complex effects of differing usage profiles of new and old vehicles.
- The future fatalities and serious injuries baseline extrapolation assumes continued improvements in vehicle and infrastructure design and road user behavior. This is modeled by reducing the fatalities and serious injuries rate per vehicle from a country's existing level to the level of a European country with good road safety outcomes to be reached in 2050.
- The level and quality of accidentology data vary from country to country. Where certain breakdowns of data, such as vehicle category pairing or impact directions, were not available, these were substituted with proportions from proxy countries applied to the country studied.
- The available information was limited about prevailing safety technology adoption rates in the in-use vehicle fleet, as well as in new or imported used vehicles. The authors applied expert estimates based on known adoption curves for other countries and the main markets from which the used vehicles were imported. These estimates can be substituted with more definitive data when available. Another underlying assumption is that these technologies remain operational throughout the vehicle's life, which may require periodic technical inspections to ensure full benefits are realized.
- Limited information was forthcoming on the types of vehicles leaving the fleet or (scrapped vehicles. The model therefore assumed that only the oldest vehicles, which were usually those not equipped with the safety technologies, were scrapped.
- The technology effectiveness studies selected were from high quality published research, but the underlying research was largely based on US or European accidentology. Although safety technology effectiveness values should be expected to vary depending on infrastructure and traffic environment, applying this research provided the best estimate in absence of country specific studies.
- Health benefits of adopting the various safety standards were quantified in saved fatalities and serious injuries. Owing to the lack of reliable serious injury data in the countries studied, and in emerging and developing economies in general, a ratio approach of serious injuries to fatalities was used. This ratio varied based on the definition and level of reporting of serious injuries, as well as on the crash type, vehicle type, and road user involved. The study examined several high income countries, and concluded to use a ratio of 10 for scenarios involving LDVs, MTWs, and pedestrians, and a ratio of five for HDVs scenarios.
- The model aims to insulate the impact of mandating stricter emission standards. For that reason, in some cases the emission reduction benefits of vehicle retirement represent a lower bound. For countries already with a mandate equivalent to Euro 6 or higher, emission reduction gains due to adopting Euro 6 are reported as Non-Applicable (N/A) for all scenarios even when namely, Scenario 3 considers retirement of non-complaint old vehicles which render benefits unto itself regardless of the emission standard in place. That is the case of India (tables table 3.8, 3.10 and 3.12). Similarly, for scenarios estimating impact of Euro 5 adoption, the model will report Non-Applicable (N/A) as the potential gain for countries already with Euro 5 or higher. Again, these results would admittedly underestimate emission benefits rendered by vehicle retirement. That is the case of Argentina, Brazil and India for scenarios considering upgrade to the Euro 5 mandate (tables 3.9, 3.11 and 3.13).

Scenario 1: Safety and emission mandates for new vehicles by 2030

In Scenario 1, the selected countries mandate that only new vehicles meet the prescribed safety and air emission standards by 2030.

The results show that the adoption of safety technologies reduces fatalities and serious injuries by up to 3.5 percent in Egypt and 2.3 percent in Brazil, with marginal benefits in Argentina, Ghana, India, Kazakhstan, and Lao PDR.[1] The adoption of AEBS prevents the most fatalities and serious injuries, followed by use of ESC. The mandated exhaust emissions standards for air pollution result in a significant reduction of nitrogen oxide emissions compared to the BAU scenario, ranging from a 15.7 percent reduction in Argentina to a 26.6 percent decrease in Lao PDR (table 3.8). The scenario results in comparatively low reductions in $PM_{2.5}$ emissions because a significant share of these emissions is caused by tire, brake, and road wear—non-exhaust emissions—which are covered by the Euro emissions standards. Notably, in Brazil, which has a significant overall crash fatalities and serious injuries burden, a 2.3 percent reduction translates to 137,943 fatalities and serious injuries prevented.

Safety model outcomes for Scenario 1

In countries where all six safety technologies are voluntary—Egypt, Ghana, Kazakhstan, and Lao PDR—most fatalities and serious injuries were prevented with the adoption of AEBS followed by ESC. For Egypt and Ghana, these two safety technologies accounted for over 90 percent of fatalities and serious injuries prevented. In Kazakhstan, they accounted for approximately 78 percent of fatalities and serious injuries prevented and about 25 percent in Lao PDR. In Lao PDR, about 42 percent of fatalities and serious injuries prevented came from mandating ABS for MTWs, which represent a large share of vehicles in the country. In Brazil and Mexico, which have four voluntary safety technologies, the most impactful technology was ABS, which resulted in 58 percent of fatalities and serious injuries prevented in Brazil and 63 percent in Mexico (figure 3.3).

Table 3.8 Impact of motorization Scenario 1, cumulative impact over 2025–2050 compared to BAU

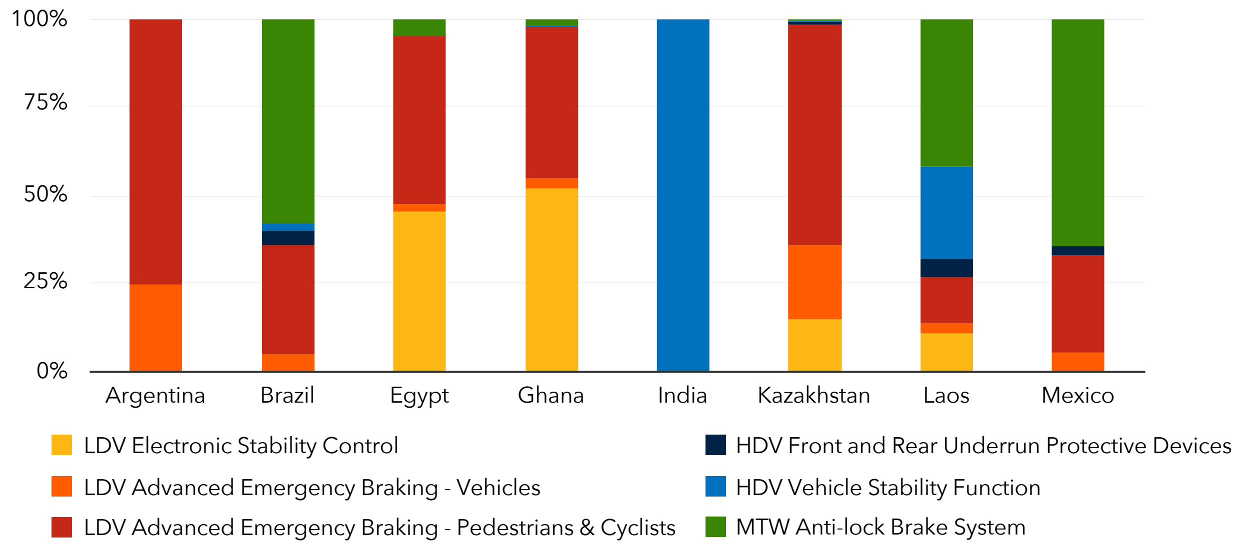
	Crash fatalities and serious injuries (FSI) reduction		$PM_{2.5}$ reduction		Nitrogen oxides reduction	
	FSI	%	kt	%	kt	%
Argentina	5,953	0.7	7	3	732.4	15.7
Brazil	137,943	2.3	77.6	5	7,139	20.2
Egypt	54,728	3.5	34	9.2	2,135	20.6
Ghana	2,307	0.5	8	6.9	663	20
India	107,009	0.5	N/A	N/A	N/A	N/A
Kazakhstan	1,479	0.3	5	5.1	462	17.6
Lao PDR	189	0.1	6	16.3	245	26.6
Mexico	44,618	1.1	118	10.7	3,132	17.8

Notes:
The modeling, by design, aims to isolate the benefits of adopting stricter emissions standards by excluding India—which already adopted Euro 6—from estimations.

kt=kiloton.

Source: Original table for this publication.

Figure 3.3 Prevented FSIs by safety technology mandates per vehicle type (Scenario 1)



Clean model outcomes for Scenario 1

For countries which have Euro 4 or lower standards, adopting Euro 5 and or Euro 6 lead to substantial improvements in air quality because of reduced pollutant emissions from the fleet. This is the case for Egypt, Ghana, Kazakhstan, Lao PDR and Mexico. Euro 6 emission standards are stricter than Euro 5 standards, particularly for HDVs, such as buses and trucks. Within the same Euro standard, decreases in nitrogen oxides emission are generally significantly higher than those of $PM_{2.5}$ (table 3.9). The comparatively low reduction in $PM_{2.5}$ emissions is because a significant share of these emissions is caused by tire, brake and road wear, or non-exhaust emissions, which are not included in the Euro emission standards.

Table 3.9 Pollutant percentage reduction Scenario 1, cumulative impact over 2025–2050 compared to BAU

	Euro 5		Euro 6	
	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x
Argentina	N/A	N/A	3	15.7
Brazil	N/A	N/A	5	20.2
Egypt	3.1	1.1	9.2	20.6
Ghana	1.4	1.2	6.9	20
India	N/A	N/A	N/A	N/A
Kazakhstan	0.9	4.7	5.1	17.6
Lao PDR	12.3	6.5	16.3	26.6
Mexico	8.3	3.6	10.7	17.8

Source: Original table for this publication.

Scenario 2: Safety and emission mandates for new vehicles and imported used vehicles by 2030

In Scenario 2, countries mandate that both new and used road motor vehicles adopt safety and emission standards by 2030. Including used imported vehicles in the mandate results in greater percentages of fatalities and serious injuries prevented compared to the BAU scenario, surpassing those observed in Scenario 1. AEB for pedestrians and cyclists, and ESC for LDVs significantly contribute to preventing fatalities and serious injuries in Ghana and Kazakhstan. In Lao PDR and Mexico, ABS for MTWs is the technology responsible for the highest prevented fatalities and serious injuries. The reduction of air pollutants relative to the BAU scenario is higher than in Scenario 1 in the countries that permit imports of used vehicles, such as in Ghana, where the reduction of air pollution almost doubles in Scenario 2, relative to Scenario 1. Euro 6 emission standards provide the maximum reduction in pollutant emissions from 2025 to 2050. In this scenario, reductions of nitrogen oxides emissions under Euro 6 are greater than those of $PM_{2.5}$ and sulfur in the four countries where the vehicle fleet comprises both new and imported used vehicles.

Results from Scenario 2 demonstrate the influence of new and imported used vehicles on safety and air quality outcomes in study countries that permit the imports of used vehicles—Ghana, Kazakhstan, Lao PDR, and Mexico. A mandate that includes used imported vehicles shows greater percentages of fatalities and serious injuries prevented compared to the BAU scenario than those observed in Scenario 1. In Ghana, this percentage is as high as eight percent, corresponding to 38,238 fatalities and serious injuries prevented. A similar trend, though with marginal changes, can be observed in the reduction of air pollutants relative to the BAU scenario. Mandating air quality standards on all vehicles entering the fleet for the first time results in the following emissions reductions in Mexico, which has a large volume of both new and used imported vehicles: 17 percent reduction in $PM_{2.5}$,13.8 percent reduction in sulfur and 39 percent reduction in nitrogen oxides compared to BAU.

Safety model outcomes for Scenario 2

An assessment of the impact of mandates on required safety technology for vehicles under Scenario 2 shows that more fatalities and serious injuries are prevented when such mandates are required for both used and new vehicles (table 3.10). Similar to Scenario 1, AEB for pedestrians and cyclists, as well as ESC for light duty vehicles significantly contribute to preventing fatalities and serious injuries in Ghana and Kazakhstan (figure 3.4). In Ghana, these two technologies account for about 95 percentage of fatalities and serious injuries prevented, whereas in Kazakhstan, they account for approximately 75 percent. A combination of AEB for pedestrians and motorcyclists accounts for 38 percent of fatalities and serious injuries prevented in Lao PDR. Due to the large number of MTWs in Lao PDR, a mandate of ABS for MTWs will contribute to preventing 32 percent of fatalities and serious injuries. This is followed by the vehicle stability function for heavy trucks, which contributes to 20 percent of fatalities and serious injuries prevented. Mexico, with its large population of new and imported used vehicles, presents a larger sample size to model the impact of mandating four vehicle technologies on all vehicles entering the fleet. The percentage of prevented fatalities and serious injuries in Mexico per technologies mandated under Scenario 2 are: ABS for MTWs: 57 percent; advanced emergency braking systems for pedestrians and cyclists: 30.5 percent; front and rear underrun protective devices for heavy duty vehicles: eight percent; vehicle stability function: three percent; and AEBS for LDVs: 1.5 percent.

Table 3.10 Impact of motorization Scenario 2, cumulative impact over 2025–2050 compared to BAU

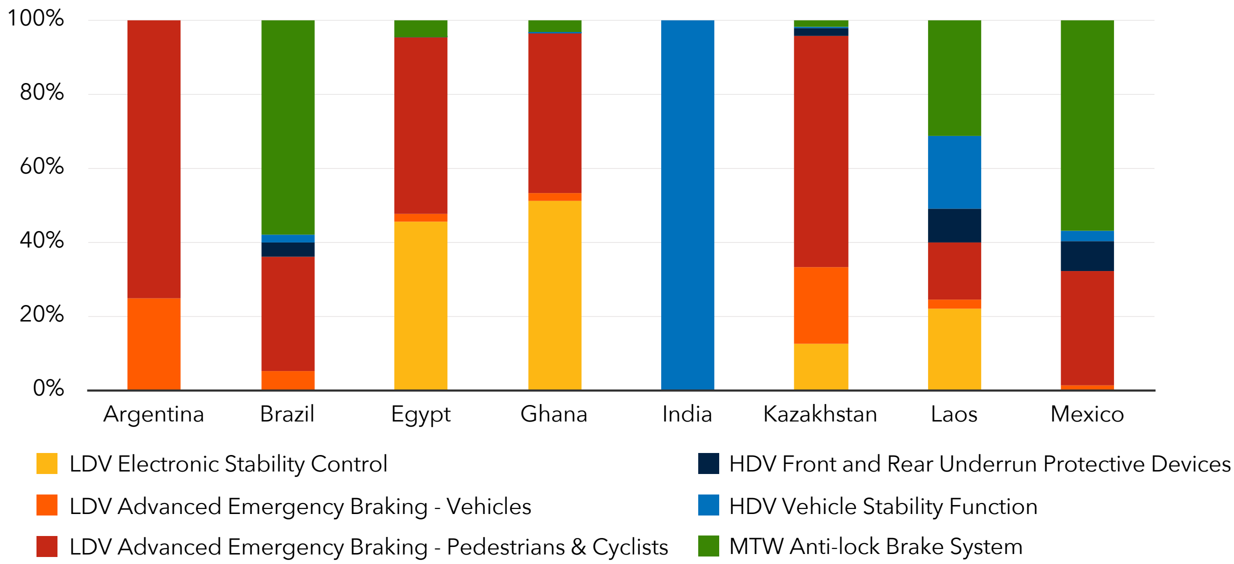
	Crash FSI reduction		$PM_{2.5}$ reduction		NO_x reduction	
	FSI	%	kt	%	kt	%
Argentina	5,953	0.7	7	3	732.4	15.7
Brazil	137,943	2.3	77.6	5	7,139	20.2
Egypt	54,728	3.5	34	9.2	2,135	20.6
Ghana	38,238	8	15.9	13.6	998	30
India	107,009	0.5	N/A	N/A	N/A	N/A
Kazakhstan	9,679	2.1	5.1	5.5	489	18.6
Lao PDR	5,905	3.6	9.1	23	278	30.2
Mexico	44,618	1.5	186.7	17	6,824	38.9

Note: kt=kiloton

Source: Original figure for this publication.

Policy benefits are largely driven by travel mode and crash distribution for a specific country. Countries which have none of the safety technology mandated—Egypt, Ghana, Kazakhstan, and Lao PDR—get maximum benefit from adoption of active braking for pedestrians and cyclists and ESC in LDVs. In addition, the high proportion of MTWs in Lao PDR correlates the anticipated benefits associated with adopting ABS for MTWs, unlike the African countries.

Figure 3.4 Prevented FSI by safety technology mandates per vehicle type (Scenario 2)



Source: Original figure for this publication.

Clean model outcomes for Scenario 2

The trends for air quality outcomes in Scenario 2 (table 3.11) are similar to those in Scenario 1. Euro 6 emission standards provide the maximum reduction in pollutant emissions from 2025 to 2050. In this scenario, reductions of nitrogen oxides emissions under Euro 6 are greater than those of $PM_{2.5}$ in the four countries where the vehicle fleet comprises both new and imported used vehicles.

Table 3.11 Pollutant percentage reduction Scenario 2, cumulative impact over 2025—2050 compared to BAU

	Euro 5		Euro 6	
	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x
Argentina	N/A	N/A	3	15.7
Brazil	N/A	N/A	5	20.2
Egypt	3.1	1.1	9.2	20.6
Ghana	1.7	1.6	13.6	30
India	N/A	N/A	N/A	N/A
Kazakhstan	1.3	3.8	5.5	18.6
Lao PDR	19.1	10.1	23	30.2
Mexico	11.5	5.3	17	38.9

Source: Original table for this publication.

Scenario 3: Safety and emission mandates for new vehicles and imported used vehicles by 2030, with retirement of vehicles older than 20 years that do not meet regulated standards

Scenario 3 shows the model outcomes when all vehicles, new and used imports, are mandated to meet the safety and air quality standards, and vehicles older than 20 years that do not meet these standards must exit circulation. The mandates in Scenario 3 lead to a more significant reduction of pollutant emissions and prevented fatalities and serious injuries than those in scenarios 1 and 2. For example, in Ghana and Egypt, Scenario 3 resulted in a nine percent increase in fatalities and serious injuries prevented and substantial reductions of nitrogen oxides emissions in both countries (table 3.12). This scenario results in many old polluting and unsafe vehicles exiting the country fleet in a short timeframe.

Safety model outcomes for Scenario 3

Mandating the fitment of safety technology for new and imported used vehicles, combined with the removal of unsafe vehicles over 20 years old, results in the most significant prevention of fatalities and serious injuries in all eight countries (figure 3.5). Mandating AEB for pedestrians and cyclists leads to the most fatalities and serious injuries prevented in Argentina, Kazakhstan, and Mexico. In Ghana and Egypt, ESC for LDVs contributes the most to fatalities and serious injuries prevention. In Brazil and Lao PDR, ABS for MTWs are most effective in reducing fatalities and serious injuries. Finally, in India, the adoption of the sole technology of vehicle stability function for heavy duty vehicles, prevents approximately 158,200 fatalities and serious injuries over the 25-year period.

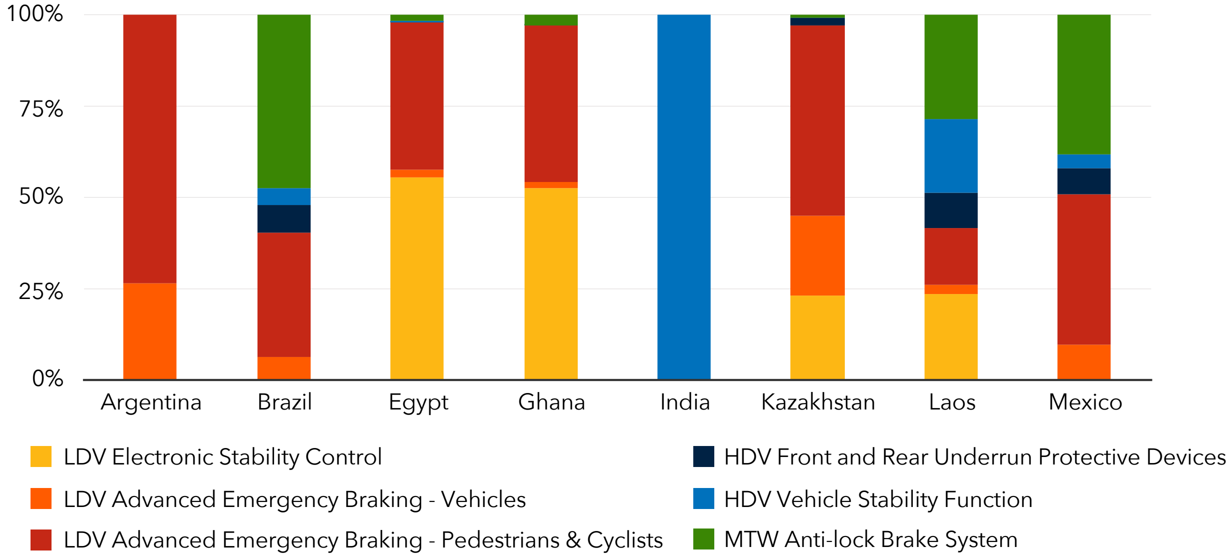
Table 3.12 Impact of motorization Scenario 3, cumulative impact over 2025–2050 compared to BAU

	Crash FSI prevented		$PM_{2.5}$ reduction		NO_x reduction	
	FSI	%	kt	%	kt	%
Argentina	8,045	0.93	17	7.4	1,300	28
Brazil	168,061	3.0	157.6	10.1	11,386	32.2
Egypt	140,921	9.1	72	19.4	4,203	40.6
Ghana	44,793	9.4	29	25.3	1,444	43.5
India	158,183	0.8	N/A	N/A	N/A	N/A
Kazakhstan	28,908	6.4	11	12.1	1,079	41.1
Lao PDR	6,515	4.1	10	25.7	320	34.8
Mexico	75,691	2.3	227	20.6	8,160	46.5

Note: kt=kiloton

Source: Original table for this publication.

Figure 3.5 Prevented FSI by safety technology mandates per vehicle type (Scenario 3)



Source: Original figure for this publication.

Clean model outcomes for Scenario 3

As in scenarios 1 and 2, the adoption of Euro 6 standards in Scenario 3 leads to the maximum reductions of $PM_{2.5}$, which are relatively lower than those of nitrogen oxides. (table 3.13).

Table 3.13 Pollutant percentage reduction Scenario 3, Cumulative impact over 2025–2050 compared to BAU

	Euro 5		Euro 6	
	$PM_{2.5}$	NO_x	$PM_{2.5}$	NO_x
Argentina	N/A	N/A	7.4	28
Brazil	N/A	N/A	10.1	32.2
Egypt	11.4	15.3	19.4	40.6
Ghana	13.1	12.2	25.3	43.5
India	N/A	N/A	N/A	N/A
Kazakhstan	6.1	20.2	12.1	41.1
Lao PDR	21.5	13.1	25.7	34.8
Mexico	9.6	14.7	20.6	46.5

Notes: For Argentina, Brazil and India, the estimation of emission benefits excludes those traceable to vehicle retirement unto itself. The modeling, by design, aims to isolate benefits of adopting stricter emission standards by excluding Argentina and Brazil—that already adopted Euro 5—as well as India—that already adopted Euro 6—from estimates. These three countries are reported as N/A for this reason.

Source: Original table for this publication.

Scenario 4: Electric vehicle (EV) 30x30 uptake as part of diversifying vehicle fleet

In Scenario 4, the safety impact of technology is considered the same for all vehicles in LDV, HDV, and MTW categories, regardless of whether they are EVs or not. Therefore, the fatalities and serious injuries prevented in Scenario 4 are assumed to be equivalent to those prevented in Scenario 1 (table 3.14). The EV 30x30 scenario for air quality introduces motorized road vehicles with no exhaust emissions in most of the case study countries. Shifting a significant share of the vehicle fleet to electric results in notable reductions in nitrogen oxides exhaust emissions. The reductions in $PM_{2.5}$ emissions are comparatively smaller because $PM_{2.5}$ is largely emitted through non-exhaust activities such as breaking and tire wear. The results show that the adoption of Euro 6 standards for vehicles results in more significant reductions of $PM_{2.5}$ and nitrogen oxides than the EV 30x30 scenario.

Crashworthiness tests conducted by the Insurance Institute for Highway Safety (IIHS) and National Highway Traffic Safety Administration (NHTSA) in the US did not find significant differences between the safety performance of EVs and of similar sized internal combustion engine vehicles.

Table 3.14 Impact of motorization Scenario 4, cumulative impact over 2025–2050 compared to BAU

	Crash FSI prevented		$PM_{2.5}$ reduction		NO_x reduction	
	FSI	%	kt	%	kt	%
Argentina	5,953	0.7	13	5.6	633	13.6
Brazil	137,943	2.3	89	5.7	4,964	14
Egypt	54,728	3.5	26	7.1	1,628	15.7
Ghana	2,307	0.5	7	5.8	383	11.5
India	107,009	0.5	195	6.6	6,411	22.8
Kazakhstan	1,479	0.3	6	6.3	257	9.8
Lao PDR	189	0.1	1.1	2.9	48	5.2
Mexico	44,618	1.1	90	8.2	2,417	13.8

Note: kt=kiloton

Source: Original table for this publication.

Scenario 5: Electric vehicle (EV) 50x50 uptake as part of diversifying vehicle fleet

Although a higher percentage and more types of vehicles transition to EVs in Scenario 5 compared to Scenario 4, this transition occurs over a longer timeframe. Consequently, air pollutant emissions in the EV 50x50 scenario are lower than in the BAU scenario, but higher than in Scenario 4, EV 30x30. This finding underscores that the early and sustained introduction of EVs is critical to achieving significant air pollution reductions by 2050.

For the same reasons explained under Scenario 4, the crash fatalities and serious injuries prevented in Scenario 5 are assumed to be equivalent to those prevented in Scenario 1 (table 3.15).

Table 3.15 Impact of motorization Scenario 5, cumulative impact over 2025—2050 compared to BAU

	Crash FSI prevented		$PM_{2.5}$ reduction		NO_x reduction	
	FSI	%	kt	%	kt	%
Argentina	5,953	0.7	7	3.2	331	7.1
Brazil	137,943	2.3	55	3.5	2,741	7.8
Egypt	54,728	3.5	18	4.8	810	7.8
Ghana	2,307	0.5	4	3.5	196	5.9
India	107,009	0.5	118	4	3,253	11.6
Kazakhstan	1,479	0.3	6	6.3	257	9.8
Lao PDR	189	0.1	2	4.7	56	6.1
Mexico	44,618	1.1	32	2.9	839	4.8

Note: kt=kiloton

Source: Original table for this publication.

Aggregate results

While all scenarios result in reduced fatalities and serious injuries and air pollution relative to BAU, the change in these outcomes varies significantly depending on the vehicles that are required to comply with them (table 3.16). Requiring imported used vehicles to comply with safety standards, Scenario 2, prevents more fatalities and serious injuries that only mandating new vehicles in all countries that permit such imports—Scenario 1— but also banning of older vehicles that do not meet safety standards, Scenario 3, is required to achieve the maximum fatalities and serious injuries prevention. In countries such as Egypt and Kazakhstan, Scenario 3 results in approximately a threefold increase in prevented fatalities and serious injuries compared in Scenario 2.

Table 3.16 Cross-country comparision of safety and emissions outcomes (in % reduction compared to BAU)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Crash FSI					
Argentina	0.7	0.7	0.9	0.7	0.7
Brazil	2.3	2.3	3.0	2.3	2.3
Egypt	3.5	3.5	9.1	3.5	3.5
Ghana	0.5	8.0	9.4	0.5	0.5
India	0.5	0.5	0.8	0.5	0.5
Kazakhstan	0.3	2.1	6.4	0.3	0.3
Lao PDR	0.1	3.6	4.1	0.1	0.1
Mexico	1.1	1.5	2.3	1.1	1.1
$PM_{2.5}$					
Argentina	3.0	3.0	7.4	5.6	3.2
Brazil	5.0	5.0	10.1	5.7	3.5
Egypt	9.2	9.2	19.4	7.1	4.8
Ghana	6.9	13.6	25.3	5.8	3.5
India	N/A	N/A	N/A	6.6	4.0
Kazakhstan	5.1	5.5	12.1	6.3	6.3
Lao PDR	16.3	23.0	25.7	2.9	4.7
Mexico	10.7	17.0	20.6	8.2	2.9
NO_x					
Argentina	15.7	15.7	28	13.6	7.1
Brazil	20.2	20.2	32.2	14	7.8
Egypt	20.6	20.6	40.6	15.7	7.8
Ghana	20	30	43.5	11.5	5.9
India	N/A	N/A	N/A	22.8	11.6
Kazakhstan	17.6	18.6	41.1	9.8	9.8
Lao PDR	26.6	30.2	34.8	5.2	6.1
Mexico	17.8	38.9	46.5	13.8	4.8

Notes: All scenarios assume raising the emission standards to Euro 6. The modeling, by design, aims to isolate benefits of adopting stricter emission standards excluding from estimations India, that already adopted Euro 6. Those emission gains are reported as N/A for that reason

Source: Original table for this publication.

Similarly, adding the requirement that older, non-compliant vehicles exit the fleet—Scenario 3—results in the most significant reductions of $PM_{2.5}$ and nitrogen oxides across countries, often twice as large as those achieved by requiring new and imported used vehicles to meet emission standards but not including older in-use vehicles in the mandate, Scenario 2. The prescribed Euro standards only limit tailpipe emissions. Consequently, electrification scenarios show a significant reduction in nitrogen oxides emissions, but relatively minor reductions in $PM_{2.5}$, which is largely emitted from non-exhaust activities. The adoption of Euro 6 standards for vehicles results in more significant reductions of $PM_{2.5}$ and nitrogen oxides than the increased participation of EVs in the fleet.

The impact from adoption of safety technology could be significant—a comprehensive policy adoption on LDV, HDV, and MTW, could reduce FSI up to nine percent in the medium term. Countries that rely on used import vehicles stand to gain the most, for instance, Egypt, Ghana.

3.3 Quantifying the potential economic benefits of improved vehicle standard adoption

For illustrative purposes, the present value (PV) of the economic benefits from the adoption of safety technology was calculated for Scenario 3, as it is the most comprehensive policy change among all scenarios affecting new, used, and older vehicles. Remaining scenarios would yield fewer economic benefits. Table 3.17 compares the PV economic benefit from safety technology adoption, Scenario 3, for the selected countries. Based on the analysis, Brazil shows the maximum potential for economic benefits on account of a combination of three factors: relatively high gross national income per capita, high magnitude of fatalities and serious injury, and finally compliance on several advanced safety technology yet to be in place. India on the other hand, which has a very high magnitude of fatalities and serious injuries, has relatively less potential for economic savings due to low gross national income per capita and as most safety technologies have already been mandated. Such estimates of economic benefits from adoption of safety technology can be used for cost–benefit analysis and policy prioritization.

Table 3.17 PV of the safety benefit estimated for Scenario 3 over the period 2025–2050

	GNI per capita (2020)	Economic benefit from FSI saved - (Scenario 3, PV)
	USD	billion USD
Argentina	9,040	17.1
Brazil	8,080	68.8
Egypt, Arab Rep.	2,960	23.5
Ghana	2,250	19.9
India	1,900	14.2
Kazakhstan	8,380	11.8
Lao PDR	2,470	2.8
Mexico	8,920	27.7

Source: Original table for this publication.

In an indicative manner rather than precise quantification, this report estimates economic benefits from adopting safety and vehicle emission standards. The numbers are only indicative for two reasons. First, because the gains in saved lives and avoided disabilities assumed that adoption comes in tandem with enforcement, that it is the exception rather than the norm in practice, and that their assessment was out of the scope of this study. It is assumed that once adopted, a standard is enforced. Second, and perhaps more complex, is that the model estimates reductions of pollutants, $PM_{2.5}$ and nitrogen oxides. However, estimating improved health outcomes from improved air quality requires an understanding how pollutant reductions translate into air pollutant exposure. To better understand how this should be done, it is important to consider the difference between primary and secondary $PM_{2.5}$ emissions and their relationship with exposure.

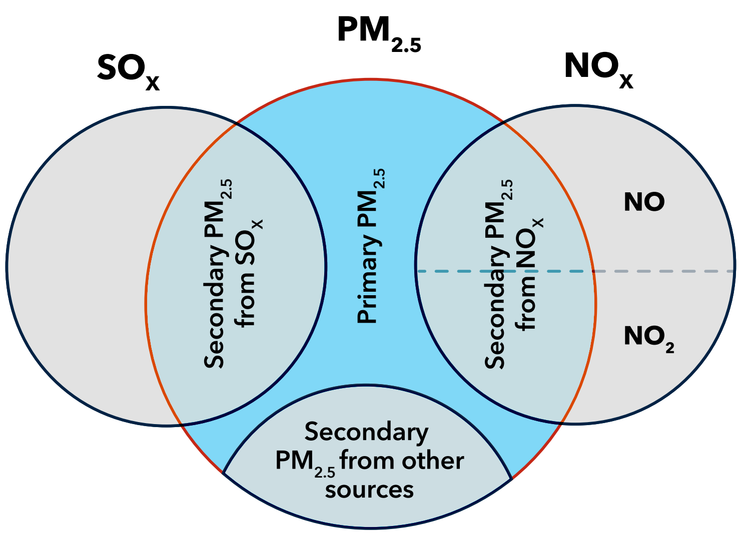
Primary $PM_{2.5}$ emissions are directly emitted from vehicles. These include tailpipe emissions—particles released directly from the exhaust of cars, trucks, and other vehicles—consisting of soot, metals, and other particulate matter. Primary emissions also include non-exhaust emissions, such as particles re-entrained from the road surface, including dust from tire and brake wear.

Secondly, $PM_{2.5}$ emissions are formed through chemical reactions in the atmosphere. They originate from precursor gases emitted by vehicles, such as sulfur dioxide, nitrogen oxides, and volatile organic compounds. These reactions typically occur downwind from the emission source and are influenced by factors such as sunlight, temperature, and humidity. Secondary $PM_{2.5}$ often constitutes the majority of total $PM_{2.5}$ levels in urban and regional areas, especially during pollution peaks (Kuang et al, 2022; Rattanapotanan et al, 2023; Zhang et al, 2022).

Modeling both pollution levels and human exposure is essential to assess the health impacts of air pollution. Pollution modeling is required to estimate the percentage of precursor gases (sulfur dioxide, nitrogen oxides, and volatile organic compounds) that is converted into secondary $PM_{2.5}$ and the percentage that remains as other pollutants, like nitrogen dioxide. However, the team preparing this report was unable to find publicly available data on such modeling for the transport sector. In the absence of this data, estimates must rely on bold assumptions, particularly regarding the conversion percentages to estimate how the reductions in nitrogen oxides affect secondary $PM_{2.5}$ and in nitrogen dioxide emissions (figure3.6).

Modeling the relationship between air pollution emissions and air pollution exposure —the amount of pollution that people breathe—is extremely complex and also out of the scope of this report. This would include the use of chemical transport models that integrate emissions, meteorological, geographical, and land use data and reaction pathways for atmospheric chemistry to simulate the dispersion and chemical transformation of pollutants in the atmosphere. These data would need to be combined with information on the number of people living in specific areas, country level or airshed, to estimate exposure levels. The study did not contemplate such modeling because it is quite costly and labor intensive.

Figure 3.6 Primary and secondary $PM_{2.5}$ emissions



Notes: Simplified figure for illustrative purposes. The image does not intend to illustrate the chemical reactions leading to the formation of different air pollutants. It excludes key chemicals and pollutants, such as ground-level ozone or volatile organic compounds.

Source: Original figure for this publication.

With all these caveats, a ballpark envelope of the potential economic benefits of adopting safety and emission standards are estimated and presented in table 3.18. The economic benefits of vehicle emission reductions are not additive—as addition would likely involve double counting (e.g. between $PM_{2.5}$ and NO_2) —and because the economic benefit of avoided IQ losses is estimated as income gains rather than using the value of statistical life approach.

Notably the benefits of NO_x or NO_2 emission reductions are substantially larger than the benefits of $PM_{2.5}$ reductions in the three LAC countries and of a similar order of magnitude in the other countries.

Table 3.18 Envelope of potential economic benefits due to improved vehicle standards, cumulative benefit over 2025-2050

		Road crash FSI		PM2.5 prematue deaths		NO2 premature deaths		PM2.5- IQ Losses	
	Country	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent
Scenario 1	Argentina	2,625	0.5	1,107	0.2	7,705	1.6	742	0.2
	Brazil	44,850	2.9	3,274	0.2	26,849	1.6	2,233	0.1
	Egypt	8,750	2.1	5,345	1.3	3,950	0.9	2,820	0.7
	Ghana	375	0.5	116	0.1	N/A	N/A	362	0.4
	India	12,500	0.4	N/A	N/A	N/A	N/A	N/A	N/A
	Kazakhstan	450	0.2	866	0.4	657	0.3	444	0.2
	Lao PDR	25	0.1	110	0.6	N/A	N/A	163	0.9
	Mexico	14,575	1.2	14,490	1.1	41,703	3.2	6,733	0.5
Scenario 2	Argentina	2,625	0.5	1,107	0.2	7,705	1.6	742	0.2
	Brazil	44,850	2.9	3,274	0.2	26,849	1.6	2,233	0.1
	Egypt	8,750	2.1	5,345	1.3	3,950	0.9	2,820	0.7
	Ghana	6,000	8.4	228	0.3	N/A	N/A	714	0.9
	India	12,500	0.4	N/A	N/A	N/A	N/A	N/A	N/A
	Kazakhstan	3,150	1.7	934	0.5	695	0.4	479	0.2
	Lao PDR	900	2.9	155	0.8	N/A	N/A	230	1.2
	Mexico	19,875	1.6	23,022	1.8	91,137	7.1	10,697	0.8
Scenario 3	Argentina	3,375	0.7	2,731	0.6	13,742	2.9	1,830	0.4
	Brazil	58,500	3.8	6,613	0.4	42,798	2.6	4,510	0.3
	Egypt	22,750	5.5	11,271	2.7	7,784	1.8	5,946	1.4
	Ghana	7,050	9.9	424	0.5	N/A	N/A	1,328	1.6
	India	20,000	0.7	N/A	N/A	N/A	N/A	N/A	N/A
	Kazakhstan	9,600	5.3	2,054	1.1	1,535	0.8	1,053	0.5
	Lao PDR	1,025	3.3	173	0.9	N/A	N/A	257	1.3
	Mexico	30,475	2.4	27,898	2.2	108,943	8.4	12,962.6	1.0

		Road crash FSI		PM2.5 prematue deaths		NO2 premature deaths		PM2.5- IQ Losses	
	Country	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent	US$ million	% of GDP equivalent
Scenario 4	Argentina	2,625	0.2	2,066	0.4	6,674	1.4	1,385	0.3
	Brazil	44,850	0.1	3,732	0.2	18,608	1.1	2,545	0.2
	Egypt	8,750	0.7	4,125	1.0	3,010	0.7	2,176	0.5
	Ghana	375	0.7	97	0.1	N/A	N/A	305	0.4
	India	12,500	1.9	16,909	0.5	22,197	0.7	13,908	0.4
	Kazakhstan	450	2.9	1,069	0.6	366	0.2	548	0.3
	Lao PDR	25	0.4	20	0.1	N/A	N/A	29	0.2
	Mexico	14,575	0.5	11,105	0.9	32,331	2.5	5,160	0.4
Scenario 5	Argentina	2,625	0.5	1,181	0.2	3,484	0.7	791	0.2
	Brazil	44,850	2.9	2,292	0.1	10,367	0.6	1,563	0.1
	Egypt	8,750	2.1	2,789	0.7	1,495	0.4	1,471	0.3
	Ghana	375	0.5	59	0.1	N/A	N/A	184	0.2
	India	12,500	0.4	10,248	0.3	11,293	0.4	8,429	0.3
	Kazakhstan	450	0.2	1,069	0.6	366	0.2	548	0.3
	Lao PDR	25	0.1	32	0.2	N/A	N/A	47	0.2
	Mexico	14,575	1.2	3,927	0.3	11,246	0.9	1,825	0.1

Notes:

The benefits of Scenario N (N=1,...,5) are calculated as: cost of health impacts in 2021 from road transport emissions multiplied by percent reduction in road transport emissions in Scenario N divided by GDP in 2021 and multiplied by 100.

All scenarios assumed raising the emission standards to EURO 6.

The modeling, by design, aims to isolate benefits of adopting stricter emission standards excluding from estimations India, that already adopted EURO 6. Those emission gains are reported as N/A for that reason.

Source: Original table for this publication.

Notes

1. Scenario 1 corresponds to new vehicles entering the fleet are mandated by 2030 to meet study prescribed safety and air quality standards while used vehicle imports may or may not meet new standards.

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Chapter 4. Policy Implications for Decision Makers

This chapter explores strategic approaches to adopting safety and emission standards for alternative scenarios. It provides evidence-based recommendations to inform decision making utilizing the model's results and highlighting the patterns and benefits of five alternative policy options.

(i) Cumulative adoption of standards for new vehicles, for used vehicle imports, and old fleet retirement.
(ii) Alternative of either adoption of vehicle standards in new vehicles together with fleet retirement, or adoption of vehicle standards in new vehicles together with targets for electric vehicle adoption.
(iii) Alternative of either adoption of vehicle standards in new vehicles together with standards for used vehicle imports or adoption of vehicle standards in new vehicles together with targets for electric vehicle adoption
(iv) Alternative of adopting either emission standard Euro 5 or emission standard Euro 6
(v) Alternative option of electric vehicle adoption between either thirty percent of electric new vehicles for 2030 or 50 percent of electric new vehicles for 2050.

The proposed policy options are clearly a starting point to bring out specific and evidence-supported recommendations to countries in adoption of safety and emission standards for vehicles. The goal is that this model can be replicated for other countries and policy scenarios to document the enormous human capital implications of regulating fleet and related motorization management policies.

Policy option 1: Cumulative adoption of standards in new vehicles, standards in used vehicle imports, and old fleet retirement

Policy makers may consider mandating vehicle standards incrementally: (i) require safety and emission standards for new vehicles, scenario 1; (ii) require safety and emission standards for both new vehicles and used imports, scenario 2, or (iii) require safety and emission standards for both new vehicles and used imports while also mandating the retirement of non-roadworthy vehicles, scenario 3.

The model's results indicate that regulating new vehicles alone has limited impact if there is no requirement for fleet retirement, as the largest gains tend to be achieved when old (over twenty-year old), non-roadworthy vehicles are removed from the fleet, particularly in what pertains to emission reduction (Table 4.1). In practice this involves mandating vehicle standards but also setting in place vehicle periodic technical inspection procedures and incentives for scrapping when needed. For health benefits linked to air pollution, the most impactful policy is the retirement of old fleet. The reductions of $PM_{2.5}$ and NO_x increase in order of magnitude when retirement is added to improving vehicle standards.

The most impactful focus to increased road safety is projected to materialize when improving standards of used imports and fleet retirement. For instance, in Kazakhstan, Ghana and Laos the safety benefits were 6, 15 and 35 times higher respectively, if standards are mandated for new vehicles, used import and fleet retirement as opposed to adopting standards for new vehicles only. This necessarily involves period vehicle inspections to enforce the mandated standards and to manage the fleet retirement program.

Good vehicle inspection practices also make sure benefits of stricter standards of air pollution emissions percolate throughout a country's vehicle stock. The benefits of emissions standards fully depend on the proper and sustained use of relevant technologies like diesel particle filters for $PM_{2.5}$ and selective catalytic reduction systems for nitrogen oxides. Ultra-low sulfur diesel, less than 10 parts per million, is generally required by Euro 5 and Euro 6-compliant technology. Higher sulfur content in diesel can reduce the potential benefits of stricter emission standards.

Table 4.1 Gains of adoption of alternative standards: policy option 1

Incremental Gains from BAU by Adoption of Standards (% Reduction)				
		Scenario 3		
		Scenario 2		
		Scenario 1		
Impact	**Country**	**Standards in New Vehicles**	**Standards in Used Vehicle Import**	**Retirement of old fleet**
FSI	Argentina	0.7	N/A	0.2
	Brazil	2.3	N/A	0.7
	Egypt	3.5	N/A	5.6
	Ghana	0.5	7.5	1.4
	India	0.5	N/A	0.3
	Kazakhstan	0.3	1.8	4.3
	Lao PDR	0.1	3.5	0.5
	Mexico	1.1	0.4	0.8
$PM_{2.5}$	Argentina	3.0	N/A	4.4
	Brazil	5.0	N/A	5.1
	Egypt	9.2	N/A	10.2
	Ghana	6.9	6.7	11.7
	India	N/A	N/A	N/A
	Kazakhstan	5.1	0.4	6.6
	Lao PDR	16.3	6.7	2.7
	Mexico	10.7	6.3	3.6
NO_x	Argentina	15.7	N/A	12.3
	Brazil	20.2	N/A	12.0
	Egypt	20.6	N/A	20.0
	Ghana	20.0	10.0	13.5
	India	N/A	N/A	N/A
	Kazakhstan	17.6	1.0	22.5
	Lao PDR	26.6	3.6	4.6
	Mexico	17.8	21.1	7.6

Notes:
a. Aspirational Safety Standards: (i) Electronic Stability Control in LDVs, (ii) Advanced Emergency Braking for vehicles in LDVs, (iii) Advanced Emergency Braking for pedestrians and cyclists in LDVs; (iv) Front- and Rear-Underrun Protective Devices in HDVs, (v) Vehicle Stability Function in HDVs; and (vi) Anti-lock Brake System in MTWs.
b. Aspirational Emission Standard: Euro 6

Source: Original table for this publication.

Ghana, Kazakhstan, and Lao PDR benefit less than one percent reduction in FSI by only focusing on new vehicles entering the fleet, however, when a comprehensive policy is adopted for used vehicle entering the fleet and retiring old vehicles, the benefits improve approximately by four to nine percent. For countries which have a domestic automotive manufacturing industry but have not mandated the adoption of advanced technology, incremental benefits can be achieved by focusing on new vehicles, used vehicles and vehicle scrappage.

Policy option 2. Alternative of either adoption of vehicle standards in new vehicles together with fleet retirement or adoption of vehicle standards in new vehicle together with targets for electric vehicle adoption

Policy makers in countries that have prohibited the import of used vehicles such as Argentina, Brazil, Egypt, and India, may consider two strategic options: require that new vehicles comply with established safety and emission standards, while also mandating the retirement of non-compliant vehicles over 20 years old, as in Scenario 3, or (ii) apply the same requirement for new vehicles, combined with the adoption of an EV 30x30 target—aiming for 30 percent of new cars, buses, and minibuses, and 70 percent of new motorcycles to be electric by 2030, as in Scenario 4.

While both approaches aim to modernize the vehicle fleet and reduce emissions, the findings suggest that developing and emerging economies derive significantly higher safety and emission reduction benefits from retiring older, high-emitting vehicles than from focusing on ambitious electrification targets. In all countries analyzed—except India—the benefits from circulation outweigh those of implementing the EV target. India is a notable exception due to its adoption of the Euro 6 standard to improve the emissions profile of its vehicle fleet. As a result, further gains from fleet renewal are limited in comparison to electrification (table 4.2).

Table 4.2 Gains of adoption of alternative standards: policy option 2

Gains with Respect to BAU by Adoption of Standards (% Reduction)			
		Scenario 3	Scenario 4
Impact	Country	Standards in New Vehicles together with Fleet Retirement	Standards in New Vehicles together with Electric Vehicles 30x30
FSI	Argentina	0.9	0.7
	Brazil	3.0	2.3
	Egypt	9.1	3.5
	India	0.8	0.5
$PM_{2.5}$	Argentina	7.4	5.6
	Brazil	10.1	5.7
	Egypt	19.4	7.1
	India	N/A	6.6
NO_x	Argentina	28.0	13.6
	Brazil	32.2	14.0
	Egypt	40.6	15.7
	India	N/A	22.8

Notes:
a. Aspirational Safety Standards: (i) Electronic Stability Control in LDVs, (ii) Advanced Emergency Braking for vehicles in LDVs, (iii) Advanced Emergency Braking for pedestrians and cyclists in LDVs; (iv) Front- and Rear-Underrun Protective Devices in HDVs, (v) Vehicle Stability Function in HDVs; and (vi) Anti-lock Brake System in MTWs.
b. Aspirational Emission Standard: Euro6

Source: Original table for this publication.

Policy option 3. Alternative of either adoption of vehicle standards in new vehicle together with standards in used vehicle imports or adoption of vehicle standards in new vehicles together with targets for electric vehicle adoption

In countries that still allow the importation of used vehicles—such as Ghana, Kazakhstan, Lao PDR, and Mexico—policy may compare two strategic options: (i) mandate that all imported vehicles, both new and used, comply with established safety and emission standards as in Scenario 2, or (ii) apply these standards only to new imported vehicles, while simultaneously adopting the EV 30x30 target, as in Scenario 4.

The results show that the safety and emissions benefits of Scenario 2 are significantly greater—often by orders of magnitude—than those under Scenario 4. While promoting EVs may be politically appealing, it is the regulation of used vehicle imports that offers the most immediate and significant gains in air quality and road safety (table 4.3).

Table 4.3 Gains of adoption of alternative standards: policy option 3

Gains with Respect to BAU by Adoption of Standards (% Reduction)			
		Scenario 2	Scenario 4
Impact	Country	Standards in New Vehicles and Standards in Imported Used Vehicles	Standards in New Vehicles together with Electric Vehicles 30x30
FSI	Ghana	8.0	0.5
	Kazakhstan	2.1	0.3
	Lao PDR	3.6	0.1
	Mexico	1.5	1.1
$PM_{2.5}$	Ghana	13.6	5.8
	Kazakhstan	5.5	6.3
	Lao PDR	23.0	2.9
	Mexico	17.0	8.2
NO_x	Ghana	30.0	11.5
	Kazakhstan	18.6	9.8
	Lao PDR	30.2	5.2
	Mexico	38.9	13.8

Notes:
a. Aspirational Safety Standards: (i) Electronic Stability Control in LDVs, (ii) Advanced Emergency Braking for vehicles in LDVs, (iii) Advanced Emergency Braking for pedestrians and cyclists in LDVs; (iv) Front- and Rear-Underrun Protective Devices in HDVs, (v) Vehicle Stability Function in HDVs; and (vi) Anti-lock Brake System in MTWs.
b. Aspirational Emission Standard: Euro 6

Source: Original table for this publication.

Policy option 4. Alternative of adopting emission standard Euro 5 or emission standard Euro 6 (or even fleet electrification)

Countries such as Egypt, Ghana, Kazakhstan, Lao PDR, and Mexico operate under the Euro 4 or lower vehicle emission standard. Policy makers in these countries face a critical decision—whether to adopt Euro 5 incrementally or to leapfrog directly to the more stringent Euro 6 standard.

Adopting Euro 6 offers significantly greater reductions in harmful emissions—particularly nitrogen oxides—compared to Euro 5. This leapfrogging strategy presents a powerful opportunity to maximize public health benefits, including reductions in premature mortality, morbidity, and cognitive impairments linked to vehicle-related air pollution.

Vehicles must be equipped with advanced emissions control technologies to comply with these standards, such as diesel particle filters to reduce $PM_{2.5}$ emissions and selective catalytic reduction systems to control nitrogen oxide emissions. These technologies require the use of ultra-low sulfur diesel, with sulfur content below 10 parts per million. Therefore, the success of stricter emission standards hinges on two critical enablers: (i) upgrade national fuel quality standards to ensure the availability of ultra-low sulfur diesel, and (ii) implement robust vehicle inspection and maintenance programs to verify the functionality of emissions control systems (table 4.4).

Policy option 4-1 compares Euro 5 with Euro 6 emission standards, while policy option 4-2 compares Euro 5 with Euro 6 emission standards as well as with the EV 30x30 emission scenario.

Table 4.4 Gains of adoption of alternative emission standards: policy option 4-1

<table>
<tr><th colspan="5">(Ratio Gains Euro 6 over Gains Euro 5)</th></tr>
<tr><th colspan="2"></th><th>Country</th><th>$PM_{2.5}$</th><th>NO_x</th></tr>
<tr><td rowspan="5">Scenario 1</td><td rowspan="5">Standards in New Vehicles</td><td>Egypt</td><td>2.97</td><td>18.73</td></tr>
<tr><td>Ghana</td><td>4.93</td><td>16.67</td></tr>
<tr><td>Kazakhstan</td><td>5.67</td><td>3.74</td></tr>
<tr><td>Lao PDR</td><td>1.33</td><td>4.09</td></tr>
<tr><td>Mexico</td><td>1.29</td><td>4.94</td></tr>
<tr><td rowspan="5">Scenario 2</td><td rowspan="5">New Vehicles and Standards in Used Vehicles</td><td>Egypt</td><td>2.97</td><td>18.73</td></tr>
<tr><td>Ghana</td><td>8.00</td><td>18.75</td></tr>
<tr><td>Kazakhstan</td><td>4.23</td><td>4.89</td></tr>
<tr><td>Lao PDR</td><td>1.20</td><td>2.99</td></tr>
<tr><td>Mexico</td><td>1.48</td><td>7.34</td></tr>
<tr><td rowspan="5">Scenario 3</td><td rowspan="5">Standards in New Vehicles and Standards in Used Vehicles and Retirement</td><td>Egypt</td><td>1.70</td><td>2.65</td></tr>
<tr><td>Ghana</td><td>1.93</td><td>3.57</td></tr>
<tr><td>Kazakhstan</td><td>1.98</td><td>2.03</td></tr>
<tr><td>Lao PDR</td><td>1.20</td><td>2.66</td></tr>
<tr><td>Mexico</td><td>2.15</td><td>3.16</td></tr>
</table>

Source: Original table for this publication.

An additional policy question is whether for new fleet emission mandates, one should think about leapfrogging even further and embrace an ambitious electrification agenda. The answer is not totally clear without analyzing the out-of-pocket and total cost of operation. What does emerge from the analysis is that –without any other consideration such as used-vehicle regulation or scrapping—in countries with Euro 4 and lower, the largest emission savings come from leapfrogging to Euro 6. Electrification brings emission gains significantly larger than mandating an incremental standard improvement to Euro 5, but not yet as high as moving to Euro 6 (table 4.5)

Table 4.5 Gains of adoption of alternative emission standards: policy option 4-2

Changes from BAU by Adoption of Standards (% Reduction)			
	Euro 5	**Euro 6**	**EV 30x30**
		$PM_{2.5}$	
Egypt	3.1	9.2	7.1
Ghana	1.4	6.9	5.8
Kazakhstan	0.9	5.1	6.3
Lao PDR	12.3	16.3	2.9
Mexico	8.3	10.7	8.2
		NO_x	
Egypt	1.1	20.6	15.7
Ghana	1.2	20	11.5
Kazakhstan	4.7	17.6	9.8
Lao PDR	6.5	26.6	5.2
Mexico	3.6	17.8	13.8

Source: Original table for this publication.

Policy Option 5. Alternative rates of electric vehicle adoption between either 30 percent of electric new vehicles for 2030 or 50 percent of electric new vehicles for 2050

Policy makers face a choice between two electrification scenarios differing timelines and levels of ambition. EV 30x30 targets 30 percent electrification of new cars, buses, and minipacebuses, and 70 percent of new motorcycles by 2030, as in Scenario 4. EV 50x50 aims for 50 percent of new cars, buses, minibuses, motorcycles, and vans to be electric by 2050, and 50 percent of new trucks by 2050, as in Scenario 5.

While EV50x50 covers a broader range of vehicles and achieves higher electrification rates, its longer implementation timeline results in lower cumulative emission reductions compared to the more immediate targets of EV 30x30. This comparison highlights the importance of early and sustained policy implementation to achieving greater air quality and health benefits over the coming decades (table 4.6).

Table 4.6 Gains of cumulative adoption of standards: policy option 5

Gains with Respect to BAU by Adoption of Standards (% Reduction)			
		Scenario 4	**Scenario 5**
Impact	Country	Standards in New Vehicles together with Electric Vehicles 30x30	Standards in New Vehicles together with Electric Vehicles 50x50
$PM_{2.5}$	Argentina	5.6	3.2
	Brazil	5.7	3.5
	Egypt	7.1	4.8
	Ghana	5.8	3.5
	India	6.6	4
	Kazakhstan	6.3	6.3
	Lao PDR	2.9	4.7
	Mexico	8.2	2.9
NO_x	Argentina	13.6	7.1
	Brazil	14	7.8
	Egypt	15.7	7.8
	Ghana	11.5	5.9
	India	22.8	11.6
	Kazakhstan	9.8	9.8
	Lao PDR	5.2	6.1
	Mexico	13.8	4.8

Note:
a. Aspirational Safety Standards: (i) Electronic Stability Control in LDVs, (ii) Advanced Emergency Braking for vehicles in LDVs, (iii) Advanced Emergency Braking for pedestrians and cyclists in LDVs; (iv) Front- and Rear-Underrun Protective Devices in HDVs, (v) Vehicle Stability Function in HDVs; and (vi) Anti-lock Brake System in MTWs.
b. Aspirational Emission Standard: Euro 6

Source: Original table for this publication.

Appendix A: Countries-At-A-Glance

Argentina

Country context and motorization characteristics

Region		Latin America
Income category		Upper middle
GDP per capita (current US$)		14,187
Population (million)		45.5
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		26,413,085 [583]
Ambient $PM_{2.5}$ (µg/m3)		17
Ambient air pollutant contribution from road transport (%), 2017	$PM_{2.5}$	9.0
	NO_2	44

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
Fatality (annual) - IRTAD Road Safety Country Profile - Argentina 2023
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✗
	New Vehicles	✓
LDV	Electronic Stability Control	✓
	Advanced Emergency Breaking - Vehicles	✗
	Advanced Emergency Breaking - pedestrians & cyclists	✗
HDV	Front and Rear Underrun Protective Devices	✓
	Vehicle Stability Function	✓
MTW	Anti-lock Brake System	✓
Adoption of Vehicle Emission Standards	Euro 4	✗
	Euro 5	✓
	Euro 6	✗

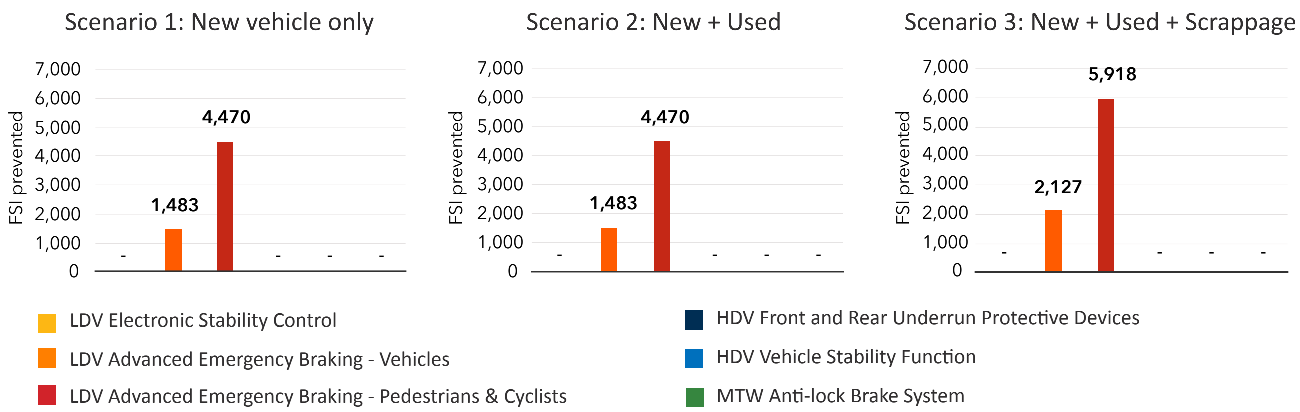
Source: Original table for this publication.

Health and cognitive impacts of motorization

Road fatality, 2021 (number)		3,983
Fatality rate per 100,000, 2021 (number)		8.8
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	1,374
	NO_2	1,830
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	0.3

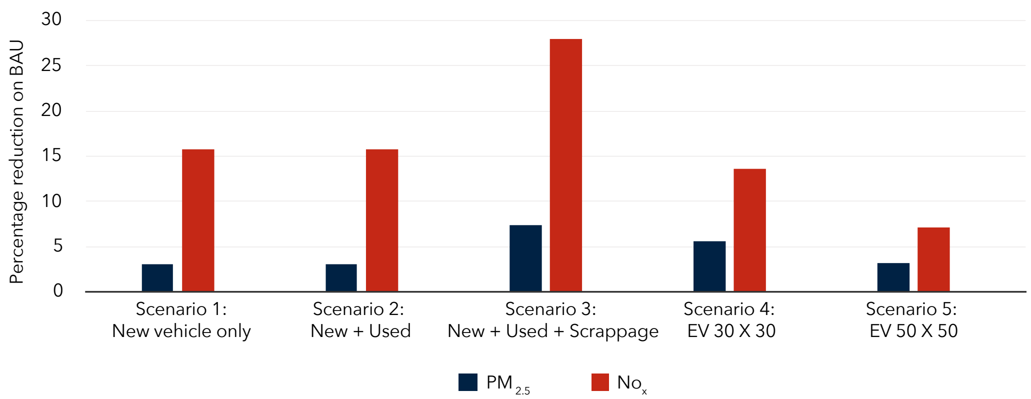
Source: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data)

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as a difference from BAU)



Note: Dashes represent that this technology/vehicle type is not applicable.

Argentina 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Brazil

Country context and motorization characteristics

Region		Latin America
Income category		Upper middle
GDP per capita (current US$)		10,295
Population (million)		211.1
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		111,446,870 [520]
Ambient $PM_{2.5}$ (µg/m3)		16
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	6.3
	NO_2	48

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✘
	New Vehicles	✓
LDV	Electronic Stability Control	✓
	Advanced Emergency Breaking - Vehicles	✘
	Advanced Emergency Breaking - pedestrians & cyclists	✘
HDV	Front and Rear Underrun Protective Devices	✘
	Vehicle Stability Function	✘
MTW	Anti-lock Brake System	✘
Adoption of Vehicle Emission Standards	Euro 4	✘
	Euro 5	✓
	Euro 6	✘

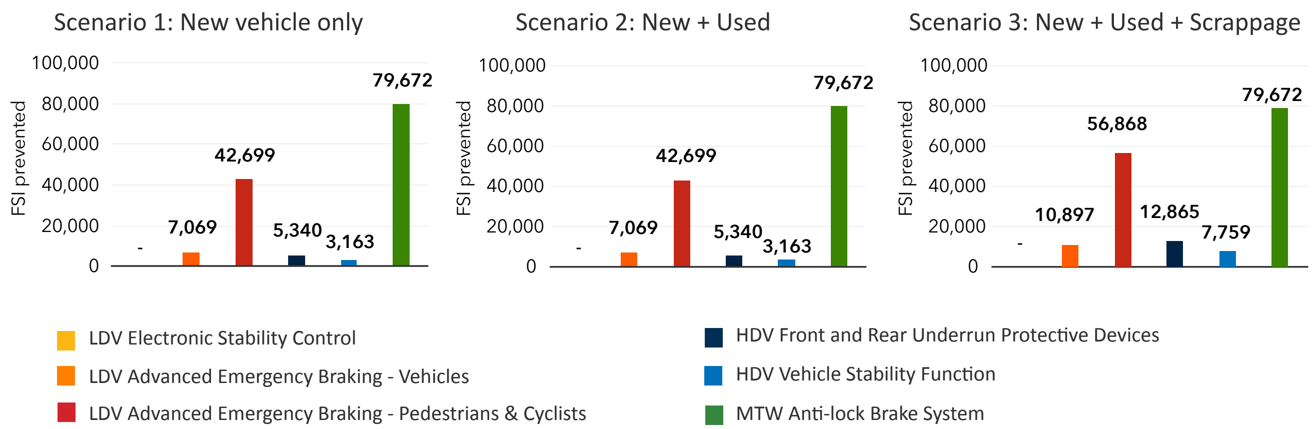
Source: Original table for this publication.

Health and cognitive impacts of motorization

Road fatality, 2021 (number)		33,586
Fatality rate per 100,000, 2021 (number)		15.7
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	3,339
	NO_2	6,772
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	0.74

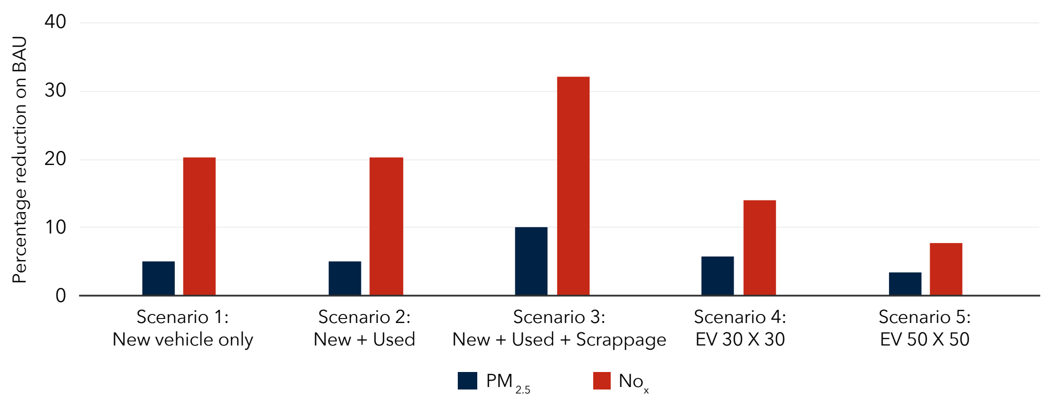
Source: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data)

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as a difference from BAU)



Note: Dashes represent that this technology/vehicle type is not applicable.

Brazil 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Arab Republic of Egypt

Country context and motorization characteristics

Region		Middle East
Income category		Lower middle
GDP per capita (current US$)		3,457
Population (million)		114.5
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		10,909,456 [100]
Ambient $PM_{2.5}$ (µg/m3)		60
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	5.8
	NO_2	17

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	x
	New Vehicles	✓
LDV	Electronic Stability Control	x
	Advanced Emergency Breaking - Vehicles	x
	Advanced Emergency Breaking - pedestrians & cyclists	x
HDV	Front and Rear Underrun Protective Devices	x
	Vehicle Stability Function	x
MTW	Anti-lock Brake System	x
Adoption of Vehicle Emission Standards	Euro 4	✓
	Euro 5	x
	Euro 6	x

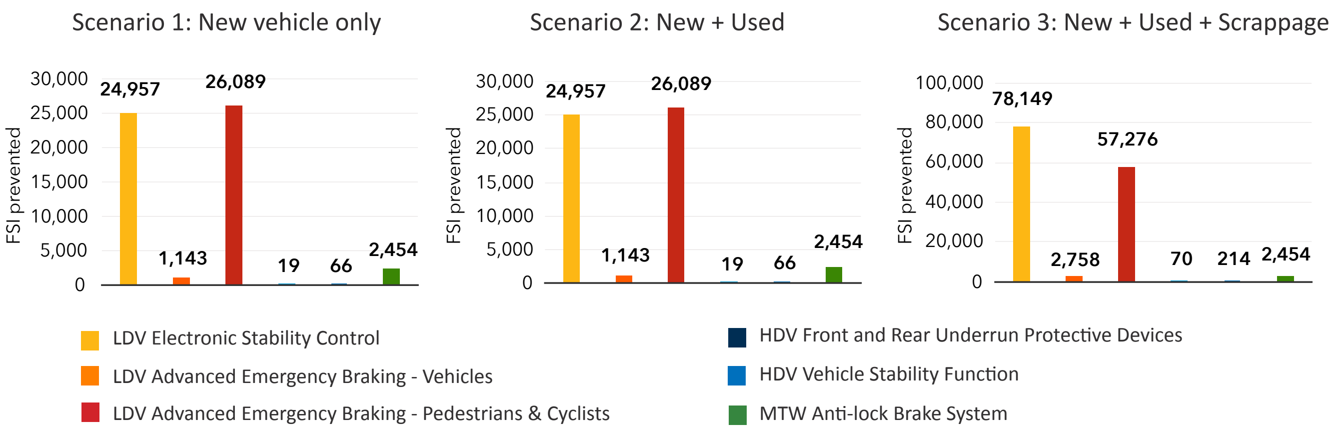
Source: Original table for this publication.

Health and cognitive impacts of motorization

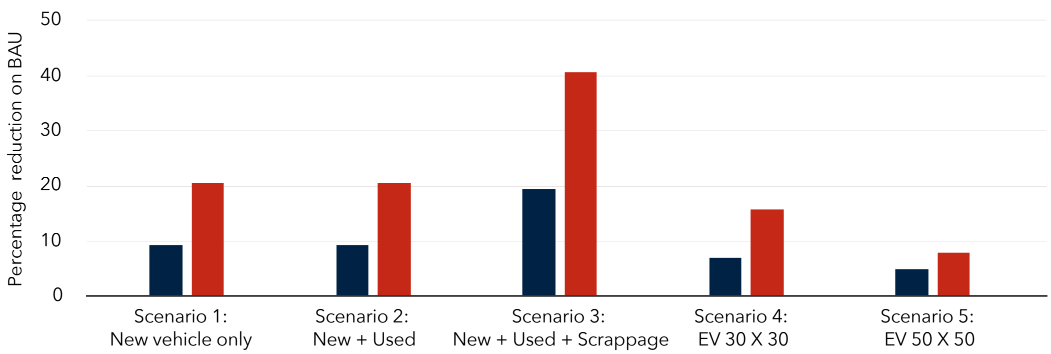
Road fatality, 2021 (number)		10,263
Fatality rate per 100,000, 2021 (number)		9.4
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	6,708
	NO_2	2,204
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	1.44

Sources: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data).

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as compared to BAU)



Egypt, Arab Rep. 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Ghana

Country context and motorization characteristics

Region		Sub-Saharan
Income category		Lower middle
GDP per capita (current US$)		2,260
Population (million)		33.8
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		3,314,215 [101]
Ambient $PM_{2.5}$ ($\mu g/m^3$)		63
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	3.1
	NO_2	26

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
Fatality (annual) – GRSF (2025) Personal communication
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✓
	New Vehicles	✓
LDV	Electronic Stability Control	x
	Advanced Emergency Breaking - Vehicles	x
	Advanced Emergency Breaking - pedestrians & cyclists	x
HDV	Front and Rear Underrun Protective Devices	x
	Vehicle Stability Function	x
MTW	Anti-lock Brake System	x
Adoption of Vehicle Emission Standards	Euro 4	✓
	Euro 5	x
	Euro 6	x

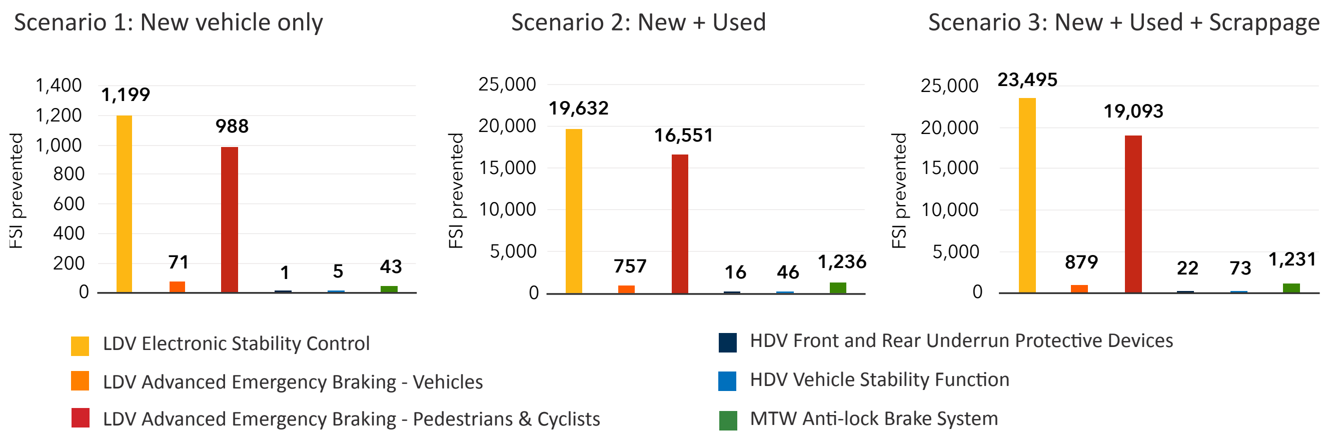
Source: Original table for this publication.

Health and cognitive impacts of motorization

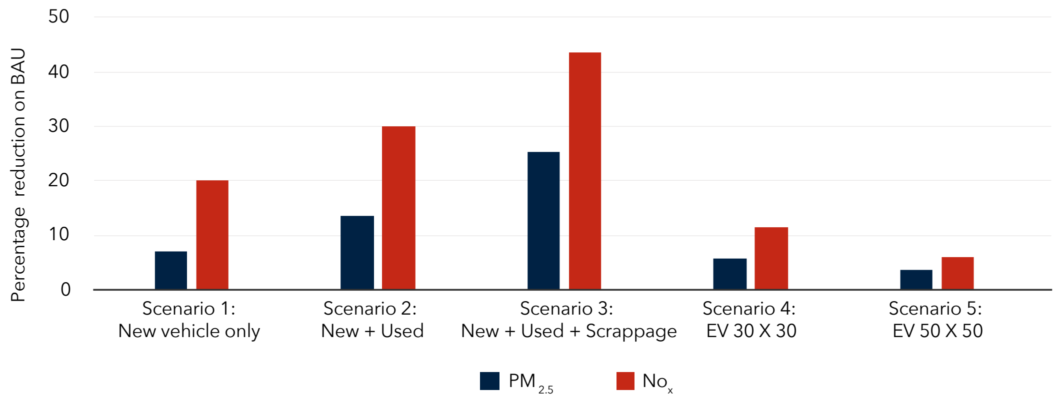
Road fatality, 2021 (number)		8,494
Fatality rate per 100,000, 2021 (number)		25.9
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	342
	NO_2	No data
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	0.27

Source: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data)

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as compared to BAU)



Ghana 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

India

Country context and motorization characteristics

Region		South Asia
Income category		Lower middle
GDP per capita (current US$)		2,481
Population (million)		1,438.10
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		326,300,000 [232]
Ambient $PM_{2.5}$ (µg/m3)		62
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	5.7
	NO_2	15

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✗
	New Vehicles	✓
LDV	Electronic Stability Control	✓
	Advanced Emergency Breaking - Vehicles	✓
	Advanced Emergency Breaking - pedestrians & cyclists	✓
HDV	Front and Rear Underrun Protective Devices	✓
	Vehicle Stability Function	✓*
MTW	Anti-lock Brake System	✓
Adoption of Vehicle Emission Standards	Euro 4	✗
	Euro 5	✗
	Euro 6	✓

** excluding trucks*

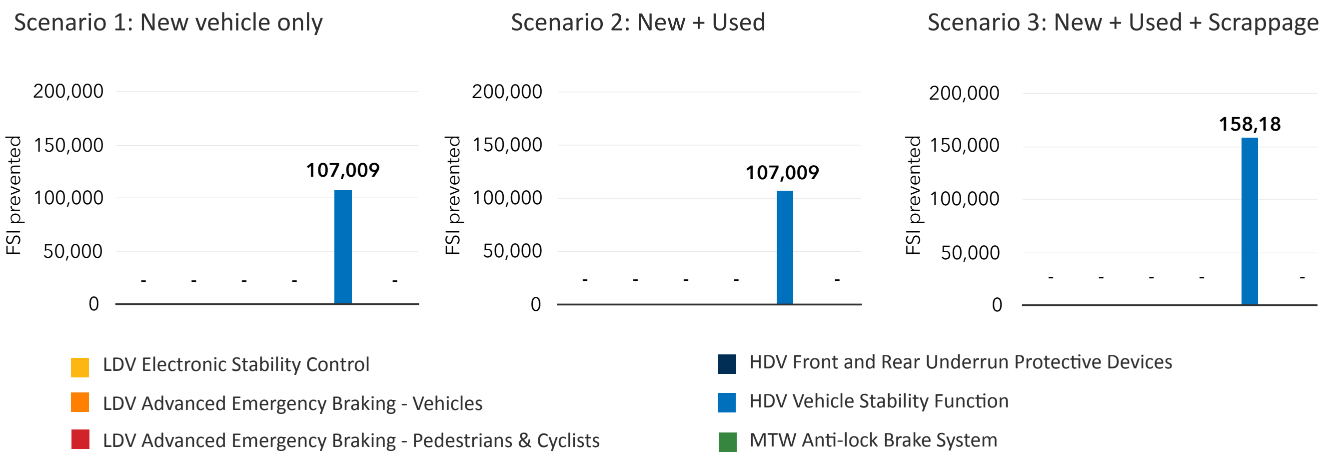
Source: Original table for this publication.

Health and cognitive impacts of motorization

Road fatality, 2021 (number)		216,618
Fatality rate per 100,000, 2021 (number)		15.4
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	54,012
	NO_2	20,771
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	13.18

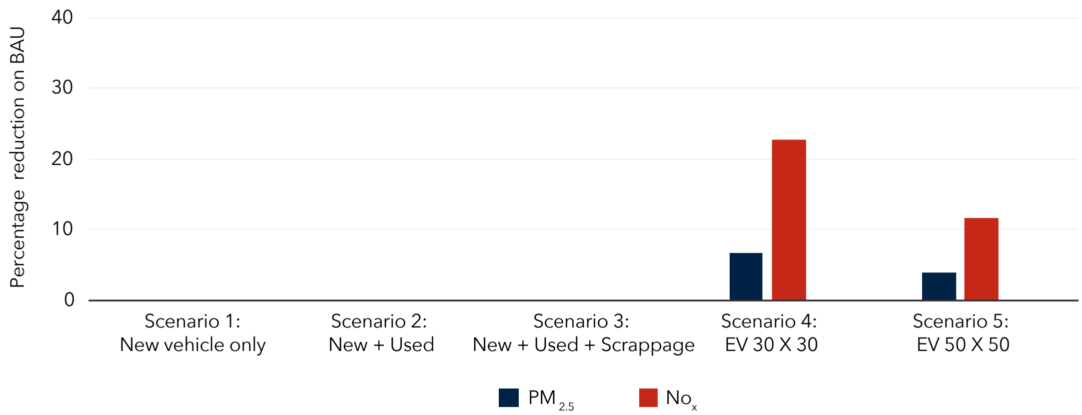
Sources: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data).

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as a difference from BAU)



Note: Dashes represent that this technology/vehicle type is not applicable.

India 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Kazakhstan

Country context and motorization characteristics

Region		Eastern Europe
Income category		Upper middle
GDP per capita (current US$)		12,919
Population (million)		20.3
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		4,338,639 [226]
Ambient $PM_{2.5}$ (µg/m3)		17
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	5.1
	NO_2	13

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✓
	New Vehicles	✓
LDV	Electronic Stability Control	x
	Advanced Emergency Breaking - Vehicles	x
	Advanced Emergency Breaking - pedestrians & cyclists	x
HDV	Front and Rear Underrun Protective Devices	x
	Vehicle Stability Function	x
MTW	Anti-lock Brake System	x
Adoption of Vehicle Emission Standards	Euro 4	✓
	Euro 5	x
	Euro 6	x

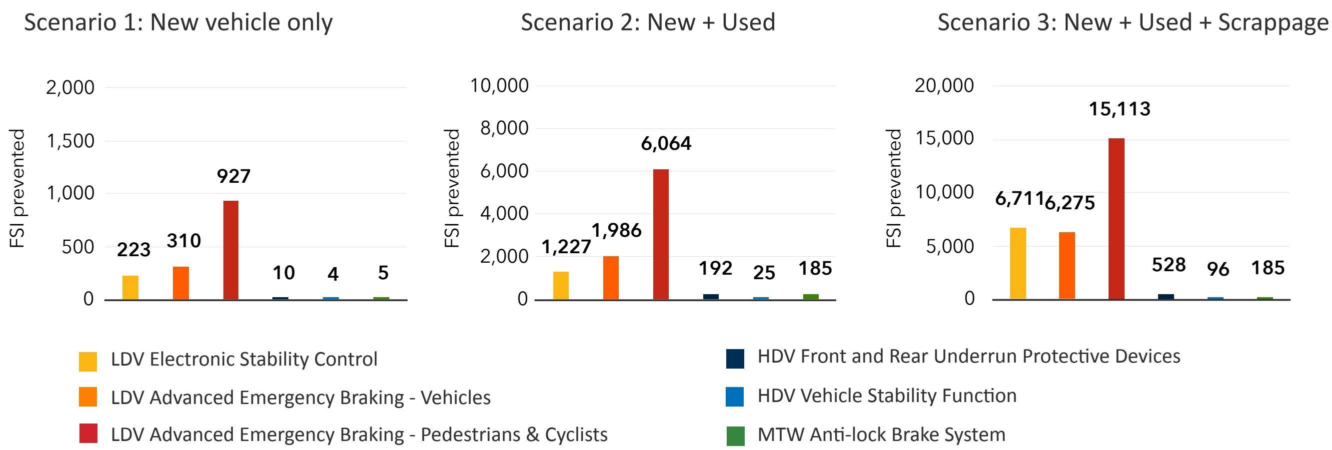
Source: Original table for this publication.

Health and cognitive impacts of motorization

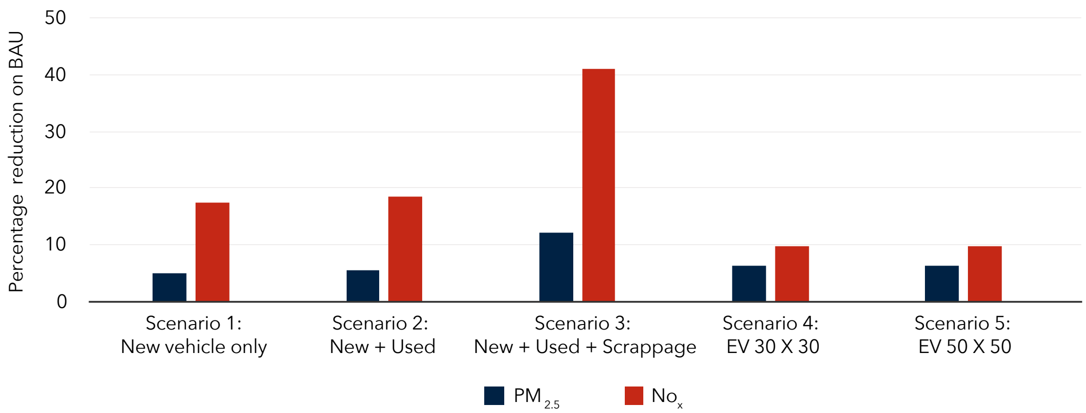
Road fatality, 2021 (number)		2,341
Fatality rate per 100,000, 2021 (number)		12.2
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	647
	NO_2	144
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	0.15

Sources: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data).

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as a difference from BAU)



Kazakhstan 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Lao PDR

Country context and motorization characteristics

Region		East Asia and Pacific
Income category		Lower middle
GDP per capita (current US$)		2,067
Population (million)		7.7
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		1,850,020 [274] *2016 data
Ambient $PM_{2.5}$ (µg/m3)		29
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	5.7
	NO_2	48

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✓
	New Vehicles	✓
LDV	Electronic Stability Control	x
	Advanced Emergency Breaking - Vehicles	x
	Advanced Emergency Breaking - pedestrians & cyclists	x
HDV	Front and Rear Underrun Protective Devices	x
	Vehicle Stability Function	x
MTW	Anti-lock Brake System	x
Adoption of Vehicle Emission Standards	Euro 4	✓
	Euro 5	x
	Euro 6	x

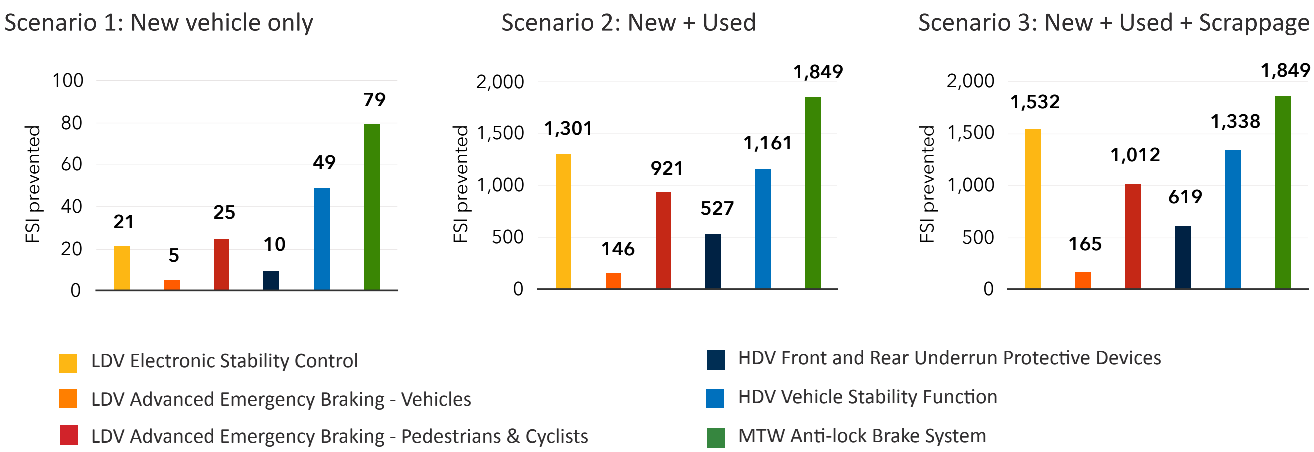
Source: Original table for this publication.

Health and cognitive impacts of motorization

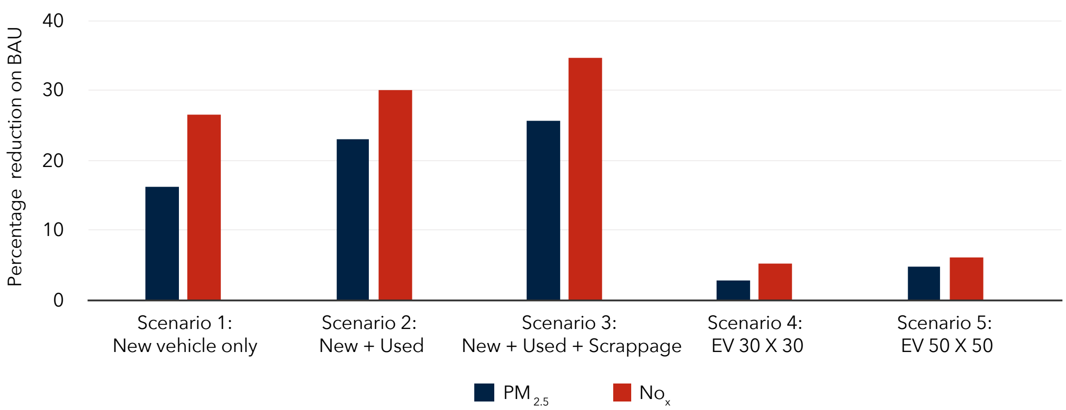
Road fatality, 2021 (number)		1,217
Fatality rate per 100,000, 2021 (number)		16.4
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	135
	NO_2	No data
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	0.07

Source: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data).

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as compared to BAU)



Lao PDR 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Mexico

Country context and motorization characteristics

Region		Latin America
Income category		Upper middle
GDP per capita (current US$)		13,790
Population (million)		129.7
Motorization level / ownership (inc. 2/3 wheelers) (Total registered [veh/1000 pop])		53,115,396 [419]
Ambient $PM_{2.5}$ (µg/m3)		31
Ambient air pollutant contribution from road transport, 2017 (%)	$PM_{2.5}$	12.3
	NO_2	60

Sources:
GDP per capita, Population – World Bank Open Data (latest data available: 2023)
Motorization level/ownership – WHO Global Status Report on Road Safety 2023 (2021 data)
GBD 2021 Risk Factors Collaborators. 2024.
McDuffie E, Martin R, Yin H, Brauer M. 2021a.
McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, Hammer MS, van Donkelaar A, Bindle L, Shah V, Jaeglé L, Luo G, Yu F, Adeniran JA, Lin J, Brauer M. 2021b.

State of analysed vehicle standards as of 2024

Adoption of Rules for Imported Vehicles	Used Vehicles	✓
	New Vehicles	✓
LDV	Electronic Stability Control	✓
	Advanced Emergency Breaking - Vehicles	✗
	Advanced Emergency Breaking - pedestrians & cyclists	✗
HDV	Front and Rear Underrun Protective Devices	✗
	Vehicle Stability Function	✗
MTW	Anti-lock Brake System	✗
Adoption of Vehicle Emission Standards	Euro 4	✓
	Euro 5	✗
	Euro 6	✗

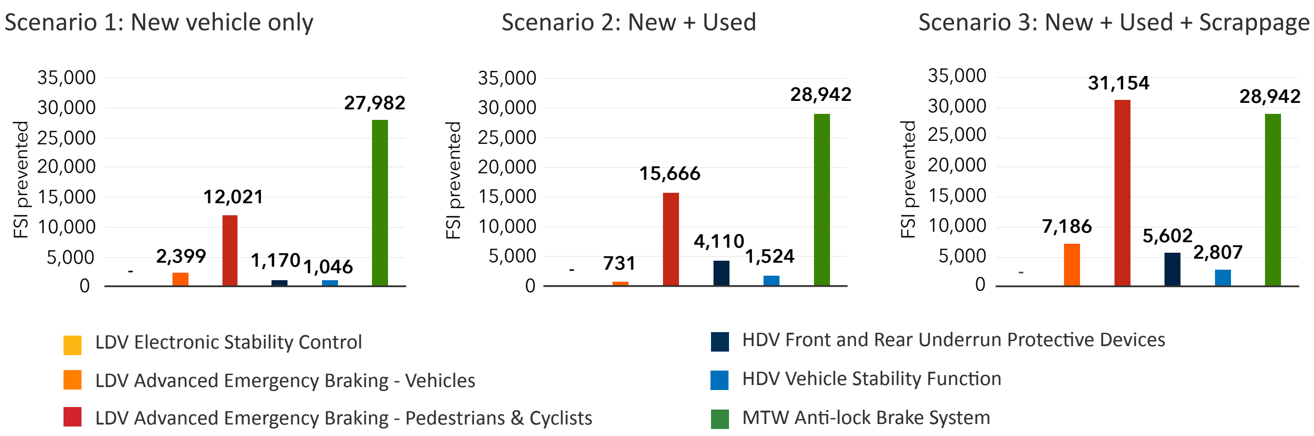
Source: Original table for this publication.

Health and cognitive impacts of motorization

Road fatality, 2021 (number)		15,267
Fatality rate per 100,000, 2021 (number)		12.0
Premature deaths per air pollutant from road transport, 2021 (number)	$PM_{2.5}$	5,128
	NO_2	8,877
IQ points lost from air pollutants from road transport, 2021 (million)	$PM_{2.5}$	1.23

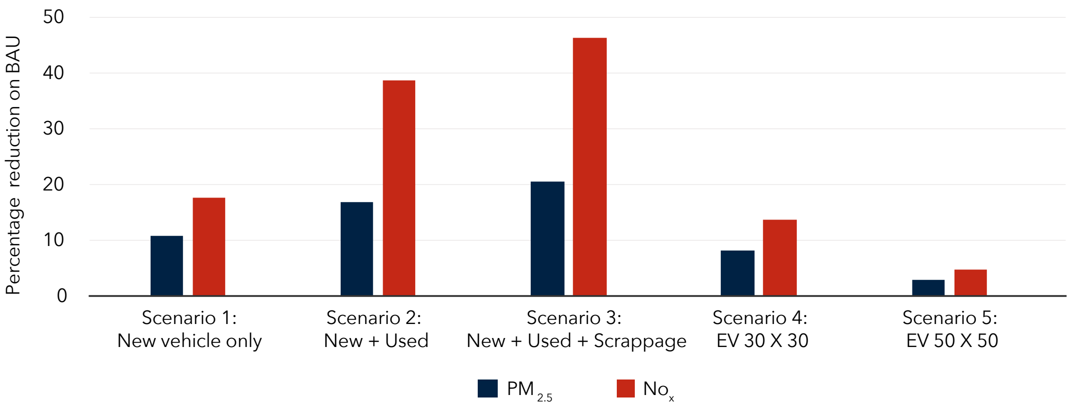
Sources: Original table for this publication, based on WHO Global Status Report on Road Safety 2023 (2021 data).

Prevented FSIs by Technology and Vehicle Type
(cumulative 2025-50 as compared to BAU)



Note: Dashes represent that this technology/vehicle type is not applicable.

Mexico 2050: Reduction in emissions, by scenario



Note: For a detailed explanation of each scenario, see Chapter 3, section 2: Evaluating the health impact of vehicle policies at the country level (page 35).

Appendix B: Global Calibration Parameters

B.1 Road Safety Cross-Country Parameters

Collision Geometry - Impact directions for FSI casualties (Share of Casualties)

Description	Share
Front-to-rear in two-vehicle LDV & LDV impacts	15.6%
Front-to-rear in two-vehicle LDV & HDV impacts	17.6%
Front-to-rear and front-to-front in two-vehicle LDV & HDV impacts	49.4%

Note: Used to define target population for technologies LDV AEB for vehicles and HDV FRUPD.

Source: Great Britain's Stats19 database (average of years 2011–2015)

Safety effectiveness values assumed for each technology in relation to the target population quoted

Technology	Safety effectiveness	Source
Electronic Stability Control	25% of fatal single vehicle collisions	Hoye (2011) *The effects of electronic stability control (ESC) on crashes–an update*
Advanced Emergency Braking vehicle	56% of injurious car-front to motor vehicle-rear collisions	Cicchino (2017) *Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates*
Advanced Emergency Braking ped./cycl.	26% of injurious car-to-pedestrian and car-to-cyclist collisions	Cicchino (2022) *Effects of automatic emergency braking systems on pedestrian crash risk* Cicchino (2019) *Effects of a bicyclist detection system on police-reported bicycle crashes*
Front- and Rear-Underrun Protective Devices	28% of fatal car occupants in car-front to truck-front or rear collisions	Average effectiveness reported by (weighted by number of FSI casualties occurring in corresponding impact configurations): Govardhan et al. (2020) *Effectiveness of rear underrun protection devices in trucks for reducing passenger car fatalities and serious injuries in India* Robinson & Riley (1991) Improving HGV Safety – *Front Underrun Guards and Antilock Braking Systems*
Vehicle Stability Function	19% of injurious HGV-single-vehicle collisions	Teoh et al. (2017) *Crash risk factors for interstate large trucks in North Carolina*
Anti-lock Brake System	30% of all FSI motorcycle collisions	Elvik et al. (2024) *The Handbook of Road Safety Measures – Online revision*

B.2 Air Quality Cross-Country Parameters

Dataset	Source	Purpose
Emission factors for different vehicle types by Euro Standard. Both exhaust and non-exhaust emissions	European Environment Agency/EMEP Air Pollutant Emission Inventory Guidebook 2023 – Update 2024	Emission factors in g/veh-km are applied to the activity (veh-kms) for each mode by the composition of vehicles of each vintage by powertrain and Euro standard.
Propensity for older vehicles to have a lower annual mileage	Kaneko, M. & Kagawa, S. 2021. *Driving propensity and vehicle lifetime mileage: A quantile regression approach.* Journal of Environmental Management, Vol 278. https://doi.org/10.1016/j.jenvman.2020.111499	Informs the shape of curves such that older vehicles have a lower mileage than new vehicles, mode specific
Weighting of emission factors by vehicle age	European Environment Agency/EMEP Air Pollutant Emission Inventory Guidebook 2023 – Update 2024	Informs the shape of curves such that older vehicles have higher emissions due to engine degradation, pollutant and powertrain specific

Appendix C: Country-Specific Datasets

Emissions

Dataset	Argentina	Brazil	Egypt	Ghana	India	Kazakhstan	Lao PDR	Mexico
Historic stock of vehicles, by mode (units)	Prepared by the Directorate of Road Statistics – National Directorate of Road Observatory (2025) based on data reported by the jurisdictions & Miller & Braun 2020 – Cost Benefit analysis of Euro VI Heavy-Duty Emission Standards in Argentina & OICA 2020 World vehicles in use	Obtained from Ministry of Transport and SENATRAN	Egypt Ministry of Transport 2024, Egypt CAPMAS Statistical Databook 2018	Motor Vehicle Registration: 1995-2023; Source – Driver and Vehicle Licensing Authority	India Ministry of Road Transport & Highways 2020 - Road Transport Year Book 2019-20 https://morth.nic.in/sites/default/files/RTYB_Publication_2019_20%20(1).pdf & Guttikunda 2024 - India Vehicle Stock Numbers & Survival Functions & Data for India 2025 - Vehicle Ownership https://www.dataforindia.com/vehicle-ownership/	UNECE 2024 - Road vehicle fleet at 31 December & Kazakhstan National Bureau of Statistics 2024 – On the number of vehicles	Lao PDR PDR, Dept of Transport Accumulating Statistics: Land Motor Vehicle Registration from 2000 to 2023	Mexico INEGI 2025 Motor Vehicles Registered In-Use
Average annual mileage per vehicle (km/year)	Grassei et al 2021 - Fleet Characterization & Assessment emission inventory of Latin American Intermediate City	Argentina used as proxy	World Bank 2020 - Egypt E-mobility Strategy White paper	Keyna & Egypt used as proxy	Goel et al 2014 - Benchmarking vehicle and passenger travel in Delhi for emissions Baidya, S. and Borken-Kleefeld, J. (2009) "Atmospheric emissions from road transportation in India", Energy Policy, 37(10), 3812- 3822	Tajikistan and European proxies used	O'Neill 2024 - Air pollutant emissions and sources in Lao PDR & World Bank 2018 - Transport Costs and Prices in Lao PDR	Generic mileage used from ICCT Roadmap model
Powertrain split, by vintage, by mode (% of vehicles)	Grassei et al 2021 - Fleet Characterization & Assessment emission inventory of Latin American Intermediate City	Calibrated to match the IEA estimate of fuel use. IEA 2024 Brazil country profile	TPA 2024, World Bank 2020 Egypt E-Mobility Strategy White Paper, JICA 2012 MiNTS, MISR National Transport Study	Source – Driver and Vehicle Licensing Authority	In-country response to request for info	Kazakhstan National Bureau of Statistics 2024 – On the number of vehicles	O'Neill 2024 - Air pollutant emissions and sources in Lao PDR	Calibrated to match the IEA estimate of fuel use. IEA 2024 Mexico country profile

Dataset	Argentina	Brazil	Egypt	Ghana	India	Kazakhstan	Lao PDR	Mexico
Age of vehicles when joining the fleet (year)	UNEP 2020 Used Vehicles and the Environment	UNEP 2020 Used Vehicles and the Environment	Egypt Ministry of Transport 2024, UNEP 2020 Used Vehicles and the Environment	UNEP 2020 Used Vehicles and the Environment, calibrated to match; Motor Vehicle Registration: 1995-2023; Source – Driver and Vehicle Licensing Authority	UNEP 2020 Used Vehicles and the Environment	UNEP 2020 Used Vehicles and the Environment	GIZ 2014 - Transport and Logistics in Lao PDR: Impact of the ASEAN Economic Community	US Commercial Service 2018 Regulations of the Importation of used Vehicles and Trucks into Mexico,
Age profile of the existing fleet, and/or the survival curve of vehicles.	Miller & Braun 2020 – Cost Benefit analysis of Euro VI Heavy-Duty Emission Standards in Argentina	ICCT 2012 – Global Transportation Roadmap	Egypt Ministry of Transport 2024, The International Council on Clean Transportation 2012. Roadmap Model Version 1-0, Held et al 2021 Lifespans of passengers cars in Europe	Motor Vehicle Registration: 1995-2023; Source – Driver and Vehicle Licensing Authority	Guttikunda 2024 - India Vehicle Stock Numbers & Survival Functions	Kazakhstan National Bureau of Statistics 2024 – On the number of vehicles	India used as a proxy	IDF 2023, LATAM VIO TRENDS Edition 1. Olguin, F., Iskakov G. & Kendall, A. 2023 US-Mexico second-hand electric vehicle trade: Battery circularity and end-of-life policy implications
Euro standard of vehicles	UNEP 2020 Used Vehicles and the Environment & Miller & Braun 2020 – Cost Benefit analysis of Euro VI Heavy-Duty Emission Standards in Argentina	UNEP 2020 Used Vehicles and the Environment	UNEP 2015 Air Quality Policies in Egypt, Daily Egypt News 2018 EOS issues new Egyptian fuel specifications	UNEP 2020 Used Vehicles and the Environment	UNEP 2020 Used Vehicles and the Environment	UNEP 2020 Used Vehicles and the Environment The Regional Environmental Centre for the Caucasus 2008 - Fuel Quality and Vehicle Emission Standards Overview	ICCT Lao PDR 2019 - Current Status of Emission and Fuel Efficiency in Lao PDF	UNEP 2020 Used Vehicles and the Environment
Sulphur content of fuel	UNEP 2024 Global Diesel Fuel Sulphur Levels & transportpolicy.net – Argentina Heavy-duty emissions	CCAC 2016 – Cleaning up the Global on-road diesel fleet & Transportpolicy.net Brazil: Fuels: Diesel and Gasoline	CEDARE 2015 Fuel Quality Roadmap for Arab States	UNEP 2024 Global Diesel Fuel Sulphur Levels & – West African Ministers adopt cleaner fuels & vehicles standards	UNEP 2024 Global Diesel Fuel Sulphur Levels & Bharat stage emission standards	UNEP 2024 Global Diesel Fuel Sulphur Levels & The Regional Environmental Centre for the Caucasus 2008 - Fuel Quality and Vehicle Emission Standards Overview:	UNEP 2024 Global Diesel Fuel Sulphur Levels & O'Neill 2024 - Air pollutant emissions and sources in Lao PDR	TransportPolicy.net Mexico Fuels

Vehicle regulatory standards in selected countries

Criteria	Egypt	Mexico	India	Ghana	Brazil	Argentina	Kazakhstan	Lao PDR
Age limit for imported used vehicles (year)	Ban on all used vehicles	9 year +	Ban on all used vehicles	10-year age limit on all used vehicles imported	Ban on all used vehicles	Ban on all used vehicles	5-year age limit on all used vehicles imported	Unknown
Existing emission standard for vehicles	Euro 4	Euro 4	Euro 6	Euro 2 (but most imports Euro 4)/Euro IV	Euro 5	Euro 5	Euro 4	Euro 4
Assumed long term GDP growth rate (World Bank)	4%	3%	5%	5%	2.5%	2.5%	2.5%	3%

Notes:
GDP (2015 Constant US$) [World Bank Open Data] was used for Gompertz curve for each country.

Forecast GDP growth [IMF to 2029: World Economic Outlook. 2030 onwards a fixed growth rate assumed.] informs the forecast increase in transport demand, hence fleet size.

Population (Historic and forecast) [UN population division: World Population Prospectus, middle forecast] informs GDP per capita which drives an increase in car ownership through the calibrated Gompertz curve.

Source: Original table for this publication.

Appendix D: Technical Estimations for Air Quality Impact

D.1 IQ losses from ambient $PM_{2.5}$ exposure

The following $PM_{2.5}$ exposure – IQ response function is applied for child *i* based on expanded number of studies and sub-analyses of the meta-analysis by Alter et al. (2024):

$$\Delta IQ_i = 0 \qquad \text{for } X_i \le X_0\ \mu g/m^3$$

$$\Delta IQ_i = -\beta_1 (X_i - X_0) \qquad \text{for } X_0 < X_i \le 11\ \mu g/m^3$$

$$\Delta IQ_i = -\beta_1 (11 - X_0) - \beta_2 (X_i - 11) \qquad \text{for } 11 < X_i \le 30\ \mu g/m^3$$

$$\Delta IQ_i = -\beta_1 (11 - X_0) - \beta_2 (30 - 11) - \beta_3 (X_i - 30) \qquad \text{for } X_i > 30\ \mu g/m^3$$

where ΔIQ_i is IQ points lost by child *i*; X_i is $PM_{2.5}$ exposure experienced by child *i*; X_0 is a lower $PM_{2.5}$ exposure threshold below which IQ loss is assumed to be zero; and *β* is IQ points lost per $\mu g/m^3$ of $PM_{2.5}$ exposure, with β_1=0.69 (95% CI: 0.22-1.17) for $X_i \le 11\ \mu g/m^3$; β_2=0.31 (95% CI: 0.21-0.40) for $11 < X_i \le 30$ µg/m3; and β_3=0 for X_i>30 $\mu g/m^3$. X_0 is set to 5 $\mu g/m^3$ based on the lower tail of $PM_{2.5}$ in the studies in the MA. The exposure-response function is assumed flat for $PM_{2.5}$ exposures above 30 $\mu g/m^3$ in order to be conservative due to limited number of studies of IQ losses at these exposures.

Total annual IQ losses in children are estimated by first calculating the children's $PM_{2.5}$ exposure distribution. The proportion of children (P_i) with $PM_{2.5}$ exposure in the range x_{i-1} to x_i ($x_{i-1} < x_i$) is:

$$P_i = F_X(x_i, \mu, \sigma) - F_X(x_{i-1}, \mu, \sigma) \qquad \text{(D1.1)}$$

where FX(x, µ, σ) is the cumulative log-normal distribution function, *x* is $PM_{2.5}$ exposure, and µ and σ are the natural logarithm of the mean and standard deviation of annual $PM_{2.5}$ exposure respectively.

Total annual IQ losses in children are then approximated by the following expression:

$$\Delta IQ_T = \frac{C}{Y} \sum_{i=1}^{n} P_i\, \Delta IQ \left(\frac{x_i + x_{i-1}}{2}\right) \qquad \text{(D1.2)}$$

where C is the total number of children under Y years of age, with the expression divided by Y by assuming that the children's IQ points are lost throughout the first Y years of life. An interval of $x_i - x_{i-1} = 0.5\ \mu g/m^3$ is applied to estimate IQ losses, with *n* such that $F_X(x_n, \mu, \sigma)$>0.999.

D.2 Valuation of IQ losses

An individual's IQ has an effect on lifetime income. This has long been established by for instance, Schwartz (1994) and Salkever (1995). The first study estimates that a loss of one IQ point is associated with a 1.76 percent decline in lifetime income. A little over one-quarter is the direct effect on earnings while nearly three-quarters is the indirect effect through reduced schooling, and through reduced lifetime work or labor force participation. The second study estimates that a loss of one IQ point reduces male and female lifetime income by 1.9 and 3.3 percent, respectively, including the effect on work participation.

Subsequently Johnson and Neal (1998) estimated an overall direct and indirect income effect of about 2.8 percent per IQ point with a much larger effect for females than for males as also found by Salkever (1995). The estimate does not include work or labor force participation effect. Zax and Rees (2002) find a much smaller direct and indirect effect of 0.39-1.39 percent per IQ point for white males. Salkever (2014a) argues, however, that this size effect is not representative as the study does not include females and minority groups for which size effects are found to be much larger by Salkever (1995) and Johnson and Neal (1998).

The size of the effect of IQ on lifetime income continues to be debated. Grosse (2014) argues that the effect is smaller than found by Salkever (1995) while Salkever (2014a,b) defends the estimates on the basis that other studies often omit females and minorities and do not include the effect on work or labor force participation. Attina and Trasande et al (2013) and Larsen and Sanchez-Triana (2023) applied a lifetime income effect of 2 percent per IQ point for their estimate of the cost of lead exposure in children in LMICs and globally. Grosse and Zhou (2021) applied an effect of 1.4 percent of lifetime income per IQ point as a conservative estimate based on a review of the literature that includes recent studies by Lin et al. (2018) and Lundborg et al. (2014). USEPA (2020) was able to undertake a reanalysis of Salkever (1995) using a more recent version of the data set used by Salkever. The reanalysis found a lifetime income effect per IQ point of 1.86 percent for males (slightly below Salkever 1995) and 3.4 percent for females (somewhat above Salkever 1995).

In this study an effect of 2.0 percent decline in lifetime income per lost IQ point is applied to all individuals participating in the labor force. This is slightly above the value used by Grosse and Zhou (2021) but substantially below the value in Johnson and Neal (1998), Salkever (1995), and USEPA (2020).

Lifetime income for a person that is or will be in the labor force is calculated as follows:

$$PV_0(I) = \sum_{i=k}^{i=n} I_0 (1+g)^i / (1+r)^i \qquad \text{(D2.1)}$$

where PV_0 (I) is the present value in year 2021 of lifetime income, I0 is annual income in year 2021, g is annual growth in real income, and r is the discount rate of future income. The equation allows for income to start from year k, and end in year n. The present value of lifetime income is calculated for a child at the age of 2.5 years, i.e., at the mid-point of 0-5 years during which IQ losses are assumed. Therefore, k is the age of entering the labor force less than 2.5 years, and n is the age of retirement less than 2.5 years.

A person's annual income in the year 2021 is calculated as follows:

$$I_0 = GDP_0\, s / L_0 \qquad \text{(D2.2)}$$

where *GDP* is the country's total GDP, L is the total labor force, and *s* is labor compensation share of GDP. *S* is from PENN World Table, Version 10.

Cost of IQ losses in each country in 2021 is then:

$$C = \alpha\, PV_0(I)\, p\, \Delta Q_T \qquad \text{(D2.3)}$$

where α is the effect of IQ on lifetime income (here 2.0 percent per IQ point), PV0(I) is the present value of lifetime income in 2021, p is the probability of future labor force participation (LFP), and ΔIQT is a country's total IQ points lost in 2021 due to $PM_{2.5}$ exposure.

The parameter values for equations D2.1-3 are presented in table D2.1. Future income growth in high-income countries is set at recent historic GDP per capita growth rates, at somewhat lower than historic rates in middle-income countries as these economies gradually mature, and at somewhat greater than historic rates in low-income countries as these countries may be expected to achieve greater “catch up” growth rates. The discount rate of future income is set at twice the per capita income growth rate as proposed by the World Bank for project economic analysis (World Bank 2016). The probability of future LFP is set at the LFP rate in 2021 reported by the World Bank (2024).

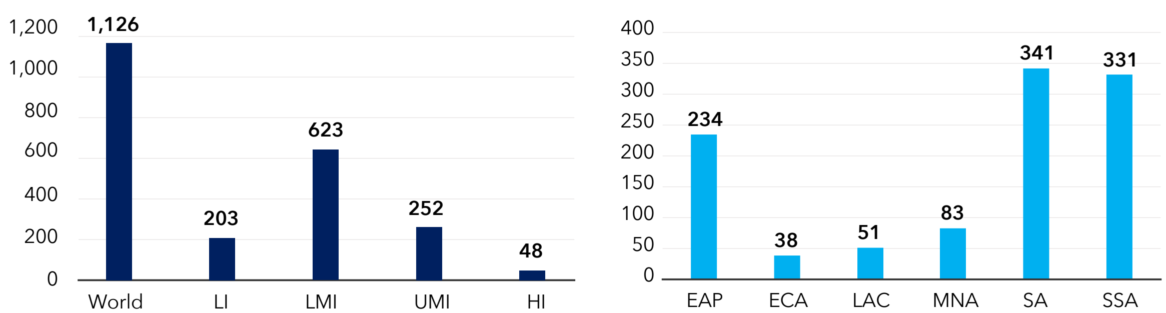
Table D2.1 Parameters for estimation of the cost of IQ losses

	Parameter	Low-income countries	Middle-income countries	High-income countries
Effect of lifetime income per IQ point	α	2.0%	2.0%	2.0%
Future income growth per year	g	2.5%	2.5%	1.5%
Rate of discounting of future income	r	5%	5%	3%
Future labor force participation rate	p	Current rate	Current rate	Current rate
Labor force participation (age)		15-60 years	18-65 years	21-65 years

Source: Original table for this publication.

D.3 Cognitive Impacts of Ambient $PM_{2.5}$ on Children's Cognitive Development.

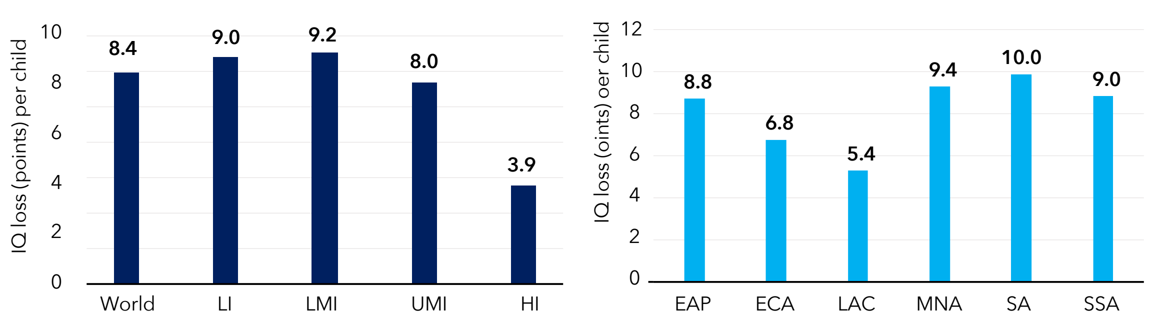
Annual IQ point losses in children (million), 2021



Notes: Only LMICs are included in regions. LI=Low-income; LMI=Lower middle-income; UMI=upper middle-income; HI=high-income. SA=South Asia; EAP=East Asia and Pacific; SSA=Sub-Saharan Africa; MNA=Middle East and North Africa; ECA=Europe and Central Asia; LAC=Latin America and Caribbean.

Source: Original figures for this publication.

Average IQ point loss per child



Source: Original figures for this publication, based on national datasets reported by the Health Effects Institute (HEI 2024).

D.4 Welfare cost of premature mortality

The predominant measure of the welfare cost of a premature death used by economists is the value of statistical life (VSL). VSL is based on valuation of mortality risk. Everyone in society is constantly facing a certain risk of dying. Examples of such risks are occupational fatality risk, risk of traffic accident fatality, and environmental mortality risks. It has been observed that individuals adjust their behavior and decisions in relation to such risks. For instance, individuals demand a greater wage (a wage premium) for a job that involves a greater occupational risk of fatal accident than in other jobs, individuals may purchase safety equipment to reduce the risk of death, and/or individuals and families may be willing to pay a premium or greater rent for properties (land and buildings) in a cleaner and less polluted location.

Through the observation of individuals' choices and willingness to pay (WTP) for reducing mortality risk (or minimum amounts that individuals require to accept a higher mortality risk), it is possible to estimate the value to society of reducing mortality risk, or, equivalently, measure the social cost of a particular mortality risk. For instance, it may be observed that a certain health hazard has a mortality risk of 2.5/10,000. This means that, on average, one individual dies from this hazard for every 4,000 individuals exposed. If each individual on average is willing to pay $40 to eliminate this mortality risk, then every 4,000 individuals are collectively willing to pay $160,000. This is the VSL, or the value that individuals collectively are willing to pay to avoid one death. Mathematically it can be expressed as follows:

$$VSL = WTP_{Ave} * 1/R \qquad \text{(D4.1)}$$

where WTP_{Ave} is the average willingness-to-pay per individual for a mortality risk reduction of magnitude R. In the illustration above, R=2.5/10,000 (or R=0.00025) and WTP_{Ave}= $40. Thus, if 10 individuals die from the health risk illustrated above, the cost to society is 10* VSL = 10* $0.16 million = $1.6 million.

The main approaches to estimating VSL are through revealed preferences and stated preferences of people's WTP for a reduction in mortality risk. Most of the studies of revealed preferences are hedonic wage studies, which estimate labor market wage differentials associated with differences in occupational mortality risk. Most of the stated preference studies rely on contingent valuation methods (CVM), which in various forms ask individuals about their WTP for mortality risk reduction.

Studies of WTP for a reduction in risk of mortality have been carried out in numerous countries. A commonly used approach to estimate VSL in a specific country without such WTP studies is therefore to use a benefit transfer (BT) based on meta-analyses of WTP studies from other countries. Many meta-analyses have been conducted in the last two decades. These meta-analyses find that VSL is strongly associated with income level.

A meta-analysis prepared for the OECD was exclusively based on stated preference studies, arguably of greater relevance for valuation of mortality risk from environmental factors than hedonic wage studies (Navrud and Lindhjem 2010; Lindhjem et al. 2011; OECD 2012). These stated preference studies are from a database of more than 1,000 VSL estimates from multiple studies in over 30 countries, including in developing countries.

World Bank and IHME (2016), Sanchez-Triana et al (2021)and World Bank (2022) applied a benefit transfer function for estimating VSL that draws on OECD (2012). The benefit transfer function is:

$$VSL_{c,n} = VSL_{OECD} * (\frac{Y_{c,n}}{Y_{OECD}})^{\varepsilon} \qquad \text{(D4.2)}$$

where $VSL_{c,n}$ is the estimated VSL for country c in year n; VSL_{OECD} is the average VSL in 2011 in the sample of OECD countries with VSL studies ($3.83 million); Y_{OECD} is the average GDP per capita for the sample of OECD countries in 2011 ($37,000); $Y_{c,n}$ is GDP per capita in country *c* in year *n*; and ε is an income elasticity of 1.2 for low- and middle-income countries and 0.8 for high income countries.

This benefit transfer function is used in this paper to estimate $VSL_{c,n}$ in each LMIC and HIC for the year n=2019. All values in equation D4.2 are in 2011 purchasing power parity (PPP) prices. $VSL_{c,n}$ is converted from 2011 to 2021 prices by the rate of inflation and from PPP prices to US dollars using country-specific PPP exchange rates for 2021 from the World Development Indicators (World Bank 2024).

Total global welfare cost (W) of global premature deaths from exposure to an environmental risk factor is calculated for the year 2019 in 2021 prices as follows:

$$W_n = \sum_c M_{c,n} VSL_{c,n'} \qquad \text{(D4.3)}$$

where $M_{c,n}$ is the estimated number of premature deaths in country c in year 2021 from exposure to the environmental risk factor; and $VSL_{c,n'}$ is $VSL_{c,n}$ in 2021 prices. Regional welfare cost and welfare cost by country income classification is calculated likewise by summing country welfare cost over the relevant group of countries.

D.5 Valuation of Morbidity

Two valuation techniques are commonly used to estimate the cost of morbidity or illness. The cost-of-illness (COI) approach includes cost of medical treatment and value of income and time lost to illness. The second approach equates the cost of illness to individuals' willingness-to-pay (WTP) for avoiding an episode of illness. Therefore, the latter includes the welfare cost of pain and suffering from illness.

Studies in many countries have found that individuals' WTP to avoid an episode of an acute illness is generally much greater than the cost of treatment and value of income and time losses (Alberini and Krupnick 2000; Cropper and Oates 1992; Dickie and Gerking 2002; Wilson 2003).

The OECD, in its report on the global economic consequences of outdoor air pollution, includes the cost of both mortality and morbidity (OECD 2016). Mortality is valued using VSL, and the cost of morbidity is estimated both in terms of

i. Market impacts or COI (reduced labor productivity and increased health expenditures associated with bronchitis, asthma, hospital admissions, and restricted activity days from illness); and
ii. Nonmarket impacts (welfare cost of pain and suffering from illness).

Globally, the OECD estimated the cost of market impacts or COI to about 0.2 percent of GDP or equivalent to 4 percent of the cost of mortality. Expressed in terms of welfare, using the equivalent variation of income, the cost was 0.4 percent of GDP or 8 percent of the cost of mortality. The nonmarket impacts or welfare cost was equivalent to 0.5 percent of GDP or 9 percent of mortality cost. Thus, the total cost of morbidity was estimated at 0.7–0.9 percent of GDP or 13–17 percent of the cost of mortality according to the OCED report.

Estimating the cost of morbidity requires much more data—and less accessible data, including baseline health data—than estimating the cost of mortality. Therefore, a simplified approach is applied in this report using the following steps:

i. YLD from $PM_{2.5}$ exposure from GBD 2021 are converted to days of illness by applying the disability weights from GBD.
ii. The cost of a day of illness is then approximated as a fraction of the average daily wage rates to reflect income losses from illness, health expenditure, time losses, and the welfare cost of pain and suffering.
iii. The cost of a day of illness is also applied to individuals without income, because illness prevents most of these individuals from undertaking household work and other activities with a social value, as well as involving all the non-income impacts of illness.

The cost of morbidity is thus estimated as follows. First, annual disease days (M) in country, k, are calculated as:

$$M_k = \sum_{i=1}^{n} M_{ki} = \sum_{i=1}^{n} (YLD_{ki} * 365/d_{ki}) \quad \text{(D5.1)}$$

where YLD_{ki} is years lost to disease, i, from exposure to $PM_{2.5}$, and d_{ki} is the disability weight for disease, *i*, in country, *k*. The disability weights are from GBD 2021 for each of the diseases associated with $PM_{2.5}$ exposure.

The disability weight is a measure used in GBD to calculate YLDs from days of illness, disease, or injury. The weighted average global disability weights for the major diseases associated with exposure to $PM_{2.5}$ range from 0.016 for ischemic heart disease (IHD) to 0.169 for lung cancer (table D5.1).

Table D5.1 Disability weights associated with $PM_{2.5}$ air pollution

	Average disability weights
Diabetes type 2	0.078
COPD	0.070
Stroke	0.162
Cataract	0.065
IHD	0.016
LRI	0.059
Lung cancer	0.169
Neonatal disorders	0.142

Source: Original table for this publication, based on GBD 2021 data (IHME 2021).

The cost of a day lived with disease, *i*, or a disease day, in country, *k*, is thus:

$$c_{ki} = w_k \, d_{ki}/D \qquad \text{(D5.2)}$$

where w_k and d_{ki} are average daily wage rate and disability weight for disease, *i*, in country, *k*, and D is a disability weight that corresponds to a severity of disease for which the cost of a disease day is assumed equal to the average wage rate. D is here set at 0.4. This is a disability weight (DW) associated with severely restricted work and leisure activity from disease and substantial medical cost, for example, severe COPD (DW = 0.41), distance-vision blindness (DW = 0.19) and Stage 5 chronic kidney disease (DW = 0.57) due to diabetes, and stroke with severity level 3 (DW = 0.32) and 4 (DW = 0.55).

Cost of morbidity (C) in country, k, is calculated as follows:

$$C_k = \sum_{i=1}^{n} (c_{ki} \, M_{ki}) \qquad \text{(D5.3)}$$

Average daily wage rate is estimated as follows:

$$w_k = GDP_k / L_k / 250 * s_k \qquad \text{(D5.4)}$$

where GDP is the country's total GDP, L is the total labor force, s is labor compensation share of GDP, and annual working days is averaging 250. GDP and L are from the World Development Indicators by the World Bank and s is from PENN World Table, version 10.

D.6 Mortality from ambient NO_2

Seven meta-analyses of the relationship between long-term NO_2 exposure and mortality outcomes are presented in table A5.1. Atkinson et al. (2018) report the smallest hazard ratios for all-cause, CVD, respiratory and lung cancer mortality from NO_2 based on dozens of cohort studies from North America, Europe and Asia. This report applies the hazard ratios and 95 percent confidence intervals (CI) from Atkinson et al. for CVD, respiratory, and lung cancer mortality to provide conservative estimates of global health effects. The ratios are applied to the population aged 25+ years to be consistent with the studies in the meta-analyses.

Table D6.1 Hazard ratios for mortality outcomes from annual NO_2 exposure

	Mortality hazard ratio (HR)				Increment
	All-cause	CVD	Respiratory	Lung cancer	
Faustini et al. 2014	1.04	1.13	1.03		per 10 µg/m3
Atkinson et al. 2018	1.02	1.03	1.03	1.05	per 10 µg/m3
Huangfu and Atkinson 2020	1.02		1.03		per 10 µg/m3
Huang et al. 2021	1.06	1.11	1.05		per 10 ppb
Stieb et al. 2021	1.047	1.058	1.062	1.083	per 10 ppb
HEI 2022	1.04	1.05*	1.05	1.04	per 10 µg/m3
Chen et al. 2024	1.03	1.07	1.03		per 10 µg/m3

** Ischemic heart disease.*

Note: 10 ppb = 18.8 µg/m^3 of NO_2.

Source: Original table for this publication.

The continuous mortality risk function from exposure to annual NO_2 is:

$$R_{ji} = e^{\frac{\ln(HR_j)}{10}(C_i - C_0)} \quad \text{for } c_i \geq c_0 \quad \text{(D6.1a)}$$

$$R_{ji} = 1 \quad \text{for } c_i < c_0 \quad \text{(D6.1b)}$$

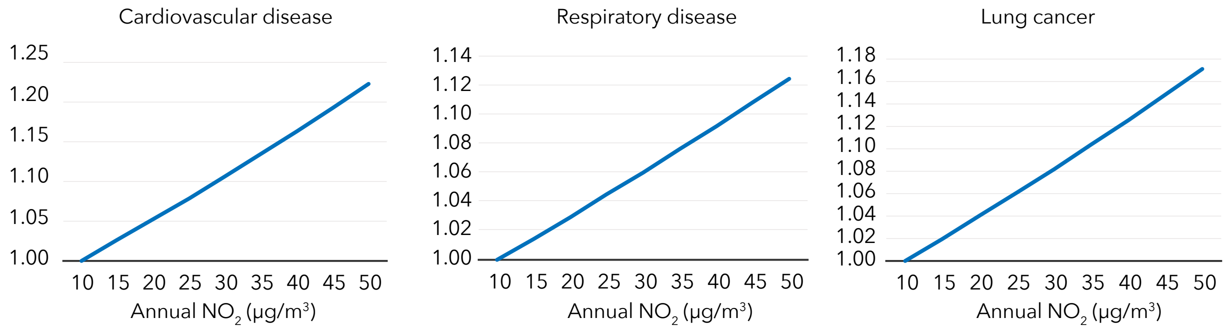
where ci is annual NO_2 concentration (µg/m3), c0 is the TMREL or annual NO_2 concentration (µg/m3) below which it is assumed that there are no mortality effects; and HRj is the increase in risk of mortality from disease j per 10 µg/m^3 of annual NO_2 exposure (table D6.2). The TMREL is set at the WHO's annual guideline value of 10 µg/m^3 (WHO 2021). The risk function is presented graphically in figure D6.1 for each of the three mortality outcomes.

Table D6.2 Mortality hazard ratios per 10 µg/m^3 of annual NO_2 exposure

	HR (central estimate)	95% Confidence Interval (CI)
Cardiovascular disease	1.03	1.02-1.05
Respiratory disease	1.03	1.01-1.05
Lung cancer	1.05	1.02-1.08

Source: Original table for this publication, based on Atkinson et al. (2018).

Figure D6.1 Relative risk of mortality from annual NO_2 exposure



Note: Solid line is central estimate. Dotted lines are the 95% confidence interval (CI).

Source: Original figures for this publication, based on Atkinson et al. (2018).

The population attributable fraction (PAF) of mortality from disease j from exposure to annual NO_2 is:

$$PAF_j = \frac{\sum_{i=1}^{n} P_i R_{ji} - 1}{\sum_{i=1}^{n} P_i R_{ji}} \qquad \text{(D6.2)}$$

where i is one of four population exposure groups; and Pi is the share of the national adult population in exposure category i. PAF is calculated for each country and for each disease j and is multiplied by baseline number of deaths from j in each country in 2021 from the GBD 2021 to arrive at an estimate of annual deaths from NO_2 exposure in each country in 2021.

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