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Reducing Air Pollution from Urban Passenger Transport

A Framework for Policy Analysis

Mark Heil
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A policy considered in isolation may be ineffective because of the countervailing impact of other factors. And the success of a policy may itself lead to perverse incentives. Thus it is important to design complementary policies that support the original goal. Controlling air pollution from urban transport requires attention to land use planning, transport needs and modes, and air quality.

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Summary findings

Air quality is declining in urban areas, in part because of the rapid motorization of societies worldwide. To combat the problem, various pollution control strategies have been used or proposed for urban passenger transport. Heil and Pargal develop a simple framework to analyze these strategies.

The virtue of this framework is its simplicity and its separation of factors.The authors examine the point of impact of different policy levers and categorize different instruments in a way that should help policymakers choose among them.

The framework explicitly recognizes behavioral incentives, especially the fact that offsetting changes in consumer behavior can often undermine the original intent of particular policies. Among the findings:

- Policies aimed at improving transport efficiency often improve air quality at the same time.
- But supply-side policies to relieve traffic congestion sometimes conflict with supply-side measures to control air pollution. Improvements in roads and traffic, for example, may increase private motorized traffic conditions, making it difficult to assess the net effect of the improvements on air pollution.
- There seems to be considerable scope for low-cost solutions to air quality problems associated with the transport sector. Inexpensive, low-technology solutions, such as establishing bus lanes or paving dirt roads, substantially improve both transport efficiency and air quality.
- Behavioral change is difficult when viable transport alternatives are unavailable. A viable public transport system is essential to reduce transport-caused air pollution in densely populated areas.
- Fuel and emission standards should become stricter over time. Standards should be gradually ratcheted up to give domestic auto industries the incentive to develop and adopt cleaner technology.

This paper — a product of Infrastructure and Environment, Development Research Group — is part of a larger effort in the group to study the impact of motorization on air pollution. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Roula Yazigi, room MC2-635, telephone 202-473-7176, fax 202-522-3230, Internet address ryazigi@worldbank.org. Sheoli Pargal may be contacted at spargal@worldbank.org. October 1998. (25 pages)

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REDUCING AIR POLLUTION FROM URBAN PASSENGER TRANSPORT
A FRAMEWORK FOR POLICY ANALYSIS

by

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I. Introduction

This paper develops a simple framework to analyze various pollution control strategies that have been used or are proposed in the urban passenger transport sector. The context is the declining quality of air in urban areas, which is among the serious problems associated with the rapid motorization of societies the world over.[1] The paper examines the point of impact of different policy levers and provides a categorization of different instruments that should assist policy makers when choosing between them. A distinguishing feature of this framework is its explicit recognition of behavioral incentives, in particular, the fact that offsetting changes in consumer behaviour can often undermine the original intent of particular policies.

The paper is organized as follows. Section II presents the basic framework we have used to examine transport emissions. Section III reviews pollutant characteristics and their impact. The resulting policy choices are discussed in more detail in section IV. Several urban transport projects supported by the World Bank are then reviewed in section VI, and section V concludes the report.

II. A Framework for Analyzing Passenger Transport Emissions[2]

We start with a decomposition of total passenger transport air emissions into the following factors: (1) emissions per unit of fuel; (2) units of fuel per passenger kilometer; and, (3) passenger kilometers traveled.[3] This is illustrated in Figure 1.[4] Each factor is influenced by a set of determinants (shown by arrows), some of which are linked to one another, as indicated by dotted lines. The decomposition provides a means of identifying the actual point of impact of different policies, and thus gives us a basis for tracing through their effects. It also makes transparent the linkages and feed-back mechanisms among them.

As an instance, it is known that in Los Angeles passenger kilometers traveled and units of fuel per passenger kilometer are high by world standards, but emissions per unit of fuel are among the world's lowest. By contrast, in Tehran, emissions per unit of fuel and units of fuel consumed per passenger kilometer are very high, but the number of passenger kilometers traveled is relatively low (though growing). The difference in the primary determinants of total vehicular emissions between the two cities means that the policies needed to control emissions will be very different.

The utility of the above framework thus lies in the clear separation of the determinants of transport related air emissions. For example, it is easily seen that reducing emissions per unit of fuel by 50 percent,

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[1] Vehicle growth rates range between 15 and 20 percent a year in many developing cities. In metropolitan Bangkok, 446 additional motor vehicles joined the fleet each day, 1978-91 (Simon 1996). For perspectives on urban motorization and its impacts, see, among others, Shalizi and Talukdar (1996), Kenworthy, Laube, Newman, and Barter (1997), and MacKenzie, Dower, and Chen (1992).

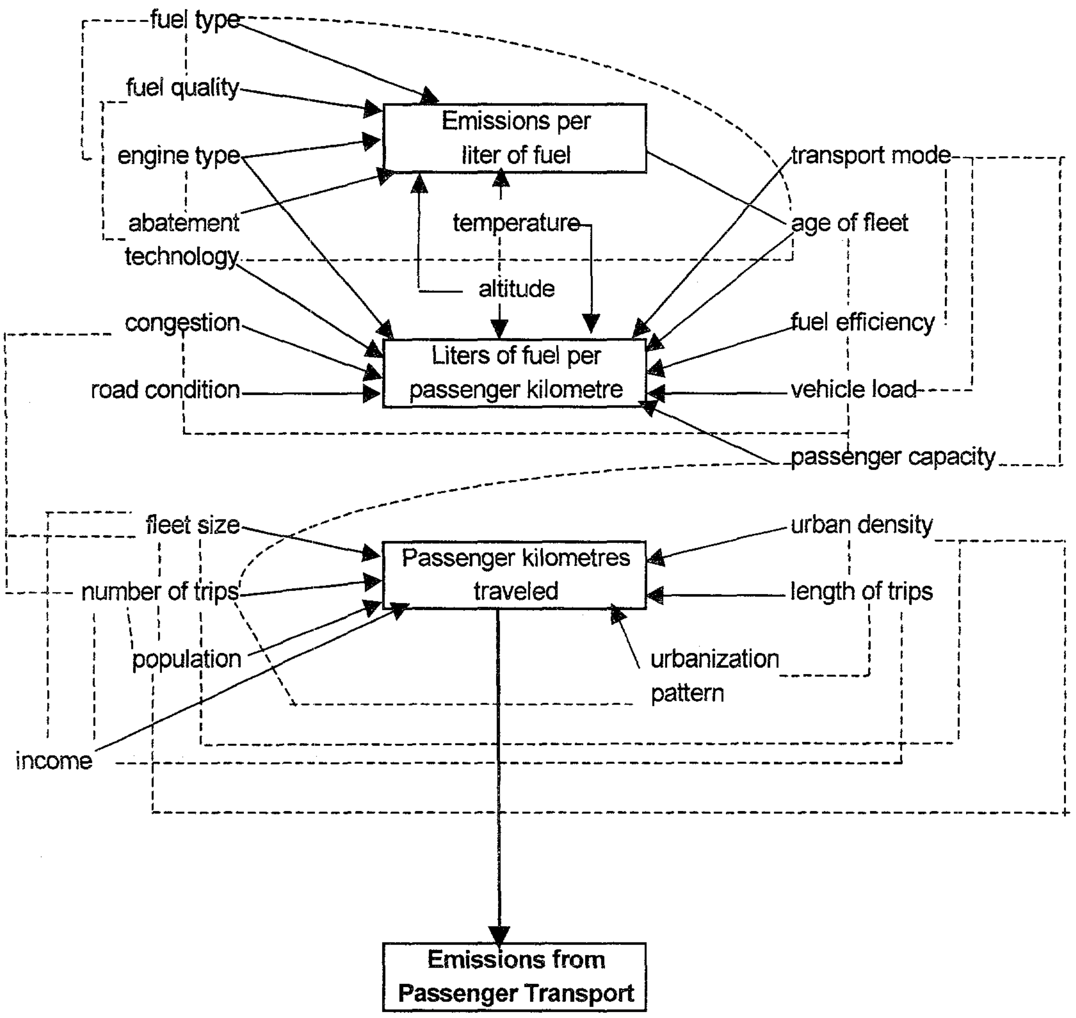
[2] The framework does not include freight transport, although freight haulage could be included with minor modifications.

[3] This decomposition follows Levinson and Shetty (1992).

[4] For presentational clarity we have not grouped the factors in Figure 1 according to the logic followed in the exposition elsewhere. The grouping we have used in Figure 2 and the tables is as follows: emissions, fuel characteristics, engine and technology related factors, traffic (volume, fleet size, congestion, number and length of trips), behavioral factors (mode choice, income), and structural factors (urban density, pattern of urban development, existence of alternatives to motorized private automobiles).

ceteris paribus, will halve total emissions, as would curbing passenger kilometers traveled by the same proportion. Also, the former is a technical fix requiring no change in behaviour, while the latter depends on substantial behavioral modification. In reality, it is more likely that emissions control would involve a combination of policies that affect two or all three factors.

Figure 1. Urban Passenger Transport Emissions: Major Determinants and Linkages



Total emissions = emissions per liter x liters per passenger km x passenger kms traveled.

Note: Solid lines represent direct determinants of the components of transport emissions
Dotted lines show linkages between determinants.

Among structural factors, urban structure or the pattern of urbanization plays a critical role in determining the volume of traffic and passenger travel patterns – and thus passenger kilometers traveled as well as liters of fuel used per passenger kilometer. For instance, public transport along high-density corridors is a fuel efficient alternative to private automobiles. In low-density areas, however, public transport may consume substantially more fuel per passenger kilometer than the private alternative.

Figure 2 rearranges the three emissions components and their determinants, and adds a list of policies that may help control them. It is clear that in practice few policies directly target *total* transport emissions, although emissions taxes and permits are theoretically possible efficient policies that would do so (Eskeland and Devarajan 1996). More common are technological requirements like emissions standards, fuel economy standards and incentives for passengers to change behavior. It is clear that policies aimed at inducing changes in the number of passenger kilometers traveled, would need to effectively alter the "price" of automobile use, and, indeed, of car ownership.

Figure 2 also suggests that the divisions between the three major components of emissions are imperfect. Some determinants (such as the age of the vehicle fleet) influence more than one component, and appear more than once, as do corresponding policies. These overlaps reflect the complex and interactive nature of transport emissions and the challenges faced in designing policies to address them.

It is vital to be conscious of complementarities across different policy levers. Policies that alleviate traffic congestion, for instance, increase average traffic speeds and thus lower emissions – idling vehicles or start-stop traffic generate large volumes of traffic emissions. At times, however, complementarities across different policy levers may counteract well designed efforts to reduce emissions. For instance, improving fuel efficiency directly lowers emissions by reducing liters of fuel per passenger kilometer and the gross effect of the intervention could be significant. However, since this reduces the cost of travel, it also tends to increase passenger kilometers traveled, placing renewed upward pressure on emissions[5], with a less significant effect on net.

III. Pollutant characteristics

Ambient data along with emissions inventories are the first step in gauging the magnitude of the air pollution problem in any city. Emissions inventories provide a breakdown of total emissions by source and pollutant. This is critical for appropriate policy design since different interventions would be dictated by the characteristics of different pollutant combinations, and cities are unlikely to have identical pollution profiles.

The primary rationale for reducing transport emissions is the health benefits from doing so. Appendix Table A1 lists World Health Organization and US Environmental Protection Agency guidelines on safe exposure levels for different air pollutants[6]. Tables A2 and A3 in the Appendix present the health impacts of these pollutants categorized by source, i.e., vehicle type, as well as by the different characteristics of motorized fleets that are the primary determinants of these emissions. This provides a means of deciding what particular aspect of the problem needs to be addressed, and is of particular relevance when designing projects that attempt to reduce transport related air pollution.

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[5] Keeping all other factors, including fuel prices, constant.

[6] Note that there is no "safe" level of exposure to many toxic chemicals.

For example, Table A2 indicates that gasoline volatility is responsible for carbon monoxide and hydrocarbon emissions.[7] Table A3 shows the rough magnitudes of emissions generated by major vehicle types.[8] The tables do not, however, indicate which health impacts would be of greater concern, nor which would be most readily addressed. This is partly due to the fact that the answers to these questions are location and circumstance specific, and partly because empirical work in this area has been fairly limited.

The Global Environmental Monitoring System (GEMS) study of 20 megacities, showed that nearly all have problems with particulate matter (PM).[9] PM sources are widespread, including industry, power generation, transport, and burning of wood, trash, etc. Contributions to total PM vary by city, but emissions inventories from World Bank URBAIR reports suggest transport is responsible for substantial shares. For example, in Manila, Jakarta, and Bombay transport-related emissions and resuspension of PM range from 33 to 43 percent of total PM (URBAIR 1996a, b, c). Within the transport sector itself, PM has several sources, thus complicating its abatement. Reduction of sulfur in gasoline and diesel would lower PM, but the great majority of transport PM (in developing cities) comes from resuspension from roads, and is exacerbated by traffic congestion. Hence, a comprehensive plan to lower PM would require at least three different (possibly concurrent) interventions: fuel reformulation, road paving/reconditioning, and the alleviation of congestion.

Another important local pollutant is ground-level ozone. Ozone formation requires both hydrocarbons (HC) and nitrogen oxides (NOx) in the presence of sunlight. Many variables are involved in the long and non-linear process, and there are a large number of sources of ozone precursors both within and beyond the transport sector. Although ozone formation can be controlled by limiting just one of its precursors the multiplicity of precursor sources complicates intervention.

The case of lead is relatively easy by comparison. If ambient concentrations of lead (Pb) are particularly high, as in many developing country cities, then policies targeting lead in gasoline can be adopted with little hesitation since, in the absence of smelters or other large industrial sources of lead emissions, blood lead concentration is highly correlated with gasoline lead levels. Lead can be controlled through a single instrument (fuel reformulation); and the costs of shifting to unleaded gasoline are relatively low when compared to the substantial benefits reaped.

The dispersion patterns of air pollutants also influence how their concentrations may best be reduced. For ambient carbon monoxide (CO) the relationship between concentration and motor vehicle traffic volume is roughly linear, although wind speed and direction, temperature inversions, and topographical characteristics also influence concentrations. Controlling CO concentrations in any particular area mainly requires controlling emissions originating in that area. On the other hand, it would be necessary to monitor many sites if a picture of city-wide concentrations is sought.

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[7] Gasoline vaporization depends upon average temperature ranges. Volatility is a vital consideration since relatively higher volatility is required to ensure vaporization under cold starting conditions (Faiz et. al 1996).

[8] Due to data limitations, the emissions factors generally pertain to developed country vehicles. Developing country vehicles correspond more closely with the uncontrolled emissions figures given in the table in many cases.

[9] Of the 20 cities, only London and Tokyo normally meet World Health Organization guidelines for ambient concentrations of particulate matter. Twelve cities have severe problems with PM, exceeding WHO guidelines by a factor of two or more (WHO/UNEP 1992). Incidentally, the GEMS study does not independently track the smaller particulates (such as PM_{10} and $PM_{2.5}$) that have been found to be relatively more harmful to human health than larger particles.

Concentrations of ozone tend to be much more spatially uniform, sometimes covering hundreds of thousands of square kilometers. This eases monitoring requirements compared to CO, but reducing ozone concentrations requires policies that affect precursor emissions on a (geographically) broad scale, encompassing at least an entire metropolitan region (Horowitz 1982). This necessitates integrated transport policy planning because wide area control of emissions calls for a variety of complementary policies.

IV. Policies to mitigate urban passenger transport emissions

Tables 1 and 2 present an array of policies to mitigate urban passenger transport emissions in the context of the framework discussed in section II. Table 1 lays out the objectives of different policies and presents the mechanisms through which they work, as well as highlighting the important incentive considerations that would determine their success. It attempts to provide a basis for integrated policies. Table 2 provides examples of both successful and unsuccessful policies, as well as implementation pointers. The tables do not, however, present a cost-based ranking of policies, since this would vary with the particular context.

The two tables clarify some of the major policy-selection and implementation issues involved with transport planning. For example, a policy maker seeking to reduce traffic congestion could choose from many policy options. If traffic volumes are not very high, but road and traffic conditions strain smooth flow, then efficiency enhancement measures (i.e. traffic engineering) may be a good first step. Alternatively, if road conditions are good, then direct demand management measures or augmentation of road supply (or both) may be appropriate. Note that if the road supply increases, the actual volume of traffic and resultant emissions may also increase. So the net impact of the policy on air pollution may be less than anticipated.

The price elasticity of demand affects car purchase and use decisions, upgrading to newer cars and better fuels, as well as the number of trips made. The choice of transport mode at the individual level also depends on many factors, including the availability of alternative means of transport (a function of population density), consumer income and price – which need to be explicitly included in the analysis of any policy lever.[10] The high dependence of transport emissions on behavioral factors means that it is difficult to predict the magnitude of abatement induced by different policies. (This is also why command and control types of policies like mandated emissions standards are much more predictable in their impact than standard market-based instruments like emissions taxes.)

Policy makers need to take account of the determinants of both supplier (manufacturer) and consumer (motorist) behaviour when analyzing the incentives implied by different policies. Policy combinations and complementarities complicate matters. Still, behavioral modifications are usually the key to reductions in automobile emissions.

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[10] See Shalizi and Talukdar (1998) for instance.

Figure 2. Policies Targeting Urban Passenger Transport Emissions and their Determinants

URBAN PASSENGER TRANSPORT EMISSIONS = EMISSIONS PER LITER OF FUEL x LITERS OF FUEL PER PASSENGER KILOMETER x PASSENGER KILOMETERS TRAVELED

Policies targeting total emissions
emissions taxes emissions permits
paving roads

EMISSIONS PER LITER OF FUEL

Determinants	***Policies targeting emissions per liter of fuel***
fuel type	emission standards[1]
fuel quality	fuel quality standards
-lead level	*-limit lead content*
-sulfur level	*-limit sulfur content*
-volatility	*-volatility limits*
-oxygenation	*-cleaner octane booster*
engine type	promote cleaner engines such as 4-stroke
technology	
-catalytic converter	mandated abatement equipment or retrofitting
-fuel injection	
-turbocharging	
age of vehicle	early scrappage incentives inspection & maintenance roadside inspections
temperature	none
altitude	none

LITERS OF FUEL PER PASSENGER KILOMETER

Determinants	***Policies targeting liters per passenger kilometer***
fuel efficiency	fuel economy standards fuel taxes/pricing
engine type	promote cleaner engines such as 4-stroke
vehicle load	promote carpooling, HOV enforce against overloading
age of vehicle	early scrappage incentive inspection & maintenance roadside inspections
congestion	traffic engineering demand management road supply
transport mode/ passenger capacity -bus, rail, metro	provide public transport to lower fuel per passenger kilometer traveled
road conditions	regular maintenance pave major roads

PASSENGER KILOMETERS TRAVELED

Determinants	***Policies targeting passenger kilometers traveled***
fleet size	new vehicle quotas cost of vehicles licensing/registration fees
number of trips	urban density/zoning road pricing/user fees parking fees no-car zones no-car days fuel taxes
distance of trips	urban planning locally based work/school
urban density	zoning laws promote walking, biking
population	urban planning
income	

1. Some countries have technology-forcing "low emission vehicle" and "zero emission vehicle" requirements that mandate manufacturers build some proportion of their fleets to higher specifications attainable only through alternative fuels.

As an instance, while strict enforcement of emissions standards has successfully controlled vehicular emissions per unit of fuel in the U.S., restraint of emissions growth will likely need to concentrate on reducing the main unregulated component, passenger kilometers traveled.[11] Shalizi and Carbajo (1994) note that the combination of greater fuel efficiency and lower fuel prices in the US has led to consumers shifting to vehicles with more powerful engines (e.g. sport utility vehicles) thus negating some of the emissions reduction achieved.[12] On the supply side, incentives to introduce cleaner burning engines and catalytic converters will depend on the cost of producing them and on whether there is a perceived demand for them at economically viable prices.[13] So far, low and zero emission vehicles introduced in the US have been costly and demand for them has been low.

V. Implementation issues

A policy considered in isolation may be ineffectual because of the countervailing impact of other factors. For instance, mandating strict emissions standards without providing unleaded gasoline would be impractical since the primary means of meeting such standards, catalytic converters, function only with unleaded fuel. And any demand management policy designed to dampen private motorized travel would function only if viable public transport (or non-motorized alternatives) were provided. As such, a "supply" of public/alternative transport is an indispensable part of the strategy. Less obviously, programs such as inspection and maintenance require more than physical space and equipment. Administrative capacity, including adequate training, staff, and competence are essential; yet they are sometimes overlooked.

It is therefore important to design complementary policies in a manner that integrates public and private transport, and combines supply-side and demand-side controls.

Ideally, measures should address not just the transport sector, but all three related areas: land-use planning, transportation needs and modes, and air quality. Land-use planning that encourages large employers to locate near residential districts may reduce travel demand and subsequent emissions. Also, high-density urban corridors have been shown to be amenable to cost-effective public transport (Midgley 1994).[14] To most effectively control transport pollution, thus, compatible strategies for land-use need to be designed prior to launching major transport initiatives (Rebelo 1996).

As mentioned earlier, the success of a policy may itself impose perverse incentives. Paving dirt roads in order to ease PM from resuspension and improving driving conditions may well raise the demand for

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[11] For example, new cars in the U.S. may emit 95 percent less CO, HC, and NOx than did uncontrolled cars in the 1960s (Harrington and Krupnick 1997). Since abatement opportunities through technological improvement have been nearly exhausted while travel demand management has received little attention in the U.S., abatement through reducing passenger kilometers traveled should be more cost effective (Eskeland and Devarajan 1996). The exception to this is the possibility of ultra-low or zero emissions vehicles. If emissions reach zero, then, in theory, passenger kilometers traveled becomes irrelevant to total emissions.

[12] They also noted that aggregate emissions in some US cities had started increasing again – due to increased automobile usage.

[13] It will also depend on relative fuel prices: lower prices for leaded than unleaded fuel can result in misfueling and the destruction of catalytic converters.

[14] Public transport also benefits from favorable land-use planning. When residences and work places are spread out, public transport becomes more difficult and costly to operate. Land-use can be made much more favorable to public transport if planned in advance.

travel. Likewise, relieving traffic congestion tends to attract more drivers since private travel becomes more efficient. Even emissions standards may send unintended signals. First, they may reduce fuel economy, and thereby raise consumption and CO_2 emissions.[15] Second, they provide no incentive for additional marginal emissions reduction once the standard is met, even if further reduction could be attained easily.

In addition, it is vital to ensure that incentive structures are compatible. For example, raising gasoline taxes to reflect the true social cost of using gasoline would have favorable impacts on passenger travel and fuel efficiency.[16] However, if a substitute such as diesel fuel were not taxed and remained substantially cheaper, then the gasoline tax policy would likely lose its punch as consumers switched to the cheaper fuel.

Finally, some instruments that permeate the full range of motorized transport systems can enhance virtually any abatement policy. Fuel taxes imposed on all fuels can help dampen demand, and they pay abatement dividends when used in concert with other policies, such as road pricing or fuel reformulation. As such, fuel taxes in tandem with other policies are nearly always a good combination (see Eskeland and Devarajan 1996).

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[15] Distinct emission control technologies have different effects on fuel economy. For example, lean-burn engines with electronic fuel injection tends to improve fuel efficiency while a three-way catalytic converter with a closed-loop carburetor tends to reduce fuel economy (Faiz et. al 1996).

[16] "Social cost" is a concept used by economists to account for both the private cost borne by the consumer of gasoline (i.e. its price) and the cost imposed on society by its use (e.g. air pollution damages, oil spills, underground seepage, political and military campaigns to safeguard oil sources, etc.).

Table 1. Policies to Mitigate Transport Emissions: Objectives and Mechanisms

Characteristic	Direct objective	Policy instruments	Functional mechanism	Incentive/Efficiency considerations
Transport emissions	Directly reduce vehicle emissions	mandated emissions standards	emissions stds: SS, control.	Standards may stimulate new technology. Increased cost of new technology and slightly reduced fuel economy may compel some to keep using older, more polluting cars longer.
Fuel quality	Reduce lead content; Reduce sulfur content; Use cleaner octane booster like oxygenation	mandated fuel standards; emissions tax; emissions permits	fuel standards: SS, control. emissions fee: DS, market.	Lower tax rate for unleaded gasoline (so unleaded is cheaper than regular) creates incentive for consumers to shift to unleaded. Lead trading and banking at the refinery level can reduce cost of converting to unleaded fuel.
Engine type	Encourage conversion away from highly polluting engines	promote halt to building & importing 2-stroke engines; retrofit existing 2-strokes; convert spark engines to run on alternative fuels	emission stds: SS, control. outright ban: SS, control. retrofitting prg: SS, control or market.	Conversion of new vehicle production to make cleaner engines is useful, but for developing countries where fleet turnover is slow, the effect on lower emissions will be very small. Retrofitting existing vehicles has greater impact, but will not likely be adopted without significant subsidies (despite low or negative costs).
Technology	Control emissions through technological measures	mandate catalytic converters in new cars; mandate PCV valves to control crankcase emissions; retrofitting program	catalytic convtr: SS, control. crankcase emiss: SS, control. retrofitting: SS, control or market.	Mandated technological fixes require adequate lead time for manufacturers to adjust. Insufficient lead time can cause loss of market share to foreign competitors or (temporary) lack of supply for consumers. Advanced 3-way catalytic converters must be imported by most developing country car manufacturers, adding to production costs.
Size of fleet	Control ownership of private vehicles	Ownership restrictions: new vehicle quotas; high ownership fees; import tariffs	quota: SS, control or market. ownership fee: DS, market. tariffs: DS, control.	Fees could have added impact if earmarked toward improving public transport systems. Import tariffs may reduce efficiency of domestic manufacturers and create political constituencies.
Age of fleet	Lower average age of vehicles in fleet; Repair or scrap old, highly polluting vehicles	scrappage incentives: higher registration fees for old cars; I/M program for at least class of high polluters; roadside inspections	registration fee: DS, market. I/M: SS, control. roadside insp: SS, control.	Early scrappage incentives may enhance prospects for new car manufacturers and dealers/distributors. However, may dampen used car market and harm relatively lower income consumers who can only afford to buy older, used vehicles. I/M and roadside insp. can reduce gross polluters, but may raise costs for those who cannot afford new cars.

Table 1 (continued)

Characteristic	Direct objective	Policy instruments	Functional mechanism	Incentive/Efficiency considerations
Congestion	Improve traffic flows; increase average speeds (congested conditions can increase exhaust emissions of CO, HC, and CO2 by 3-fold over free-flowing urban traffic)	Direct: new vehicle quotas; high taxes on ownership; no-car zones; no-car days; area pricing; road pricing; insurance adjustments according to vehicle usage Efficiency enhancement: computerized traffic lights; dedicated road lanes; staggered work hours; carpooling incentives; light rail or bus system Road supply: state-built roadways; joint public-private roads; private new toll roads	quota: SS, control or market. ownership fee: DS, market. no-car zones: DS, control. no-car days: DS, control. area pricing: DS, control. road pricing: DS, control. insurance: DS, market lights: efficiency, control. dedicated lanes: SS, control. staggered hrs: DS, control. carpools: DS, market. rail/bus: SS, state (control) or private (market). roads: SS, state. joint roads: SS, state/private. private roads: SS, private.	Disincentives for private vehicle ownership can pay long-run dividends by preventing widespread use and entrenchment/dependency. But stiff quotas/fees may harm domestic vehicle manufacturers, and becomes a political issue. Quotas on only new cars may encourage purchases of older, more polluting ones. Electronic road pricing technology permits variable fee assessment on cars to reflect marginal social cost according to degree of congestion, pollution, etc. Improving flow of traffic reduces congestion, but this may encourage more private travel. Efficient mass transit is a critical component of complementary policies that both deter consumers from private motorized transport and attract them to public transport. Incentive and profitability for private sector provision and operation of public transport may hinge in part on the extent and severity of the disincentives for consumer ownership and use of private cars. Increasing roads raises incentive to drive. But, if toll rates reflect construction/maintenance costs, then incentive structure yields more allocatively efficient consumer choices.
Number and length of trips	Control number and distance of private vehicle trips taken by passengers	reduce need for private travel: zoning laws - "living downtown" urban plans, high density corridors, higher urban density; provide efficient public transport reduce incentive to drive: high peak hr. driving fees; high parking fees; high fuel taxes; no-car zones	zoning: DS or SS, control. public transport: SS, market. driving fees: DS, control. parking fees: DS, market. fuel taxes: DS, market. no-car zones: DS, control.	Well designed zoning policies reduce consumer demand for private motorized travel. May also create sufficient incentives for private sector to provide public transport (since high density/ridership along accessible routes may be profitable). Urban density amenable to pedestrians may stimulate small retail business due to walk-by traffic and window-shopping. Pedestrian-friendly urban areas call for safeguards: well-enforced crosswalks, sidewalks, and night time illumination. High car usage/parking fees may spark resentment among consumers, especially in the absence of adequate public transport. May dampen private car sales.
Public transport	Reduce congestion and emissions per passenger kilometer	provide well-coordinated public transport systems that can diminish number of private commuters	buses: SS, market. trains: SS, market. metro: SS, market.	Public transport is key to attracting consumers away from private motorized transport. Incentives needed to attract commuters: efficiency, reliability, convenience. Private provision/operation of public bus systems may be viable without subsidy (Seoul, Hong Kong).

Table 2. Policies to Mitigate Transport Emissions: Implementation Issues and Examples

Characteristic	Policy instruments	Implementation issues	Examples
Transport emissions	directly reduce vehicle emissions through stds.	Emissions standards may be technology-forcing or technology-following.	Emission standards: highly successful in U.S.
Fuel quality	mandated fuel standards; emissions tax; emissions permits	Mandated fuel standards have been highly successful in U.S., Japan, Europe. Reformulation cost can be significant, but much lower than health benefit. Oxygenation reduces HC and CO emissions, but may raise NOx.	Zero-lead stds: Thailand, Mexico, Brazil, Colombia, Japan. Volatility limits: U.S., Sweden, Finland. Oxygenation stds: U.S., Brazil, S. Africa, S. Korea, Thailand, Sweden, Finland. Emissions fees: none
Engine type	promote a halt to building and importing dirty 2-stroke engines; convert new 2-strokes; convert bus/truck/taxi engines to run on alternative fuels	Adequate lead-time is required for manufacturers to comply at low-cost. Cost to consumers is about 6% for motorcycles (to add catalytic converters to 2-strokes in Taiwan). Some conversions may have low or negative costs (due to fuel cost savings, etc.). Others may require strong incentive/support programs.	Elimination of 2-stroke motorcycles by setting emissions standards: U.S. Taiwan: adopted U.S. standards, but more recent technology allows some advanced 2-strokes to meet standards. Retrofitting tuk tuks to run on LPG: Bangkok Converting taxis to run on LPG: Tehran Converting buses to run on CNG: Santiago
Technology	mandate catalytic converters in new cars; mandate PCV valves to control crankcase emiss.; retrofitting program	Consumer tampering with catalytic converters may be problematic. I/M program can mitigate this.	Catalytic converters: U.S. Crankcase emissions: U.S. Retrofitting catalytic converters: Germany, Sweden, Hungary
Size of fleet	Ownership restrictions: new vehicle quotas; high ownership fees	Requires strong policies to succeed amid economic growth. More feasible if: consumer demand is relatively low, cities are dense, public transport is efficient, and complementary policies (like high parking fees, road/area pricing, high fuel taxes) exist.	Quota: Singapore High ownership fees: Singapore, Vietnam
Age of fleet	scrappage incentives: higher registration fees for old vehicles; I/M program for at least class of high polluters; roadside inspections	Scrappage programs have worked, e.g., subsidized trade-in programs; I/M programs are costly to set-up and administer. Inspecting subset of vehicles may be more feasible.	Scrappage incentive: Singapore, Mexico City (taxis) I/M: U.S., European Union, Japan Roadside insp: Hong Kong, Mexico, Thailand

Table 2 (continued)

Congestion	Direct: new vehicle quotas; high taxes on ownership no-car zones; no-car days; area pricing; road pricing; insurance adjustments	Direct policies succeed in some cities. Require political will and strength (bec. consumer opposition). No-car days in Mexico had perverse effect of raising emissions. No car zones have been well-received by consumers and business owners in some areas. Area and road pricing requires initial investment, but fees generate revenue. Insurance: verification of usage rates is difficult.	Quota: Singapore High ownership fees: Singapore, Vietnam No-car zones: Curitiba Brazil, Tokyo, Hong Kong No-car days: Athens, Mexico City, Santiago Area pricing: Singapore, Amsterdam, unsucsful in Kuala Lum Road pricing: widespread Insurance adjustment: U.S.
	Efficiency enhancement: computerized traffic lights; dedicated road lanes; staggered work hours; carpooling incentives; light rail or bus system	Traffic engineering can work, but sometimes there is an immediate one-time benefit followed by gradual deterioration. Initial cost may be high (but usually outweighed by benefits). Commuter spacing has mixed record. Mass transit done well is effective, but may be costly (esp. subway systems). Buses are relatively cheaper.	Synchronized traffic lights: widespread (London is advanced) Dedicated bus lanes: Bangkok, Jakarta, Manila, Sao Paulo, Tehran, Tokyo; HOV lanes for cars are widespread Staggered work hours: Singapore, Surabaya Carpooling incentives: U.S., Singapore Light rail/metro: Cairo, Calcutta, Hong Kong, Mexico City, Pusan, Rio de Janeiro, Santiago, Sao Paulo, Seoul, Singapore
	Road supply: state built roadways; joint public-private roads; private new toll roads	Increasing road supply has low prospects for success in long run (since it may encourage more driving), but can help in short run.	New public road construction: widespread New private toll road construction: U.S., Malaysia
Number and length of trips	reduce private travel need zoning laws, "living downtown" urban plans; high density corridors; provide public transport	Zoning laws/action may be politically-laden. Zoning reorganization may be too late in established cities. No car zones have been popular in some cities.	Living downtown zoning: Washington, DC High density corridors: Curitiba, Arlington, VA. Peak time driving fees: Singapore Parking fees: widespread No car zones: Curitiba Brazil, Tokyo, Hong Kong
	reduce incentive to drive: high fees to drive during peak hours; high parking fees; high fuel taxes; no-car zones		
Public transport	provide well-coordinated mass transit systems that can diminish number of private commuters	Provision of public transport may be costly. Private suppliers may relieve burden from the state. Lower fares do not necessarily attract more riders. Coordination of mass transit such as feed-in routes and park and ride schemes improve efficiency.	Buses: widespread Trains: widespread Metro: Cairo, Calcutta, Hong Kong, Mexico City, Pusan, Rio de Janeiro, Santiago, Sao Paulo, Seoul, Singapore Park and ride: widespread

VI. Review of selected urban transport projects

The salient features of the following projects are briefly summarized in Table 3.

- Singapore Area Licensing Scheme
- Malaysia Second Kuala Lumpur Urban Transport Project
- Hong Kong Vehicle Pollution Control program
- Seoul Bus Lane Priority program
- Bangkok Traffic Management Project
- Santiago Urban Streets and Transport Project
- Brazil Curitiba Urban Transport Project
- Mexico Transport Air Quality Management Project for the Mexico City Metropolitan Area
- Islamic Republic of Iran Tehran Transport Emissions Reduction Project.

This selection includes projects that were Bank assisted as well as government programs that did not receive any assistance from the World Bank. It is interesting to note that before the 1990s most traffic management projects did not explicitly talk about air pollution, although many of the steps they proposed would have had a direct or indirect impact on transport related emissions. These projects tended to affect pollution through their impact on total passenger kms or liters of fuel per passenger km.[17]

Demand management requires a degree of political will that is rare, but surprisingly few of these projects include components focusing on land-use planning and public transport provision, which are less politically charged. These three measures are the hallmarks of the most successful project in our sample – the well-known case of Singapore. The case of Curitiba is almost as famous for its emphasis on integrated land use and transport planning.

Quite a few projects in the sample explicitly consider per-vehicle emissions reduction via technical control components such as fuel reformulation, emissions standards and technology, and inspection and maintenance programs. But even without technological controls, demand management and public transport provision can reduce two of the three major components of total emissions: liters of fuel per passenger kilometer and passenger kilometers traveled. The various demand management measures (increased bus fares, road user charges, and parking fees) tend to dampen kilometers traveled, while public transport reduces fuel use per person in high density urban areas.

It is worth stating that unrelated government programs often undermine air pollution and transport efficiency goals. For instance, in Mexico City and Seoul government policies promoted the ownership and use of private cars (in part to support their domestic automobile industries) even as they tried to reduce air pollution by lowering congestion.

VII. Conclusion

This report has attempted to clarify some of the key issues affecting passenger transport-related air pollution in urban areas by presenting a simple framework for analysis. The virtue of this framework lies in its separation of factors and its simplicity, which can provide a sound basis for designing appropriate transport air pollution abatement policies.

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[17] This paper has not examined non-motorized alternatives to the automobile. To that extent, we have ignored a whole set of possible solutions to the problem of poor urban air quality due to transportation related emissions.

- It is clear that any significant urban transport project or policy has implications for air pollution. As we have indicated, policies intended to improve transport efficiency often enhance air quality at the same time. This appears obvious when one notes that transport mode, road conditions and congestion levels are critical determinants of fuel use per passenger km, and that land-use planning choices would have a sizeable impact on passenger km traveled.

- In contrast to demand management, supply-side policies to relieve motor vehicle congestion may conflict with supply side measures to control air pollution. The countervailing impact of the rise in private motorized traffic in response to road and traffic improvements often makes it difficult to assess the net effect on air pollution. Building new roadways (absent road pricing) to alleviate heavy traffic can encourage a rise in the quantity of vehicles owned and on the road by making driving easier and relatively more cost effective. This would tend to worsen air pollution. However, other supply side measures can have the opposite effect on air pollution. If public mass transit systems (including bus and rail service) are well designed and efficient, commuters can be induced to use those alternatives to private vehicles *if* the appropriate demand management policies are adopted.[18]

- Finally, there appears to be considerable scope for low cost solutions to air quality concerns regarding the transport sector. Often low technology, inexpensive policies such as establishing bus lanes or paving dirt roads substantially improve both transport efficiency and air quality.

The review of urban transport projects supplies a second perspective on these concerns. Overall there appear to be useful lessons to be learnt.

- The presence of a viable public transport system is necessary. Singapore's system, to cite the best known example, is critical to the success of the process of demand management adopted by that city. For cities contemplating measures to ease urban congestion, the provision of public transport has to be a priority if the enforcement of regulations limiting road usage or road pricing is not to be a complete sham. Behavioral change is very difficult, the more so in the absence of viable alternatives, as can be seen from the experience of Kuala Lumpur and Bangkok.

- As seen in Hong Kong, Singapore, and Mexico City, fuel and emissions standards should gradually become stricter over time. This ensures that the incentive to develop and adopt cleaner technology does not disappear, and the gradual ratcheting up of standards prevents major disruptions in production, which can be politically important when a domestic auto industry exists.

- Sustained enforcement appears to be key to limiting congestion and controlling related air pollution. Cities like Seoul and Bangkok have suffered reversals in their campaign against congestion primarily because incremental improvements in congestion led to disproportionate increases in the number of vehicles on the streets.

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[18] There is little empirical evidence on consumers switching from an automobile-oriented lifestyle to using public transport in the absence of strong policy intervention.

Table 3. Summary Comparison of selected Transport projects

City (year)	Project	Overall aim	Specific objectives	Demand side measures	Supply side measures	Impact upon air pollution	Critical factors	Comments
Hong Kong (1995-)	Vehicle Pollution Control Program.	Reduce ambient concentrations of PM and Lead.	Curtail emissions of PM and lead per unit of fuel.		Reformulation of diesel fuel to reduce sulfur content New, tighter vehicle emission standards.	Lower emissions from using cleaner fuel.	Fuel and emission standards become stricter over time.	Future plans include introducing vehicle inspection, and converting light duty diesel vehicles to run on gasoline.
Seoul (1995-)	Bus lane priority.	Improve urban road transport.	Increase central city traffic speeds. Reduce congestion.		Improve bus service by establishing bus priority lanes.	Lower emissions since less congestion and high bus ridership reduces fuel use per passenger km.	Earlier pro-car policies helped create congestion problems.	Bus lanes have reduced congestion, but enforcement must be sustained. Situation would be worse without intervention
Bangkok (1979-85)	Bangkok Traffic Management Project.	Improve road transport efficiency.	Increase traffic speeds. Reduce car use. Reduce congestion.	Cut number of downtown parking spaces.	Establish bus lanes. Modernize traffic signals.	Initial declines in congestion & poor public transport led to more vehicles so overall impact on emissions unclear.	Lack of long range planning spawned acute congestion problems.	Maintenance of traffic signals and enforcement of bus lanes are critical. Situation would be worse without intervention
Santiago (1989-95)	Urban Street and Transport Project.	Improve roads and curb air pollution.	Integrate transport modes.	Weekly ban on vehicles without catalytic converters. Ban empty taxis in CBD.	Pave and repair dirt roads. Retire old buses. Computerize traffic lights. Develop and enforce emissions & fuel standards. Introduce unleaded gas.	Paving roads directly reduces total PM emissions. Despite encouraging greater car use, the level of air pollution declined post project.	Low-cost paving method permitted a quadrupling of expected new pavement.	Increasing supply of roads encourages more car use. Bikeway was scrapped.
Curitiba (1979-85)	Brazil Urban Transport Project.	Improve access and efficiency of transport system.	Synchronize bus system, improve energy efficiency. Reduce commute time for residents of outlying areas.		Establish trunk/ branch bus line system. Pave feeder roads. Establish high-density corridors along trunks.	Likely lower emissions due to road paving, greater fuel efficiency on better roads and higher bus use.	Bus system's success became a model for other cities.	Bus system requires passengers to change buses. Fare system should be integrated.

Table 3. (continued)

City (year)	Project	Overall aim	Specific objectives	Demand side measures	Supply side measures	Impact upon air pollution	Critical factors	Comments
Singapore (1975)	Area Licensing Scheme	Manage urban transport and constrain motorization	Reduce demand for cars. Restrain car usage. Reduce congestion. Change modal split.	Increase private cost of vehicle ownership through car taxes. Auction car licenses. Raise cost of usage via monthly user fees and high parking fees in the Restricted Zone (RZ). Restricted travel zones. Land-use planning.	Provision of a high quality, integrated public transportation system. Increased road capacity and traffic engineering.	Concentrations of NOx, CO, PM declined within RZ, suggesting impact of policy.	Sound public transport alternative. Authority of central govt. Policy fine-tuned over time.	Traffic declined in RZ during operational hours but increased on routes outside and during hours preceding.
Mexico (1992)	Transport Air Quality Management Project	Improve urban air quality	Reduce vehicle emissions. Improve fuel quality. Restrain car usage.	Increase gasoline price; make unleaded fuel competitive; make CNG cheapest. Hoy no circula, with exemptions for clean vehicles.	Fuel reformulation. Encourage clean fuels; CNG retrofitting. Taxi replacement.	Impact on emissions through cleaner fuels.	Program fine-tuned over time.	Cheap local "people's car" and low cost of car ownership undermines program. Limits to tech solutions like emissions standards.
Kuala Lumpur (1975)	Second Urban Transport Project	Improve efficiency of transport system in KL.	Restrain car usage. Improve public transport.	Area Licensing Scheme	New road construction. Phase-out seat tax on buses.	Indeterminate.		ALS collapsed due to political/admin problems, inadequate public transport
Teheran (1995-)	Transport Emissions Reduction Project	Reduce emissions per unit fuel (via emissions standards). Reduce fuel use per passenger km.			New vehicle emission and fuel use standards.	Unknown since plan has not yet been implemented.	Tech solutions are easier to implement than those requiring behavioral changes.	Emissions from installed base unaffected. Limits to tech. solutions.

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Appendix

Table 1A shows guidelines and standards for acceptable exposure levels to many of the pollutants related to urban passenger transport. World Health Organization standards are for Europe, developed by the WHO Regional Office for Europe. U.S. Environmental Protection Agency standards are those developed under the Clean Air Act and subsequent associated legislation.

Two major classes of human health effects of exposure to outdoor air pollution exist. Acute effects are those that occur immediately (within 24 hours) after exposure. Often, acute effects are brief in duration, and may disappear after exposure ends. However, sometimes exposures to very high concentrations of pollutants can cause irreversible acute effects or even death. The entries in Table 1A showing relatively shorter exposure durations intend to establish safety thresholds for acute effects. However, highly sensitive individuals may suffer acute effects at lower ambient concentrations or briefer exposure durations (i.e., lower doses).[19] Moreover, several pollutants in combination may trigger acute effects despite "safe" doses of individual pollutants.

Chronic effects are long-lasting responses to pollution, usually the outcome of repeated exposures over a lengthy period of time. Chronic effects are usually delayed rather than immediate. The longer exposure entries in the table are designed to prevent the onset of chronic effects. However, the long term effect of mixtures of contaminants are not fully considered in these standards.

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[19] Dose is equal to the product of ambient concentration and duration of exposure.

Table 1A. **Standards and Guidelines for Transport-Related Air Pollution**
(Maximum acceptable outdoor exposures)

Pollutant	World Health Organization standards	U.S. Environmental Protection Agency standards
Carbon dioxide	1800 micrograms/m3	1440 micrograms/m3
(CO_2)		
Carbon monoxide	100 micrograms/m3 (15 minute average)	
(CO)	60 micrograms/m3 (30 minute average)	
	30 micrograms/m3) (1 hour average)	40 micrograms/m3 (1 hour average)
	10 micrograms/m3) (8 hour average)	10 micrograms/m3 (8 hour average)
Lead (Pb)	0.5 microgram/m3 (annual average)	1.5 microgram/m3 (annual average)
Nitrogen dioxide	500 micrograms/m3 (10 minute average)	
(NO_2)	125 micrograms/m3 (24 hour average)	
	50 micrograms/m3 (annual average)	100 micrograms/m3 (annual average)
Ozone	120 micrograms/m3 (8 hour average)	235 micrograms/m3 (1 hour average)
		156 micrograms/m3 (8 hour average)
Particulate matter		150 micrograms/m3 (24 hour average)
(PM10)		
Fine particulate matter		65 micrograms/m3 (24 hour average)
(PM2.5)		15 micrograms/m3 (annual average)
Sulfur dioxide	500 micrograms/m3 (10 minute average)	
(SO_2)	125 micrograms/m3 (24 hour average)	365 micrograms/m3 (24 hour average)
	50 micrograms/m3 (annual average)	80 micrograms/m3 (annual average)

Notes:
1. Concentration limits for carbon dioxide are associated with indoor air.
2. CO2 effects are associated with global climate change, not direct health effects
3. WHO guidelines do not include a PM10 standard: "For PM10, available epidemiological data did not facilitate the establishment of a level below which no effects would be expected. Therefore, no specific guideline value was established, but, instead, exposure-effect information was provided, giving guidance to risk managers about the major health impact for short and long term exposure to various levels of this pollutant."
4. All ambient concentrations given in micrograms per cubic meter

Sources:
World Health Organization. 1998. "WHO Air Quality Guidelines for Europe." 2d ed.
California Environmental Protection Agency, Air Resources Board. 1998, "Review of existing standards and guidelines applicable to indoor air quality" (Draft memo).

Table A2. Impacts of Transport-Related Air Pollution by Contributing Characteristic

Characteristic	Pollutant	Source	Health Impacts
fuel quality / fuel volatility	CO	CO: exhaust emiss. from fuel volatility	CO: reduced blood oxygen
	HC	HC: exhaust emiss. from fuel volatility	HC: ozone precursor (ozone: respiratory illness, asthma, eye irritation, activity restriction
	Pb	Pb: lead in gasoline	Pb: hypertension, loss of IQ pts, premature death
	SOx	SOx: sulfur in gasoline, diesel[1]	SOx: respiratory illness, premature death
	PM	PM: from sulfur in gasoline and diesel	PM: respiratory illness, asthma, chronic bronchitis, premature death
	VOC	VOC: evaporative emissions from gasoline[2]	VOC: some (like benzene) are carcinogenic; also photochemical smog precursor)
congestion	CO	CO: frequent acceleration, low speeds[3]	CO: reduced blood oxygen
	HC	HC: frequent acceleration, low speeds	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	CO2	CO2: frequent acceleration, low speeds	CO2: greenhouse gas
	PM	PM: low speeds	PM: respiratory illness, asthma, chronic bronchitis, premature death
age of fleet	CO	CO: old, poorly maintained cars[4]	CO: reduced blood oxygen
	HC	HC: old, poorly maintained cars	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	CO2	CO2: older vehicles, less fuel efficient	CO2: greenhouse gas
size of fleet	all	contributes to congestion number of cold starts[5]	see above
number of trips	all	number of cold starts contributes to congestion	see above
length of trips	all	kilometers traveled	see above
road conditions	CO	may slow travel, overburden engines;	CO: reduced blood oxygen
	HC	similar effect to congestion	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	CO2	reduce fuel efficiency	CO2: greenhouse gas
	PM	unpaved/poorly maintained roads cause PM from resuspension	PM: respiratory illness, asthma, chronic bronchitis, premature death

Notes:

1. Typically, diesel fuel has a much higher sulfur content (0.1 to 0.5 percent) than gasoline (0.02 to 0.07 percent) (Harrington and Krupnick 1997). Besides SOx, reducing sulfur in gasoline can lower HC, CO, and NOx by improving performance of catalytic converters (Faiz et. al 1996).
2. Reducing gasoline volatility from 9 psi to 8 psi lowers total evaporative emissions by 34 percent with no appreciable effect on fuel economy. It also lowers HC emissions by 4 percent and CO by 9 percent (Faiz et. al 1996).
3. Acceleration in modern cars propels engines into "enrichment mode" whereby CO emissions rise by a factor of 100 and those of HC increase by a factor of 10 (Harrington and Krupnick 1997). Emissions from heavy diesel vehicles are especially sensitive to speed and acceleration. In France, congested conditions increase automobile exhaust emissions of CO, HC, and CO2 by 3-fold over free-flowing urban traffic (Faiz et. al 1996).
4. Poorly maintained vehicles without catalysts can generate 4 or more times the HC and CO of well maintained vehicles without catalysts (Faiz et. al).
5. Under cold conditions, engines require additional fuel to start, generating very high HC and CO emissions. Cold starts account for over 80 percent of total HC and CO emissions from modern, emission-controlled vehicles (Faiz et. al 1996).

Table A3. Impacts of Transport-Related Air Pollution by Vehicle Type

Vehicle Type	Pollutant	Quantity (grams per kilometer)	Health Impacts
Motorcycles and scooters	CO[1]	CO: in EU: controlled 4-stroke 20; unctrld 40 controlled 2-stroke 22; uncontrolled 24.6	CO: reduced blood oxygen
	HC	HC: in EU: uncontrolled 4-stroke 5.9; uncontrolled 2-stroke 19.0	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	PM[2]	PM:in US: uncontrolled 2-stroke 0.206; uncontrolled 4-stroke 0.048	PM: respiratory illness, asthma, chronic bronchitis, premature death
	NOx	NOx: in EU: controlled 4-stroke 0.1; controlled 2-stroke 0.3	NOx: ozone precursor (ozone: respiratory illness, asthma, eye irritation, activity restriction)
	VOC[3]	VOC: in EU: 4-stroke 2.8; 2-stroke 14.9	VOC: some (like benzene) are carcinogenic; also photochemical smog precursor
	CH4	CH4: in EU: 4-stroke 0.20; 2-stroke 0.15	CH4: greenhouse gas
	CO2	CO2: depends on fuel quality	CO2: greenhouse gas
Gasoline-powered passenger cars[4]	CO	CO: in US: 6.2; uncontrolled: 42.67	CO: reduced blood oxygen
	HC	HC: in (uncongested) urban France 3.52	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	PM	PM: in EU: 0.00	PM: respiratory illness, asthma, chronic bronchitis, premature death
	NOx	NOx: in US: 0.52, uncontrolled: 2.70	NOx: ozone precursor (ozone: respiratory illness, asthma, eye irritation, activity restriction)
	VOC	VOC: in US: 0.67; uncontrolled: 5.62	VOC: some (like benzene) are carcinogenic; also photochemical smog precursor
	CH4	CH4: in US: 0.04; uncontrolled: 0.19	CH4: greenhouse gas
	CO2	CO2: in US: 200; uncontrolled: 399	CO2: greenhouse gas
diesel buses and trucks[5]	CO	CO: in US: 6.33; uncontrolled: 7.31	CO: reduced blood oxygen
	HC	HC: in US: 1.32; uncontrolled: 2.52	HC: ozone precursor (respiratory illness, asthma, eye irritation, activity restriction)
	PM	PM: in EU: 1.6	PM: respiratory illness, asthma, chronic bronchitis, premature death
	SOx	SOx: in India: 1.5	SOx: respiratory illness, premature death
	NOx	NOx: in US: 5.09; uncontrolled: 15.55	NOx: ozone precursor (ozone: respiratory illness, asthma, eye irritation, activity restriction)
	VOC	VOC:	VOC: some (like benzene) are carcinogenic; also photochemical smog precursor
	CH4	CH4: in EU: 0.175	CH4: greenhouse gas
	CO2	CO2: in US: 982; uncontrolled: 1249	CO2: greenhouse gas

Notes:

1. Emissions data for CO, HC, NOx, VOC, and CH4 from Faiz et. al (1996), Table 2.6 for uncontrolled emissions and Table A2.1.3 for controlled.
2. Emissions for PM is average FTP emissions from U.S. uncontrolled motorcycles (Chan and Weaver 1994, Tables 5-1 and 5-2).
3. All VOC emissions data refer to non-methane volatile organic compounds.
4. Emissions figures for U.S. refer to advanced 3-way catalysts for "controlled" and no catalyst for "uncontrolled" (Faiz et. al 1996: Table 2.1). PM figure derived from Tables A2.1.1, A2.1.2.
5. U.S. data refer to heavy-duty trucks (Faiz et. al 1996: Table 2.4., Table A2.2.5). Data for EU covers heavy-duty vehicles in urban conditions (Table A2.2.3). Emissions for India cover heavy-duty trucks (Table A2.2.12).

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